SECTION 4

POWER SUPPLY CIRCUITS

PART A. ELECTRON-TUBE CIRCUITS

SINGLE-PHASE, HALF-WAVE RECTIFIER.

APPLICATION.

The single-phase, half-wave rectifier is used in all types of electronic equipment for applications requiring high-voltage dc at a low load current. The rectifier circuit can be arranged to furnish negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

Uses high-vacuum or gas-filled electron-tube diode as rectifier.

Output requires filtering; d-c output ripple frequency is equal to primary line-voltage frequency.

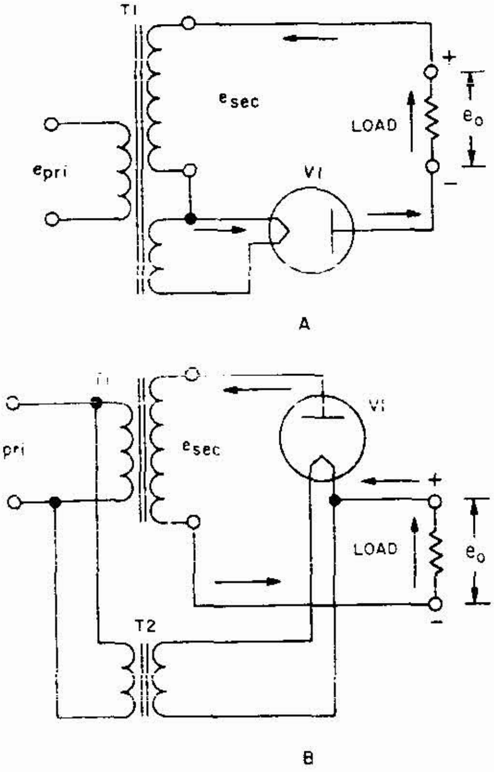
Has poor regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

CIRCUIT ANALYSIS.

General. The single-phase, half-wave rectifier is one of the simplest types of rectifier circuits. The circuit consists of a rectifier (diode) in series with the alternating source and the load. Since the rectifier conducts in only one direction, electrons flow through the load and through the rectifier once during each complete cycle of the impressed voltage. Rectifier conduction occurs only during the interval of time the plate is positive with respect to the filament (cathode). Thus, the electrons flow through the load in pulses, one pulse for each positive half cycle of the impressed voltage.

Circuit Operation. In the accompanying circuit schematic, parts A and B illustrate an electron-tube diode, V1, used in a basic single-phase, half-wave rectifier circuit. The circuit given in part A uses a single transformer, T1, to step up the alternating-source voltage to a high value in the secondary. The filament of the tube, V1, is operated from a low-voltage secondary winding located on the same core and connected to the high-voltage winding. The circuit given in part B is shown with two separate transformers: T1 is a step-up transformer to obtain high voltage, and T2 is a step-down transformer to obtain the correct filament voltage for the operation of V1. Although separate transformers are shown in part B, the low-voltage secondary of T2 could just as well be wound on the core of transformer T1, provided that the high- and low-voltage secondary windings are adequately insulated from one another and that the simultaneous application of plate and filament voltages to the tube is permissible.

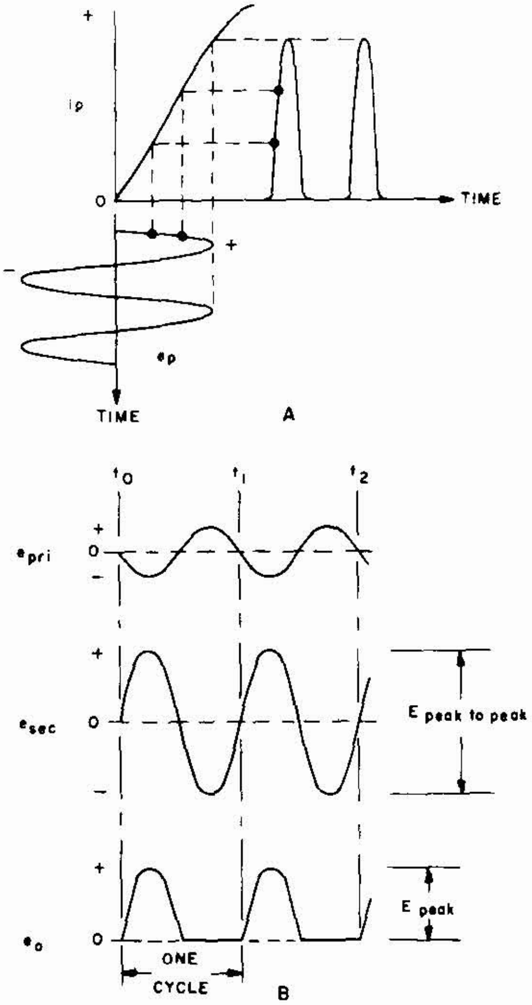


Basic Single-Phase, Half-Wave Rectifier Circuits

In the two circuits illustrated, either terminal of the load may be placed at ground potential, depending upon whether a positive or negative d-c output is desired. The circuit illustrated in part A is commonly used as a negative high voltage supply with the positive terminal of the load connected to ground (chassis); the circuit illustrated in part B is commonly used as a positive high-voltage supply with the negative terminal of the load connected to ground.

The operation of a half-wave rectifier circuit can be understood from the waveforms given in the accompanying illustration.

In part A, the E_p-I_p characteristic curve for the rectifier is given. When high-voltage ac is applied to the rectifier circuit, electrons flow through the tube and the load whenever the plate is positive with respect to the filament or cathode; the amount of current is determined by the characteristic curve of the tube. Part A of the illustration shows that for each positive half cycle of the applied voltage, a current pulse passes through the rectifier, the load, and the secondary winding of the transformer, T1. For each negative half cycle of the applied voltage, the plate is negative with respect to the filament or cathode and no current pulse is obtained. Thus, the electrons flow through the load circuit in pulses, to produce a pulsating current waveform as shown in part A of the illustration.



Waveforms for Half-Wave Rectifier Circuit

In part B of the illustration, voltage waveforms for the half-wave rectifier circuit are given. The primary winding of transformer T1 is connected to an a-c source, represented as waveform e_{pri}. The transformer, T1, increases the primary voltage to a higher value in the secondary winding by step-up transformer action. The purpose of the small secondary winding of T1 (or T2) is to supply voltage to the filament of rectifier tube V1. The alternations of the a-c source, e_{pri}, are applied to the primary of the transformer and induce a voltage, e_{sec}, in the secondary winding of the transformer. The waveform illustration shows a 180-degree change in phase between the primary (e_{pri}) and secondary (e_{sec}) voltages because of transformer action and the fact that the secondary-output voltage is an induced voltage. Since the transformer is a step-up transformer, the amplitude of the secondary voltage, e_{sec}, is greater than the applied primary voltage, e_{pri}. The induced secondary voltage, e_{sec}, is applied across the rectifier and the load. On positive half cycles of e_{sec}, current passes through the rectifier and the load resistance, producing an output voltage, e_o, across the load resistance. The output voltage e_o, has a pulsating waveform which results in an irregularly shaped ripple voltage; the frequency of the ripple voltage is the same as the frequency of the a-c source. Because the output voltage and current are not continuous, the half-wave rectifier circuit requires considerable filtering to smooth out the ripple and produce a steady d-c voltage.

The half-wave rectifier utilizes transformer T1 during only one half of the cycle; therefore, for a given transformer less power can be developed in the load than could be developed if the transformer were utilized for both halves of the cycle. Thus, if a considerable amount of power is to be developed in the load, the half-wave transformer must be relatively large compared with a transformer in which both halves of the cycle are utilized. This disadvantage limits the use of the transformer-type half-wave rectifier circuit to applications which require a relatively small load current. Since the d-c load current passes through the secondary winding in only one direction, the laminated-iron core of the transformer tends to become magnetized. This effect is called **d-c core saturation** and reduces the effective inductance of the transformer. The net effective inductance with the d-c core saturation effect present is known as **transformer incremental inductance.** Thus, transformer incremental inductance is reduced as the d-c load current is increased. The resultant effect is to decrease the primary counter emf to a greater degree and thereby increase the load component of primary current. Therefore, the efficiency of the transformer is reduced, and the regulation of the circuit is impaired.

The half-wave rectifier, assuming half sine waves as the waveform for the output voltage, e_o (unfiltered), produces the following root-mean-square voltage:

$$E_{rms} = \frac{E_{max} \times 0.707}{2}$$

where: E_{max} =maximum instantaneous voltage.
The corresponding average output voltage is:

$$E_{av} = 0.45\ E_{rms}$$

Similarly, the root-mean-square and average output currents can be expressed as:

$$I_{rms} = \frac{I_{max} \times 0.707}{2}$$

and: $I_{av} = 0.45\ I_{rms}$

The **peak inverse voltage** of a rectifier tube is defined as the maximum instantaneous voltage in the direction opposite to that in which the rectifier is designed to pass current. The peak inverse voltage across the rectifier in a half-wave rectifier circuit during the period of time that the tube is nonconducting is approximately 2.83 times the rms value of the transformer secondary voltage. The peak inverse voltage can be expressed as:

$$E_{inv} = 2.83 \, E_{rms}$$

where: E_{rms} = transformer secondary (or applied) voltage

The output of the rectifier circuit is connected to a suitable filter circuit, to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in part D of Section 4.)

FAILURE ANALYSIS.

No Output. In the half-wave rectifier circuit, the no-output condition is likely to be limited to one of three possible causes: a defective rectifier tube (open filament), the lack of applied a-c voltage, or a shorted load circuit (including shorted filter-circuit components).

A visual check of a glass envelope rectifier tube can be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of correct filament voltage at the tube socket should be determined by measurement.

The a-c secondary voltage, e_{sec}, should be measured at the terminals of transformer T1 to determine whether the voltage is present and of correct value. If necessary, measure the applied primary voltage, e_{pri}, to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, continuity (resistance) measurements of the primary and secondary windings should be made to determine whether one of the windings is open, since an open (discontinuity) in either winding will cause a lack of secondary voltage. Also, continuity measurements should be made between each transformer secondary terminal and the corresponding tube socket or load terminal to determine whether either one of these two leads is open.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. If the filter circuit incorporates an electrolytic capacitor, the resistance measurements made across the output of the rectifier circuit may vary depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the circuit test points for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value. A short in the components of the filter circuit or in the load will cause an excessive load current to flow. If the rectifier tube is a high-vacuum type, the heavy load current will cause the plate to become heated and emit a reddish glow when the plate dissipation is exceeded and, if allowed to continue, may result in permanent damage to the tube. If a gas-filled rectifier is used in the circuit, a heavy current overload will likely result in damage to the tube, because gas-filled rectifiers are more susceptible to damage from current overload than are high-vacuum rectifiers.

Low Output. The rectifier tube should be checked to determine whether the cause of low output is low filament emission. The load current should be checked to make sure that it is not excessive, because the half-wave rectifier circuit has relatively poor regulation and a decrease in output voltage can be caused by an increase in load current (decrease in load resistance). Also, the a-c secondary voltage, e_{sec}, and the primary voltage, e_{pri}, should be measured at terminals of transformer T1 to determine whether these voltages are present and of the correct value. Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. Shorted turns are not easily detected by resistance measurement; a voltage measurement is a more reliable indication. If the transformer losses (due to shorted turns) are excessive, the transformer may also become overheated. Another check to determine whether the transformer is defective is to disconnect the secondary load (s) and measure the primary current with the transformer unloaded; excessive primary current is an indication of shorted turns. Still another check is to disconnect all primary and secondary leads from the transformer terminals and make measurements between the individual windings and the core, using an ohmmeter or a Megger (insulation tester), to determine whether any of the windings are shorted to the core or to the Faraday shield (noise-reduction shield between primary and secondary).

SINGLE-PHASE, FULL-WAVE RECTIFIER.

APPLICATION.

The single-phase, full-wave rectifier is commonly used in all types of electronic equipment for applications requiring high-voltage dc at a relatively high load current. The rectifier circuit can be arranged to furnish negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

Uses two high-vacuum or gas-filled electron-tube diodes as rectifiers, or one twin-diode rectifier.

Output requires filtering; d-c output ripple frequency is twice the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Uses power transformer with center-tapped, high-voltage secondary winding.

CIRCUIT ANALYSIS.

General. The single-phase, full-wave rectifier is the most common type of rectifier circuit used in electronic equipment. The circuit consists of a high-voltage transformer with a center-tapped secondary winding. One plate of the rectifier tube (s) is connected to one end of the transformer secondary, and the other plate is connected to the other end. The load is connected between the center-tap of the secondary winding and the filament (cathode) of the secondary winding and the filament (cathode) of the rectifiers (s). Since the secondary winding is center-tapped, the voltage developed in each half of the secondary winding is in series with the other half; therefore, only one rectifier plate is positive at any instant. As a result, electrons flow through one half of the secondary winding, the load, and a rectifier diode on each half cycle of the impressed voltage, with first one diode conducting then the other. Thus, the electrons flow through the load in pulses, one pulse for each half cycle of the impressed voltage.

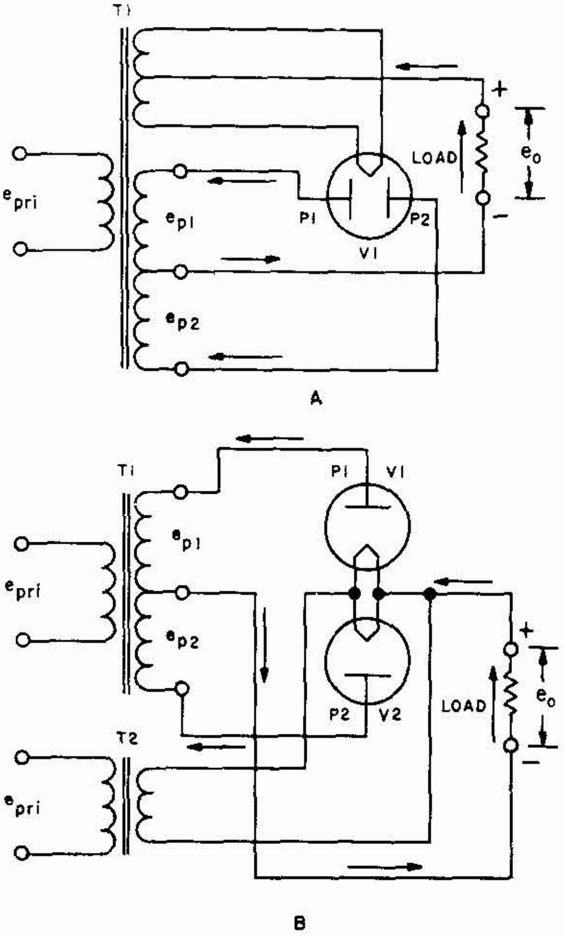
Circuit Operation. In the accompanying circuit schematic, part A illustrates a "full-wave" twin-diode rectifier, V1, used in a basic single-phase, full-wave rectifier circuit. The rectifier circuit uses a single transformer, T1, to step up the alternating-source voltage to a high value in each half of the secondary winding. The filament of tube V1 is operated from a low-voltage secondary winding located on the same transformer core with the high-voltage secondary. The low-voltage secondary winding is center-tapped and is the mid-point of the filament (cathode) circuit to which the load is connected. The circuit given in part A is typical of plate-voltage and bias supplies designed to meet medium power requirements such as those found in communication receivers and transmitters, audio amplifiers, radar sets, etc.

The rectifier circuit given in part B is shown with two separate transformers; T1 is a step-up transformer to obtain high voltage in each half of the secondary winding, and T2 is a step-down transformer to obtain the correct filament voltage for the operation of the two rectifiers, V1 and V2. The circuit is fundamentally the same as that given in part A. The separate transformer arrangement permits the primary voltage to be applied to transformer T2 independent of, and prior to, the application of primary voltage to T1 so that the rectifier filaments may be heated to the normal operating temperature before the plate voltage is applied. Although provision for a time delay in the application of plate voltage is not too important in the case of high-vacuum rectifiers, a time interval to permit preheating of the filament is usually necessary for gas-filled rectifiers. The circuit arrangement given in part B is typical of high-voltage, d-c supplies designed for use in radar sets and communication transmitters.

In the two circuits illustrated, either terminal of the load may be placed at ground potential, depending upon whether a positive or negative d-c output is desired.

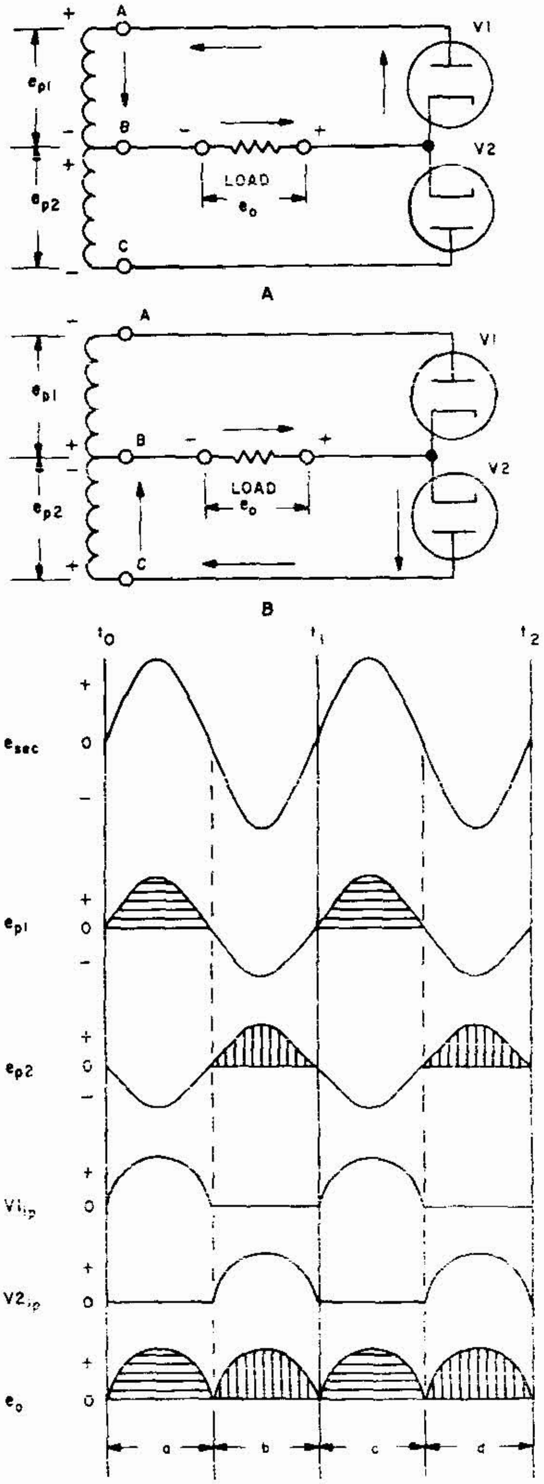
The operation of a full-wave rectifier circuit can be understood from the simplified circuit schematics (parts A and B) and the waveforms (part C) given in the accompanying illustration.

This circuit requires two rectifier diodes and a transformer with a center-tapped secondary winding. Each end terminal of the secondary winding (terminals A and C) is connected to a rectifier plate, as shown in the simplified circuit schematic. Since only one half of the secondary winding is in use at any one time, the total secondary voltage (e_{sec}) must be twice the voltage that would be required for use with a half-wave rectifier circuit (previously described).



Basic Single-Phase, Full-Wave Rectifier Circuits

The part of the secondary winding between terminals A and B, (e_{p1}) shown in the schematic of part A, may be considered a voltage source that produces a voltage of the polarity given in the illustration. This voltage is applied in series with the load resistance between the plate and cathode of the rectifier, V1. During one half cycle, time interval **a** (part C of the illustration), the plate of V1 is positive with respect to its cathode; therefore, electrons flow in the direction indicated by the arrows on the schematic of part A. Thus, during the time interval **a**, an output voltage is developed across the load resistance. Also during this half cycle, the voltage produced across the part of the secondary winding between terminals B and C (e_{p2}) is negative; there-



Simplified Full-Wave Rectifier Circuit and Waveforms

fore, the plate of V2 is negative with respect to its cathode, and V2 is nonconducting.

During the *next half cycle*, time interval **b** (part C of the illustration), the polarity of the voltage is reversed. The part of the secondary between terminals B and C (e_{p2}), shown in the schematic of part B, produces a voltage of the polarity given in the illustration. This voltage is applied in series with *the load resistance* between the plate and cathode of the rectifier, V2. During time interval **b** (part C of the illustration), the plate of V2 is positive with respect to its cathode, and electrons flow in the direction indicated by the arrows on the schematic of part B. Thus, during time interval **b**, an output voltage *is developed* across the load resistance. Also, during this half cycle, the voltage produced across the part of the secondary winding between terminals A and B (e_{p1}) is negative and, therefore V1 is nonconducting. From the waveforms given in part C, it can be seen that only one rectifier conducts at any instant of time; thus, on alternate half cycles, electrons flow through the load resistance to produce a pulsating output voltage, e_o. This output voltage has a pulsating waveform which results in an irregularly shaped ripple voltage because the output voltage and current are not continuous; the frequency of the ripple voltage is twice the frequency of the a-c source. The full-wave rectifier circuit requires filtering to smooth out the ripple and produce a steady d-c voltage.

The full-wave rectifier circuit utilizes the transformer (T1) for a greater percentage of the input cycle than the *half*-wave rectifier, because there are two pulsations of current in the output for each complete cycle of the applied alternating voltage. Therefore, the full-wave rectifier circuit is more efficient, has less output ripple amplitude, and has better voltage regulation than the half-wave rectifier circuit. The d-c load current passes through each half of of the secondary winding on alternate half cycles, flowing in opposite directions in each half of the winding. Since the windings are electrically equal (ampere turns) to one another, the current passes first in one direction for one half of the secondary winding and then in the other direction for the other half; thus, there is no tendency for the transformer core to become permanently magnetized. Furthermore, since little d-c core saturation occurs, the effective inductance of the transformer remains relatively high. As a result, the transformer has much higher efficiency than the transformer used in a half-wave rectifier circuit.

The full-wave rectifier, assuming a series of half sine waves as the waveform for the output voltage e_o (unfiltered), produces the following root-mean-square voltage:

$$E_{rms} = E_{max} \times 0.707$$

where: E_{max} = maximum instantaneous voltage.

The corresponding average output voltage is:

$$E_{av} = 0.9\ E_{rms}$$

Similarly, the root-mean-square and average output currents can be expressed as:

$$I_{rms} = I_{max} \times 0.707$$

and: $I_{av} = 0.45\ I_{rms}$

The **peak inverse voltage** across a rectifier in a full-wave rectifier circuit during the period of time the tube is not conducting is approximately [illegible] half of the transformer secondary, or 1.41 times the rms voltage across the entire secondary. The peak inverse voltage can be expressed as:

$E_{inv} = 2.83\ E_{rms}$

where: E_{rms} = rms voltage across half of transformer secondary

or, $E_{inv} = 1.41\ E_{rms}$

where: E_{rms} = rms voltage across entire transformer secondary

The output of the full-wave rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in part D of this section.)

FAILURE ANALYSIS.

No Output. In the full-wave rectifier circuit the no-output condition is likely to be limited to one of three possible causes: defective rectifier tube or tubes (open filaments), the lack of applied a-c voltage, or a shorted load circuit (including shorted filter-circuit components).

A visual check of glass-envelope rectifier tube (s) can be made to determine whether the filament is lit; if the filament is not lit, the filament of the tube is likely to be open or the filament voltage may not be applied. The tube filament(s) should be checked for continuity; the presence of correct filament voltage at the tube socket should be determined by measurement.

The a-c secondary voltage applied to each rectifier plate should be measured between the secondary center-tap and each rectifier plate to determine whether voltage is present and of the correct value. If necessary, measure the applied primary voltage to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, continuity (resistance) measurements of the primary winding should be made to determine whether the winding is open, since an open (discontinuity) in the primary winding will cause a lack of secondary voltage.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including filter, is shorted. If the filter circuit incorporates an electrolytic capacitor, the resistance measurements made across the output of the rectifier circuit may vary depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the circuit test points for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value. A short in the components of the filter circuit or in the load will cause an excessive load current to flow; if the rectifier-tube type is a high-vacuum type, the heavy load current will cause the plate to become heated and emit a reddish glow when the plate dissipation is exceeded and, if allowed to continue, may result in permanent damage to the tube. If a gas-filled rectifier is used in the circuit, excessive load current will likely result in damage to the tube because gas-filled rectifiers are more susceptible to damage from current overload than are high-vacuum rectifiers.

Low Output. The rectifier tube(s) should be checked to determine whether the cause of low output is low filament emission. Also, since the full-wave rectifier circuit normally supplies current to the load on each half cycle, failure of either rectifier or an open in either half of the secondary winding will allow the circuit to act as a half-wave rectifier circuit, and the output voltage will be reduced accordingly. Furthermore, whenever this occurs, the ripple amplitude will also increase, and the ripple frequency will be that of the a-c source (instead of twice the source frequency). In the case of two separate rectifier tubes, if one tube is lit and the other is not, the trouble is obviously associated with the tube that is not lit.

With the primary voltage removed from the circuit, resistance measurements can be made to check the continuity between the center-tap and each rectifier plate; this will determine whether one of the windings or plate leads is open. As an alternative, the a-c secondary voltage applied to each rectifier plate can be measured between the secondary center-tap and each rectifier plate to determine whether both voltages are present and are of the correct value.

The primary voltage should be measured to determine whether it is of the correct value, since a low applied primary voltage can result in a low secondary voltage. Also, shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. Shorted turns are not easily detected by resistance measurement; a voltage measurement is a more reliable indication. If the transformer losses (due to shorted turns) are excessive, the transformer may also become overheated. Another check to determine whether the transformer is defective is to disconnect the secondary load(s) and measure the primary current with the transformer unloaded; excessive primary current is an indication of shorted turns. Still another check is to disconnect all primary and secondary leads from the transformer and make measurements between the individual windings and the core, using an ohmmeter or a Megger (insulation tester), to determine whether any of the windings are shorted to the core or to the Faraday shield (noise-reduction shield between primary and secondary).

The rectifier-output current (to the filter circuit and to to the load) should be checked to make sure that it is within tolerance and is not excessive. A low-output condition due to a decrease in load resistance would cause an increase in load current; for example, excessive leakage in the capacitors of the filter circuit would result in increased load current.

SINGLE-PHASE, FULL-WAVE BRIDGE RECTIFIER.

APPLICATION.

The single-phase, full-wave bridge rectifier is used in electronic equipment for applications requiring high-voltage dc at a high load current. The rectifier circuit can be arranged to furnish negative or positive high-voltage output to the load, although the circuit is commonly used as a positive high-voltage power supply in most applications.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

Uses four high-vacuum or gas-filled electron-tube diodes as rectifiers, or two diodes and one twin-diode as rectifiers.

Output requires filtering; d-c output ripple frequency is twice the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Requires three separate filament transformers or separate filament windings for rectifier tubes.

Uses power transformer with single high-voltage secondary winding; modified circuit to supply two output voltages simultaneously uses transformer with center-tapped, high-voltage secondary winding.

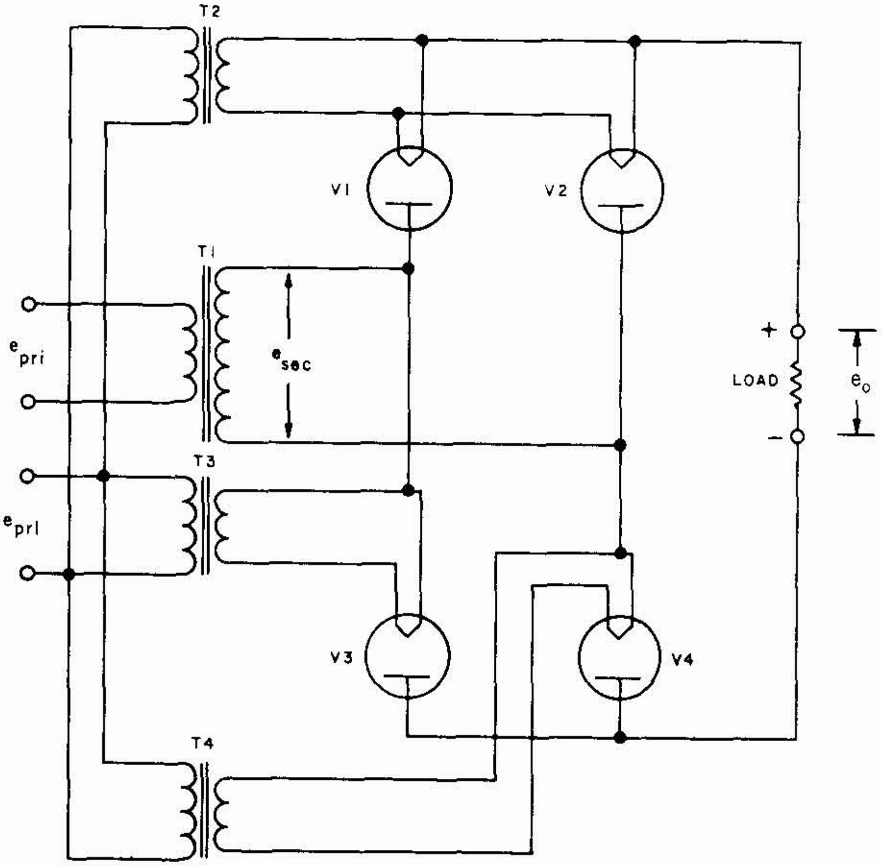
CIRCUIT ANALYSIS.

General. The single-phase, full-wave bridge rectifier circuit uses two half-wave rectifier tubes in series on each side of a single transformer high-voltage secondary winding (the transformer secondary winding does not require a center tap); a total of four rectifiers are used in the bridge circuit. During each half cycle of the impressed a-c voltage, two rectifiers, one at each end of the secondary, conduct in series to produce an electron flow through the load. Thus, electrons flow through the load in pulses, one pulse for each half cycle of the impressed voltage. Since two d-c output pulses are therefore produced for each complete input cycle, full-wave rectification is obtained and the output is similar to that of the conventional full-wave rectifier circuit.

One advantage of the bridge rectifier circuit over a conventional full-wave rectifier is that for a given transformer total-secondary voltage the bridge circuit produces an output voltage which is nearly twice that of the full-wave circuit. Another advantage is that the peak inverse voltage across an individual rectifier tube, during the period of time the tube is nonconducting, is approximately half the peak inverse voltage across a tube in a conventional full-wave rectifier circuit designed to produce the same output voltage. One disadvantage of the bridge rectifier circuit, however, is that at least three filament transformers (or three separate windings) are required for the rectifier tubes.

In many power-supply applications, it is desirable to provide two voltages simultaneously -- one voltage for high-power stages and the other voltage for low-power stages. For these applications the single-phase, full-wave bridge rectifier circuit can be modified to supply an additional output voltage which is equal to one half of the voltage provided by the full-wave bridge rectifier circuit.

Circuit Operation. A single-phase, full-wave bridge rectifier is shown in the accompanying circuit schematic. Four identical-type electron-tube diodes, V1, V2, V3, and V4, are connected in a bridge circuit across the secondary winding of transformer T1. Each tube forms one arm of the bridge circuit; the load is connected between the junction points of the balanced arms of the bridge. Transformer T1 is a step-up transformer to provide high voltage for the bridge rectifiers. The circuit given shows three separate filament transformers, T2, T3, and T4. A single filament transformer may be used, provided that it incorporates three separate filament secondary windings that are well insulated from each other and from ground (chassis). Note that the filaments of V1 and V2 are at the same potential with respect to each other, whereas the filaments of V3 and V4 are not. The filaments of V3 and V4 are connected to opposite ends of the high-voltage secondary and therefore operate at the full potential difference that exists across the secondary of T1; thus, if the filaments of V3 and V4 were supplied by a single transformer winding, the common connection would place a short across the high-voltage secondary winding. The filaments of V3 and V4 must, therefore, be insulated from each other and must also be well insulated from ground. In either case, whether three separate filament transformers or a single filament transformer with multiple secondary windings is used, the filament primary voltage is applied independent of, and prior to, the primary voltage to T1. This arrangement permits the rectifier filaments to be preheated to the normal operating temperature before the high voltage is applied to the bridge-rectifier circuit.



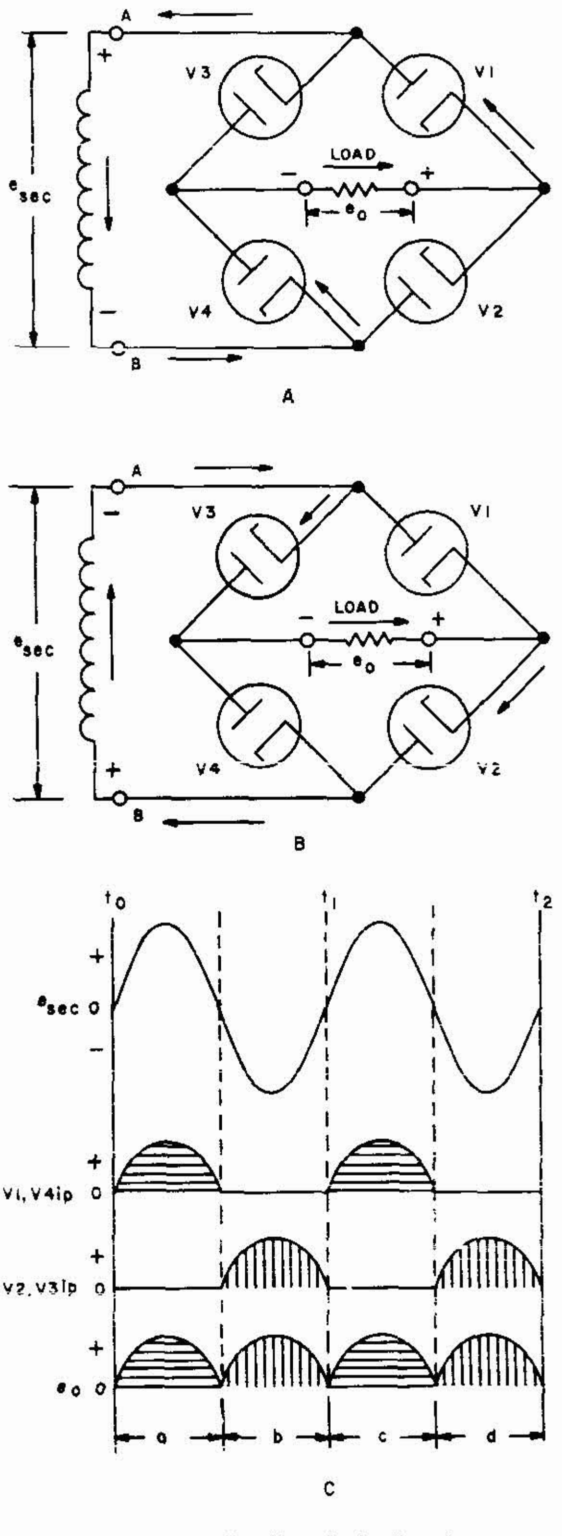
Basic Single-Phase, Full-Wave Bridge Rectifier Circuit

The circuit arrangement given in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired. The circuit is typical of high-voltage, d-c supplies designed for use in radar sets and communication transmitters.

The operation of the full-wave bridge rectifier circuit can be understood from the simplified circuit schematic (parts A and B) and the waveforms (part C) shown in the accompanying illustration. The basic bridge rectifier schematic, given earlier in this discussion, has been simplified and redrawn in the the form of a simple bridge circuit; the rectifier tube reference designations used correspond to those assigned in the basic bridge rectifier schematic. The bridge circuit uses four identical-type rectifiers. The end terminals of the transformer high-voltage secondary winding are connected to opposite cathode-plate junction points of the rectifiers comprising the arms of the bridge circuit, as shown. The load is connected between the remaining two cathode-plate junction points of the bridge circuit.

During the first half cycle, the transformer secondary winding (terminals A and B), shown in the schematic of part A, may be considered a voltage source that produces a voltage of the polarity given in the illustration. During time interval **a**, terminal A is positive with respect to terminal B; as a result, electrons will flow in the direction indicated by the arrows through the series circuit composed of rectifier V4, the load, and rectifier V1. This electron flow produces an output pulse of the polarity indicated across the load resistance. Also, during this period (time interval **a**), V2 and V3 are nonconducting.

During the next half cycle, time interval **b**, a secondary voltage is produced of the polarity given in part B of the illustration. Terminal B is positive with respect to terminal A; as a result, electrons will flow in the direction indicated by the arrows through the series circuit composed of rectifier V3, the load, and rectifier V2. The electrons flowing in the series circuit once again produce an output of the same polarity as before across the load resistance. During this period (time interval **b**), V1 and V4 are nonconducting.



Simplified Full-Wave Bridge Rectifier Circuit and Waveforms

From the waveforms given in part C, it can be seen that two rectifiers conduct at any instant of time; thus, on alternate half cycles, electrons flow through the load resistance to produce a pulsating output voltage, e_o. This output voltage has a pulsating waveform, which results in an irregularly shaped ripple voltage because the output voltage and current are not continuous; the frequency of the ripple voltage is twice the frequency of the a-c source. The full-wave bridge rectifier circuit requires filtering to smooth out the ripple and produce a steady d-c voltage.

The full-wave bridge rectifier circuit makes continuous use of the transformer secondary; therefore, there are two pulsations of current in the output for each complete cycle of the applied a-c voltage. The d-c load current passes through the entire secondary winding, flowing in one direction for one half cycle of the applied voltage, and in the opposite direction for the other half cycle; thus, there is no tendency for the transformer core to become permanently magnetized. Since little d-c core saturation occurs, the effective inductance of the transformer, and therefore the efficiency, is relatively high.

The full-wave bridge rectifier, assuming a series of half sine waves as the waveform for the output voltage, e_o (unfiltered), produces the following root-mean-square voltage:

$$E_{rms} = E_{max} \times 0.707$$

where: E_{max} = maximum instantaneous voltage

The corresponding average output voltage is:

$$E_{av} = 0.9\ E_{rms}$$

Similarly, the root-mean-square and average output currents can be expressed as:

$$I_{rms} = I_{max} \times 0.707$$

and: $I_{av} = 0.9\ I_{rms}$

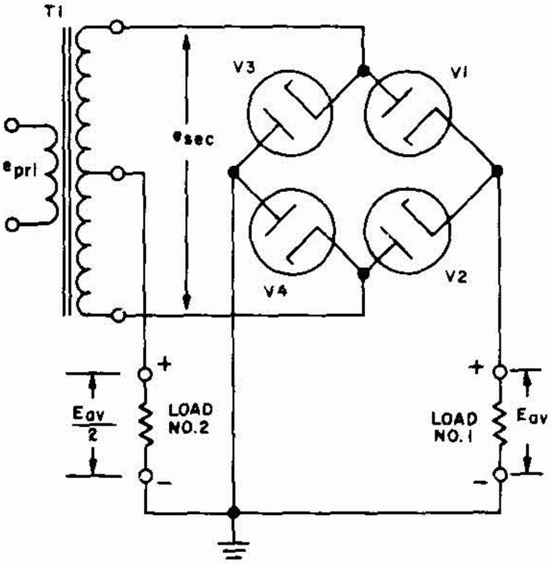
The **peak inverse voltage** across an individual rectifier in a full-wave bridge rectifier circuit during the period of time the tube is nonconducting is approximately 1.41 times the rms voltage across the secondary winding. The secondary voltage, e_{sec}, is applied to two rectifier tubes in series; therefore, since less peak inverse voltage (approximately one half) appears across each tube, the bridge circuit can be used to obtain a higher output voltage than can be obtained from a conventional full-wave rectifier circuit using equivalent rectifier tubes. The peak inverse voltage **per tube** can be expressed as:

$$E_{inv} \text{ (per tube)} = 1.41\ E_{rms}$$

where: E_{rms} = rms voltage across entire secondary

The output of the full-wave bridge rectifier is similar to that of the conventional full-wave rectifier circuit. The bridge rectifier provides twice the output voltage for the same total transformer secondary voltage and d-c output current as does the full-wave rectifier circuit using a center-tapped secondary. The output of the bridge rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in the latter part of this section.)

A variation of the full-wave bridge rectifier circuit uses a transformer with a center-tapped secondary winding to supply two output voltages simultaneously to two separate loads. The circuit is fundamentally the same as that given earlier; for this reason the accompanying circuit schematic has been simplified and redrawn to eliminate the filament transformers and associated filament circuitry. The reference designations previously assigned remain unchanged.



Simplified Full-Wave Center-Tap and Full-Wave Bridge Rectifier Circuit

One advantage of the circuit is that two voltages may be supplied from the same set of rectifiers. One ouput voltage (E_{av}) is obtained from the output of the bridge circuit; the second output voltage $\frac{(E_{av})}{2}$, which is equal to one half of the bridge output voltage, is obtained by using two rectifiers, V3 and V4 of the bridge, and the center tap of the secondary winding as a conventional full-wave rectifier circuit. (The operation of the full-wave rectifier circuit was previously described in this section.) Although this circuit variation can supply two output voltages simultaneously to two separate loads, there is a limitation on the total current which can be carried by the rectifiers, V3 and V4.

FAILURE ANALYSIS.

No Output. In the full-wave bridge rectifier circuit, the no-output condition is likely to be limited to one of several possible causes: an open filament supply circuit, defective rectifier tubes, the lack of applied a-c voltage, or a shorted load circuit (including shorted filter-circuit components).

A visual check of glass-envelope rectifier tubes can be made to determine whether the filaments are lit. If the filaments are not all lit, the primary voltage may not be applied to the filament transformers (T2, T3, and T4). If only the filaments of V1 and V2 are not lit, there will be no d-c output from the rectifier circuit, and transformer T2 or both tubes may be defective. The tube filaments should be checked for continuity; the presence of correct filament voltage at the tube sockets (V1 and V2) should be determined by measurement. If necessary, the primary and secondary voltages should be checked at the terminals of transformer T2 to determine whether the transformer is defective.

The a-c secondary voltage, e_{sec}, should be measured at the terminals of transformer T1 to determine whether the voltage is present and of correct value. If necessary, measure the applied primary voltage, e_{pri}, to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, continuity measurements of the primary and secondary windings should be made to determine whether one of the windings is open, since an open (discontinuity) in either winding will cause a lack of secondary voltage.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including filter, is shorted. A short in the components of the filter circuit or in the load will cause an excessive load current to flow. If the rectifiers are of the high-vacuum type, the heavy load current will cause the plates of the rectifiers to become heated and emit a reddish glow when the plate dissipation is exceeded and, if allowed to continue, may result in permanent damage to the tubes. The high-voltage bridge circuit normally employs gas-filled rectifiers; an excessive load current will very likely result in permanent damage to the tubes because they are susceptible to damage from current overload. Therefore, once the difficulty in the load circuit has been located and corrected, the gas-filled rectifiers may require replacement as a result of the overload condition.

Low Output. The rectifier tubes should be checked to determine whether the filaments are lit; one or more defective rectifiers in the bridge can cause the low-output condition. Also, failure of only one rectifier in the bridge will allow the circuit to act as a half-wave rectifier with current supplied to the load on alternate half cycles only, and the output voltage will be reduced accordingly. If rectifier tube V1 or V2 is not lit, the trouble is obviously associated with the tube that is not lit; however, if V3 or V4 is not lit, then the trouble may be either the tube (V3 or V4) or its associated filament transformer (T3 or T4). The tube filament should be checked for continuity; the presence of correct filament voltage at the tube socket should be determined by measurement. If necessary, the primary and secondary voltages should be checked at the terminals of the filament transformer (T3 or T4) to determine whether the transformer is defective.

The load current should be checked to make sure that it is not excessive, because a decrease in output voltage can be caused by an increase in load current (decrease in load resistance); for example, excessive leakage in the capacitors of the filter circuit would result in increased load current. Also, the a-c secondary voltage, e_{sec}, and the primary voltage, e_{pri}, should be measured at the terminals of transformer T1 to determine whether these voltages are of the correct value. Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. Shorted turns are not easily detected by resistance measurement; a voltage measurement is a more reliable indication. If the transformer losses (due to shorted turns) are excessive, the transformer may also become overheated. Another check to determine whether the transformer is defective is to disconnect the secondary load (s) and measure the primary current with the transformer unloaded; excessive primary current is an indication of shorted turns. Still another check is to disconnect all primary and secondary leads from the transformer and make measurements between the individual windings and the core, using an ohmmeter or a Megger (insulation tester), to determine whether any of the windings are shorted to the core or to the Faraday shield (noise-reduction shield between primary and secondary).

THREE-PHASE, HALF-WAVE (THREE-PHASE STAR) RECTIFIER.

APPLICATION.

The three-phase, half-wave star or wye-connected rectifier is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c power requirements exceed 1 kilowatt. The rectifier circuit can be arranged to furnish negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses three high-vacuum or gas-filled electron-tube diodes as rectifiers.

Output is relatively easy to filter; d-c output ripple frequency is equal to three times the primary line-voltage frequency.

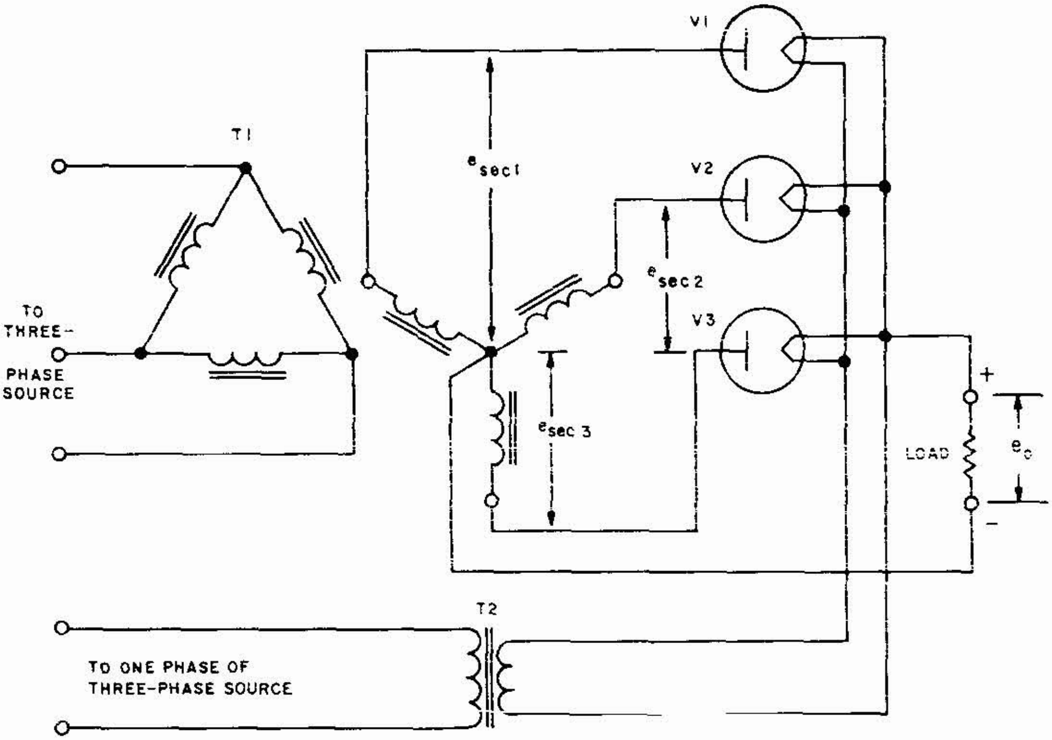
Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Uses multiphase power transformer with star- or wye-connected secondary windings; primary windings may be either delta- or wye-connected.

CIRCUIT ANALYSIS.

General. The three-phase, half-wave (three-phase star) rectifier is the simplest type of three-phase rectifier circuit. The term **three-phase** refers to the primary a-c source, which is the equivalent of three single-phase sources, each source supplying a sine-wave voltage 120 degrees out of phase with the others. Fundamentally, this rectifier circuit resembles three single-phase, half-wave rectifier circuits, each rectifier circuit operating from one phase of a three-phase source and sharing a common



Basic Three-Phase, Half-Wave (Three-Phase Star) Rectifier Circuit load. The voltages induced in the transformer secondary windings differ in phase by 120 degrees; thus, each half-wave rectifier conducts for 120 degrees of the complete input cycle and contributes one third of the d-c current supplied to the load. Electrons flow through the load in pulses, one pulse for each positive half cycle of the impressed voltage in each of the three phases; therefore, the output voltage has a ripple frequency which is three times the frequency of the a-c source.

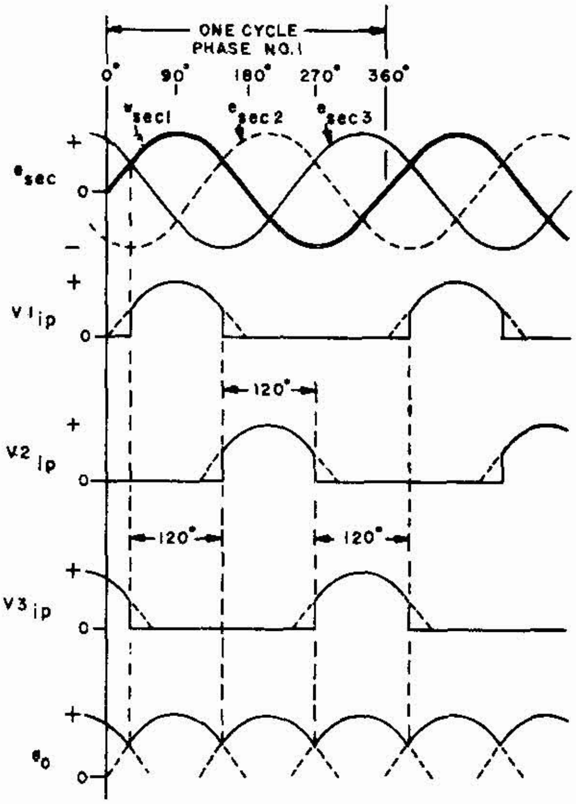
Circuit Operation. A basic three-phase, half-wave rectifier is illustrated in the circuit schematic on page 4-A-11. The circuit uses a three-phase transformer, T1, to step up the alternating source voltage to a high value in the star- or wye-connected secondaries. The primary windings of transformer T1 are shown delta-connected, although in some instances the primary windings may be wye-connected (as for a three- or four-wire system). The plate of each rectifier tube, V1, V2, and V3, is connected to a high-voltage secondary winding. One filament transformer, T2, is used to supply the filament voltage to all three rectifiers since the filaments of the rectifiers are all at the same potential. The primary of transformer T2 is connected to one phase of the three-phase source. The load is connected between the junction point of the wye-connected secondary windings and the filament circuit of the rectifier tubes.

In the circuit illustrated, either terminal of the load may be placed at ground potential, depending upon whether a positive or negative d-c output is desired.

The operation of the three-phase, half-wave rectifier circuit can be understood from the circuit schematic previously given and from the waveforms shown in the accompanying illustration.

Each phase of the three-phase secondary voltage is applied across a rectifier and the common load. The secondary voltage of phase No. 1 ($e_{sec}1$) is applied to rectifier V1, the secondary voltage of phase No. 2 ($e_{sec}2$) is applied to rectifier V2, and the secondary voltage of phase No. 3 ($e_{sec}3$) is applied to rectifier V3. The waveform given in the accompanying illustration as e_{sec} shows each of the three secondary voltages displaced 120 degrees from each other. On positive half cycles of $e_{sec}1$, electrons flow through the load and rectifier V1; the pulse of plate current for rectifier V1 is identified in the illustration as the waveform, V1 i_p. On positive half cycles of $e_{sec}2$, electrons flow through the load and rectifier V2; the pulse of plate current for V2 is identified as V2 i_p. On positive half cycles of $e_{sec}3$, electrons flow through the load and rectifier V3; the pulse of plate current for V3 is identified as V3i_p. From the three individual plate-current waveforms it can be seen that the start of a conduction period for any rectifier occurs 120 electrical degrees from the start of a conduction period for another rectifier in the circuit. The output voltage, e_o, across the load resistance is determined by the instantaneous currents flowing through the load; therefore, the output voltage has a pulsating waveform which never drops to zero because of the nature of the rectifier conduction periods.

If it were not for the overlapping of applied three-phase secondary voltages, the rectifiers would each conduct for 180 degrees of the cycle; however, during the first 30 degrees of a half cycle, the plate of the rectifier is negative with respect to its positive filament (cathode), and it will not conduct until the positive voltage applied to the plate exceeds the d-c output voltage pulsations present across the load and at the filament circuit. Also, during the last 30 degrees of a half cycle, the plate is again negative with respect to the filament, and rectifier conduction ceases because the rectifier of another phase has started to conduct and produce a positive voltage across the load. In other words, each rectifier tube conducts for only one-third cycle, and this results in a series of d-c output voltage pulsations with an irregularly shaped ripple voltage; the frequency of the ripple voltage is equal to three times the frequency of the a-c source. Because the ripple frequency is higher than that of a single-phase rectifier circuit, the three-phase, half-wave rectifier circuit requires less filtering to smooth out the ripple and produce a steady d-c voltage.



Three-Phase, Half-Wave Rectifier Waveforms

In order to keep d-c core saturation to a minimum (because of current flowing in one direction only in the secondary windings) and to keep the efficiency relatively high, it is necessary to use a single three-phase transformer in this circuit, rather than three separate single-phase transformers.

The three-phase, half-wave rectifier produces across the load a pulsating (unfiltered) d-c output voltage, E_{av}, as follows:

$$E_{av} = 1.17\,E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of three-phase transformer

The **peak inverse voltage** across an individual rectifier in the three-phase, half-wave rectifier circuit during the period of time the tube is nonconducting is approximately 2.45 times the rms voltage across the secondary winding of one phase. Some pulsating d-c voltage is always present across the load, and this voltage is in series with the a-c voltage applied to the plate; therefore, the sum of the instantaneous value of pulsating d-c voltage across the load and the instantaneous peak voltage across the secondary represent the value of peak inverse voltage across the rectifier tube. The peak inverse voltage **per tube** can be expressed as: E_{inv} (per tube) = 2.45 E_{rms}

where: E_{rms} = rms voltage across one secondary winding of the three-phase transformer

The output of the three-phase, half-wave rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in part D of this section.)

FAILURE ANALYSIS.

No Output. In the three-phase, half-wave rectifier circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of a-c filament supply, the lack of applied a-c high voltage, or a shorted load circuit (including shorted filter components).

A visual check of the glass-envelope rectifier tubes can easily be made to determine whether all filaments are lit; if they are not lit, the filament voltage should be measured at the secondary terminals of transformer T2. If necessary, measure the applied primary voltage to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, continuity (resistance) measurements of the primary and secondary windings should be made to determine whether one winding is open, since an open winding (primary or secondary) will cause a lack of filament voltage.

With the primary voltage removed from the circuit, continuity (resistance) measurements should be made of the secondary and primary windings, to determine whether one or more windings are open and whether the common terminal (s) of the wye-connected secondaries is connected to the load circuit. If necessary, the a-c secondary voltage applied to the rectifier plates may be measured between the common terminal of the wye-connected secondaries and the plate of one or more rectifiers, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage to determine whether it is present and of the correct value.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including filter, is shorted. A short in the components of the filter circuit or in the load circuit will cause an excessive load current to flow; if the rectifier tube is of the high-vacuum type, the heavy load current will cause the plate of the rectifiers to become heated and emit a reddish glow when the plate dissipation is exceeded and, if allowed to continue, may result in permanent damage to the tubes. If gas-filled rectifiers are used in the circuit, excessive load current will result in permanent damage to the tubes because gas-filled rectifiers are very susceptible to damage from current overload. Therefore, once the difficulty in the load circuit has been located and corrected, the gas-filled rectifiers will require replacement as a result of the overload condition.

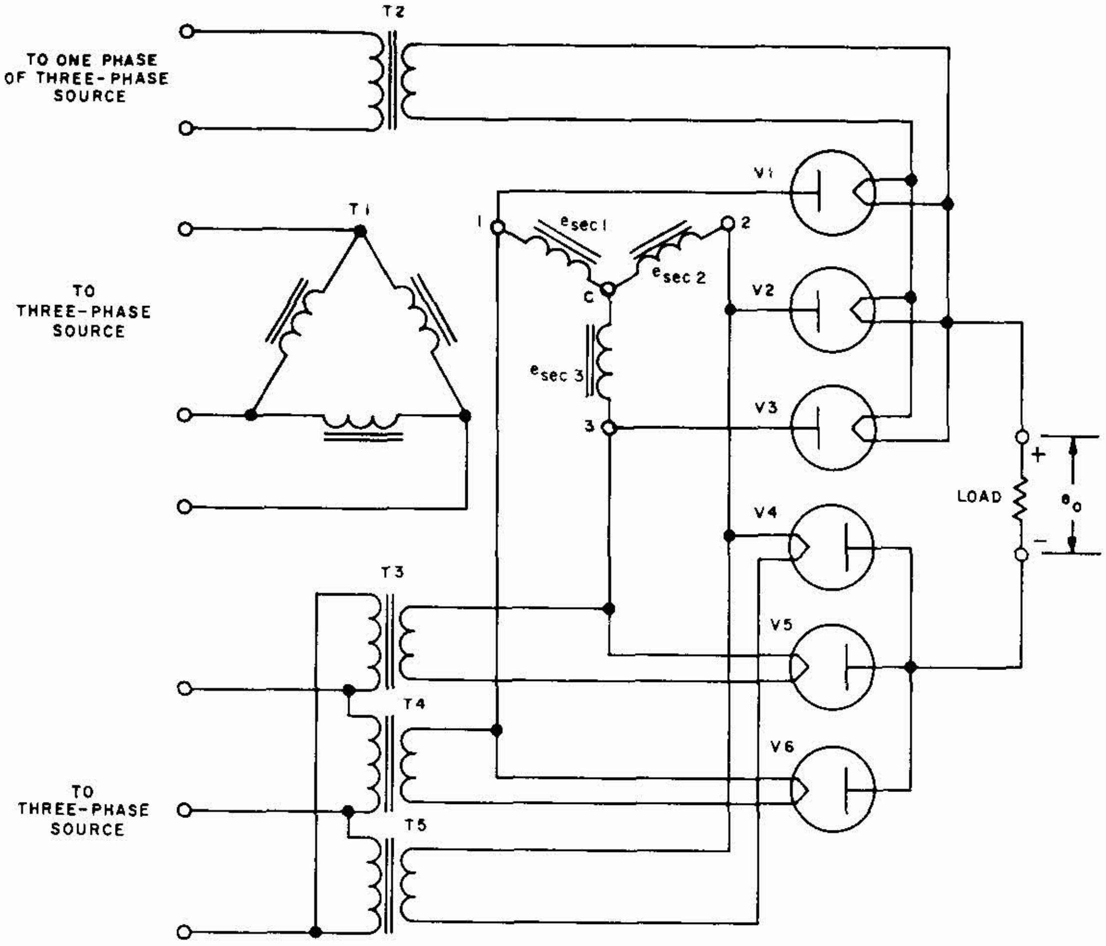
Low Output. If only one or two phases of the three-phase, half-wave rectifier circuit are operating normally the output voltage will be lower than normal. For example, if only one secondary winding and associated rectifier is in operation, the effect is the same as though it were a single-phase, half-wave rectifier circuit and, as a result, the output voltage is much lower than normal. When two phases are operating, the output voltage is somewhat higher and, when all three phases are operating, the output is normal. Thus, the low-output condition can be due to the fact that one or more secondary-phase circuits are not functioning normally.

The rectifier tubes should be checked first to determine whether all filaments are lit. All rectifier filaments are in parallel; therefore, if one filament is not lit, the trouble is obviously associated with this particular tube. The tube filament should be checked for continuity; the presence of correct filament voltage at the tube socket should be determined by measurement.

With the three-phase primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings, to determine whether one (or more) of the windings is open. If necessary, the a-c secondary voltage applied to each rectifier plate may be measured between the common terminal of the secondary wye connection and the plate of each rectifier, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage at each of the phases, to determine whether each voltage is present and of the correct value, since a low applied primary voltage can result in a low secondary voltage.

Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. Disconnect all secondary leads from the transformer, T1, and measure the primary current in each leg of the three-phase primary with the transformer unloaded; excessive primary current is an indication of shorted turns. A secondary winding which is shorted to the core can cause a low-output voltage indication; all leads should be disconnected from the transformer and measurements made between the individual windings and the core, using an ohmmeter or a Megger (insulation tester), to determine whether any of the windings are shorted to the core.

The rectifier-output current (to the filter circuit and to the load) should be checked to make sure that it is within tolerance and is not excessive. A low-output condition due to a decrease in load resistance would cause an increase in load current; for example, excessive leakage in the capacitors of the filter circuit would result in increased load current.



Basic Three-Phase, Full-Wave (Single "Y" Secondary) Rectifier Circuit

THREE-PHASE, FULL-WAVE (SINGLE "Y" SECONDARY) RECTIFIER.

APPLICATION.

The three-phase, full-wave rectifier with single-wye secondary is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses six high-vacuum or gas-filled electron-tube diodes as rectifiers.

Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Requires separate filament transformers or separate filament windings for rectifier tubes.

Uses multiphase power transformer with wye-connected secondary windings; primary windings may be either delta- or wye-connected.

CIRCUIT ANALYSIS.

General. The three-phase, full-wave (single-wye-connected secondary) rectifier is extensively used where a large amount of power is required by the load, such as for large shipboard or shore electronic installations. The term **three-phase** refers to the primary a-c source, which is the equivalent of three single-phase sources, each source supplying a sine-wave voltage 120 degrees out of phase with the others. Because of the three-phase transformer secondary configuration, the circuit is sometimes referred to as a **bridge** or **six-phase** rectifier circuit.

In many power-supply applications, it is desirable to provide two voltages simultaneously—one voltage for high-power stages and the other voltage for low-power stages. For these applications the three-phase, full-wave rectifier circuit can be modified to supply an additional output voltage, which is equal to one half of the voltage provided by the full-wave rectifier circuit.

Circuit Operation. The basic three-phase, full-wave rectifier circuit is illustrated in the accompanying circuit schematic. The circuit uses a conventional three-phase power transformer, T1, to step up the alternating source voltage to a high value in the wye-connected secondaries. The primary windings of transformer T1 are shown delta-connected, although in some instances the primary windings may be wye-connected (as for a three- or four-wire system). The plate of rectifier V1 and the filament (cathode) of rectifier V6 are connected to secondary terminal No. 1 of transformer T1; the plate of rectifier V2 and the filament of rectifier V4 are connected to secondary terminal No. 2; the plate of rectifier V3 and the filament of rectifier V5 are connected to secondary terminal No. 3.

One filament transformer, T2, is used to supply the filament voltage to rectifiers V1, V2, and V3, since the filaments of these rectifiers are all at the same potential. However, since the filaments of rectifiers V4, V5, and V6 have a high potential difference existing between them, three separate filament transformers (T3, T4, and T5) are used. A single filament transformer may be used for this purpose, provided that it incorporates three separate filament windings that are well insulated from each other and ground (chassis). The primary windings of filament transformers T3, T4, and T5 are connected to different phases of the three-phase source. The a-c voltage for the primaries of the filament transformers is applied independent of, and prior to, the primary voltage to the three-phase power transformer, T1. A time-delay arrangement, either manually operated or automatic, normally permits the rectifier filaments to be preheated to the normal operating temperature before the high-voltage ac can be applied to the rectifier circuit.

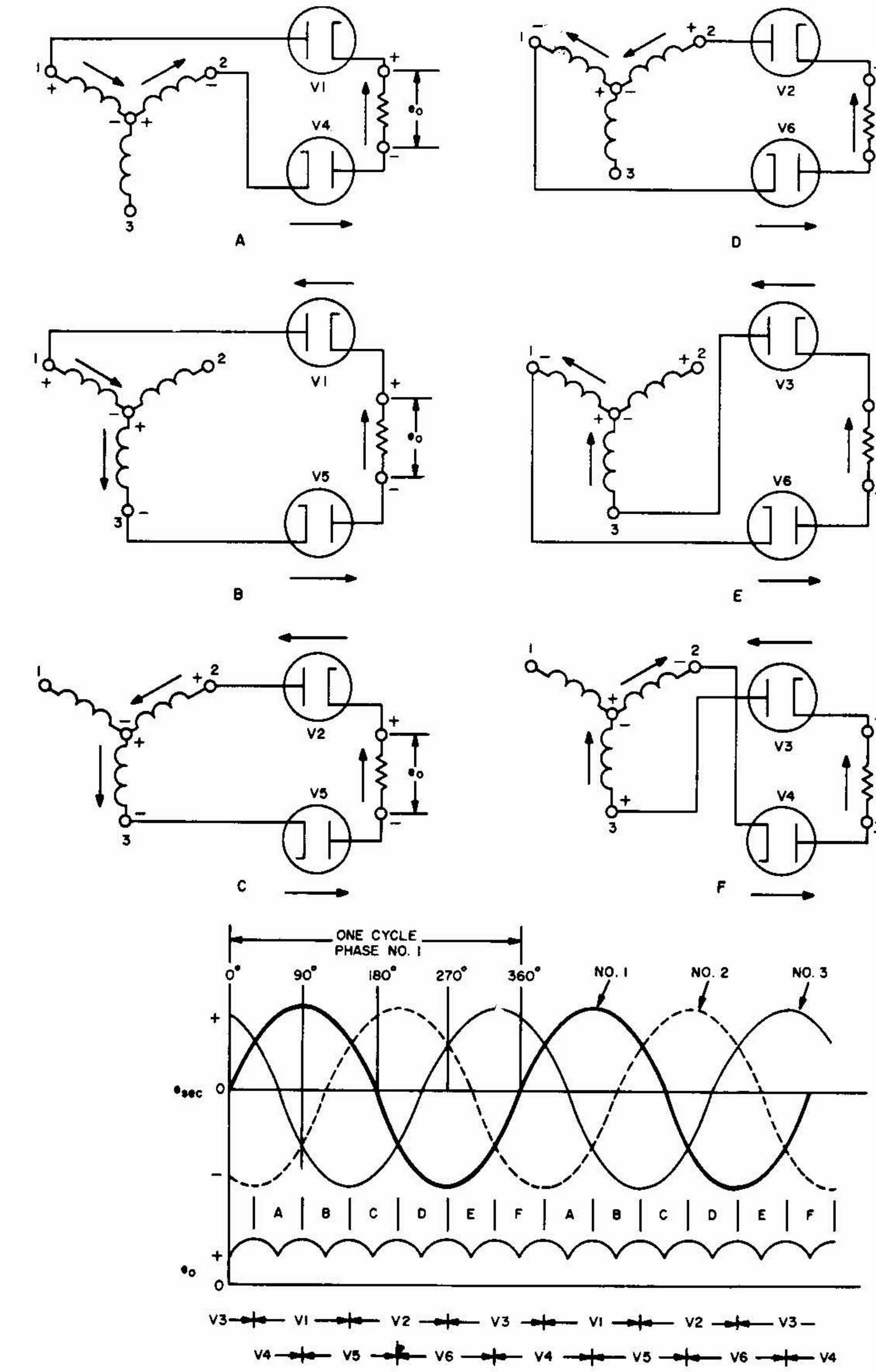
The circuit arrangement given in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). The circuit is typical of high-voltage d-c supplies designed for use in radar sets, communication transmitters, or other equipment for which the d-c power requirement is several kilowatts or more.

The operation of the three-phase, full-wave rectifier circuit can be understood from the simplified circuit schematics (parts A through F) and the waveforms given in the accompanying illustration. The basic three-phase, full-wave rectifier schematic, given earlier in this discussion, has been simplified to show the circuit action throughout the electrical cycle; the reference designations used correspond to those assigned in the basic circuit schematic.

The voltages developed across the secondary windings of transformer T1 are 120 degrees out of phase with relation to each other and are constantly changing in polarity. The polarities indicated for the secondary windings in the simplified circuit schematics (parts A through F) of the accompanying illustration represent the instantaneous polarity of the induced voltages in the secondary. The arrows on the schematics are used to indicate the directions of electron flow in the circuit.

The plates of rectifiers V1, V2, and V3 are connected to secondary windings No. 1, No. 2, and No. 3, respectively; the filaments (cathode) of rectifiers V6, V4, and V5, are connected to secondary windings No. 1, No. 2, and No. 3, respectively. When the plates of V1, V2, and V3 are positive with respect to their filaments, the tubes will conduct; when the filaments of V4, V5, and V6 are negative with respect to their plates, these tubes will conduct. At any given instant of time in the three-phase, full-wave rectifier circuit, a rectifier, the load, and a second rectifier are in series across two of the wye-connected transformer secondaries and, therefore, two rectifiers are conducting. Each of the six rectifiers conducts for 120 degrees of an electrical cycle; however, there is an overlap of conduction periods, and the rectifiers conduct in a sequence which is determined by the phasing of the instantaneous secondary voltages of the power transformer. In the circuit described, two rectifiers are conducting at any instant of time, with rectifier conduction occurring in the following order: V1 and V4, V1 and V5, V2 and V5, V2 and V6, V3 and V6, V3 and V4, V1 and V4, etc.

Refer to the secondary-voltage waveform, e_{sec}, shown in the accompanying illustration. Assume that the a-c voltage induced in secondary No. 1 (between 30 and 90 electrical degrees, phase No. 1) is approaching its maximum positive value (at 90 degrees); also, the voltage induced in secondary No. 2 has reached its maximum negative value (at 30 degrees) and is decreasing. (Secondary No. 3, although positive at 30 degrees, is decreasing to zero.) This condition is shown by the simplified schematic of part A in the accompanying illustration. The plate of rectifier V1 becomes positive with respect to its filament



Simplified Circuit Schematics and Waveforms for
Three-Phase, Full-Wave Rectifier

(cathode), and the filament of rectifier V4 is negative with respect to its plate; therefore, both tubes conduct, and the electrons flow through V4, the load, and V1 for 60 degrees of the electrical cycle.

In part B, the a-c voltage induced in secondary No. 1 reaches its maximum positive value (at 90 degrees) and starts to decrease during the next 60 degrees of the cycle; the voltage induced in secondary No. 3 is approaching its maximum negative value. The plate of V1 remains positive with respect to its filament, and the filament of V5 becomes negative with respect to its plate; therefore, V1 continues to conduct and V5 takes over conduction from V4, with V1 and V5 conducting in series with the load. Electrons flow through V5, the load, and V1 for another 60 degrees of the cycle.

In part C, the a-c voltage induced in secondary No. 3 reaches its maximum negative value and the positive voltage in secondary No. 2 is increasing. The filament of V5 remains negative with respect to its plate, and the plate of V2 becomes positive with respect to its filament; therefore, V5 continues to conduct and V2 takes over conduction from V1, with V2 and V5 conducting in series with the load. Electrons flow through V5, the load, and V2 for another 60 degrees of the cycle.

In part D, the a-c voltage induced in secondary No. 2 reaches its maximum positive value and starts to decrease; the voltage induced in secondary No. 1 is approaching its maximum negative value. The plate of V2 remains positive with respect to its filament, and the filament of V6 becomes negative with respect to its plate; therefore, V2 continues to conduct and V6 takes over conduction from V5, with V2 and V6 conducting in series with the load. Electrons flow through V6, the load, and V2 for another 60 degrees of the cycle.

In part E, the a-c voltage induced in secondary No. 3 is approaching its maximum positive value, and the negative voltage in secondary No. 1 is decreasing. The filament of V6 remains negative with respect to its plate, and the plate of V3 becomes positive with respect to its filament; therefore, V6 continues to conduct and V3 takes over conduction from V2, with V3 and V6 conducting in series with the load. Electrons flow through V6, the load, and V3 for another 60 degrees of the cycle.

In part F, the a-c voltage induced in secondary No. 2 is approaching its maximum negative value, and the positive voltage in secondary No. 3 is decreasing. The plate of V3 remains positive with respect to its filament, and the filament of V4 becomes negative with respect to its plate; therefore, V3 continues to conduct and V4 takes over conduction from V6, with V3 and V4 conducting in series with the load. Electrons flow through V4, the load, and V3 for another 60 degrees of the cycle.

The cycle of operation is repeated, as shown in part A, when the a-c voltage induced in secondary No. 2 reaches its maximum negative value and the positive voltage in secondary No. 1 is increasing. The filament of V4 remains negative with respect to its plate, and the plate of V1 becomes positive with respect to its filament; therefore, V4 continues to conduct and V1 takes over conduction from V3, with V1 and V4 conducting in series with the load. Electrons flow through V4, the load, and V1, to initiate another complete cycle.

Thus, from the action described above, it can be seen that each positive and negative peak in each of the three phases produces a current pulse in the load. Because of the nature of the rectifier conduction periods, each rectifier tube conducts for 120 degrees of the cycle and carries one third of the total load current. The output voltage, e_o, produced across the load resistance is determined by the instantaneous currents flowing through the load; therefore, the output voltage has a pulsating waveform, which results in an irregularly shaped ripple voltage, because the output current and voltage are not continuous. The frequency of the ripple voltage is six times the frequency of the a-c source. Since this ripple frequency is higher than the ripple frequency of a single-phase, full-wave rectifier circuit or a three-phase, half-wave rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage.

The three-phase, full-wave rectifier circuit makes continuous use of the transformer secondaries, with the d-c load current passing through a secondary winding first in one direction and then in the other; thus, there is no tendency for the transformer core to become permanently magnetized. Since little d-c core saturation occurs, the effective inductance of the transformer, and therefore the efficiency, is relatively high.

The three-phase, full-wave rectifier produces across the load a pulsating (unfiltered) d-c output voltage, E_{av}, as follows:

$$E_{av} = 2.34\, E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of three-phase transformer

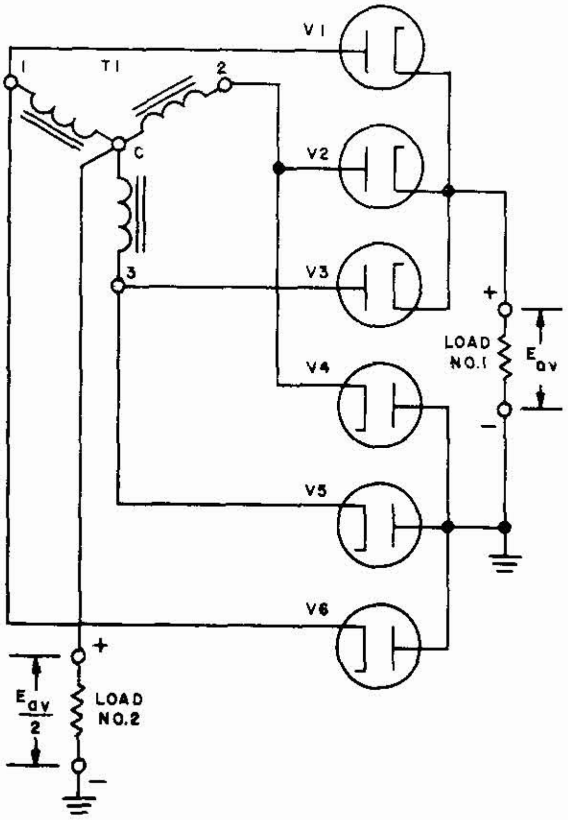
The **peak inverse voltage** across an individual rectifier in the three-phase, full-wave rectifier circuit during the period of time the tube is nonconducting is approximately 2.45 times the rms voltage across the secondary winding of one phase. Some pulsating d-c voltage is always present across the load, and this voltage is in series with the applied a-c secondary voltage; therefore, the sum of the instantaneous pulsating d-c load voltage and the instantaneous peak secondary voltage represents the peak inverse voltage across the rectifier tube. The peak inverse voltage **per tube** can be expressed as:

$$E_{inv} \text{ (per tube)} = 2.45\, E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of the three-phase transformer

The output of the three-phase, full-wave rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in part D of this section.)

A variation of the three-phase, full-wave rectifier circuit uses the common terminal of the wye-connected secondaries and rectifiers V4, V5, and V6 to form a three-phase, half-wave rectifier circuit. The circuit is fundamentally the same as that given earlier; for this reason the accompanying circuit schematic has been simplified and redrawn to eliminate the filament transformers and associated filament circuitry. The reference designations previously assigned remain unchanged.



Simplified Three-Phase, Half-Wave and Three-Phase, Full-Wave Rectifier Circuit

One advantage of the circuit is that two voltages may be supplied from the same transformer and rectifier combination. One output voltage (E_{out}) is obtained from the full-wave circuit; the other voltage $\frac{E_{out}}{2}$, which is equal to one half of the full-wave output voltage, is obtained by using rectifiers V4, V5, and V6 and the common terminal of the wye-connected secondaries as a conventional three-phase, half-wave rectifier circuit. (The operation of the three-phase, half-wave rectifier circuit was previously described in this section.) Although this circuit variation can supply two output voltages simultaneously to two separate loads, there is a limitation on the total current which can be carried by the rectifiers (V4, V5, and V6).

FAILURE ANALYSIS.

No Output. In the three-phase, full-wave rectifier circuit, the no-output condition is likely to be limited to the following possible causes: the lack of a-c filament or filament-transformer primary supply voltage, the lack of applied a-c high voltage, or a shorted load circuit (including shorted filter components).

A visual check of the glass-envelope rectifier tubes can easily be made to determine whether all filaments are lit. The filaments of V1, V2, and V3 should be observed first, because if these rectifiers are not lit there can be no d-c output. If the filaments of V1, V2, and V3 are not lit, the filament voltage should be measured at the secondary of transformer T2 to determine whether it is present; if necessary, check the primary voltage of T2 to determine whether it is present and of the correct value. If none of the rectifier filaments are lit, the primary voltage source for the operation of transformers T2, T3, T4, and T5 should be checked for the presence of voltage.

With the primary voltage removed from the circuit, continuity (resistance) measurements should be made of the secondary and primary windings to determine whether one or more windings are open. If necessary, the a-c secondary voltage at each of the three high-voltage secondaries may be measured between the common terminal of the wye-connected secondaries and the individual secondary terminal or the corresponding rectifier plate, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage to determine whether it is present and of the correct value.

With primary voltage removed from the rectifier circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. A short in the components of the filter circuit or in the load circuit will cause an excessive load current to flow. If the rectifier tubes are of the high-vacuum type, the heavy load current will cause the plate of the rectifiers to become heated and emit a reddish glow when the plate dissipation is exceeded and, if allowed to continue, may result in permanent damage to the tubes. If gas-filled rectifiers are used in the circuit, excessive load current will result in permanent damage to the tubes because gas-filled rectifiers are very susceptible to damage from current overload. Therefore, once the difficulty in the load circuit has been located and corrected, the gas-filled rectifiers will require replacement as a result of the overload condition.

Low Output. The rectifier tubes should be checked to determine whether the filaments are lit. Because of the normal overlap in rectifier conduction periods and the conduction of tubes in series to obtain full-wave output, one or more defective rectifiers in the three-phase, full-wave rectifier circuit can cause the low-output condition. Failure of only one rectifier in the circuit will cause a loss of rectifier conduction and no delivery of current to the load for approximately 120 degrees of the electrical cycle, and the output voltage will be reduced accordingly. If rectifier tube V1, V2, or V3 is not lit, the trouble is obviously associated with the tube that is not lit since the filaments of these tubes are in parallel; however, if V4, V5, or V6 is not lit, then the trouble may be either the tube or its associated filament supply (T3, T4, or T5). The tube filament should be checked for continuity; the presence of correct filament voltage at the tube socket should be determined by measurement. If necessary, the primary and secondary voltages should be checked at the terminals of the filament transformer (T3, T4, or T5) to determine whether the transformer is defective.

With the three-phase primary voltage removed from the circuit, continuity measurements should be made of the primary (and secondary) windings, to determine whether one (or more) of the windings is open. If necessary, the a-c voltage of each secondary winding may be measured between the common terminal of the wye connection and the individual secondary terminal or the corresponding rectifier plate, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage at each of the phases, to determine whether each voltage is present and of the correct value, since a low applied primary voltage can result in a low secondary voltage.

Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. Disconnect all secondary leads from the transformer, T1, and measure the current in each leg of the three-phase primary with the transformer unloaded; excessive primary current is an indication of shorted turns. A secondary winding which is shorted to the core can cause a low output voltage indication; to determine whether a winding is shorted to the core, all leads should be disconnected from the transformer and a measurement made between each individual winding and the core, using an ohmeter or a Megger (insulation tester).

Since a decrease in load resistance can cause an increase in load current and possibly result in a low-output condition, the rectifier-output current (to the filter circuit and to the load) should be checked to make sure that it is within tolerance and not excessive.

THREE-PHASE, FULL-WAVE (DELTA SECONDARY) RECTIFIER.

APPLICATION.

The three-phase, full-wave rectifier with delta secondary is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses six high-vacuum or gas-filled electron-tube diodes as rectifiers.

Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Requires separate filament transformers or separate filament windings for rectifier tubes.

Uses multiphase power transformer with delta-connected secondary windings; primary windings may be either delta- or wye-connected.

CIRCUIT ANALYSIS.

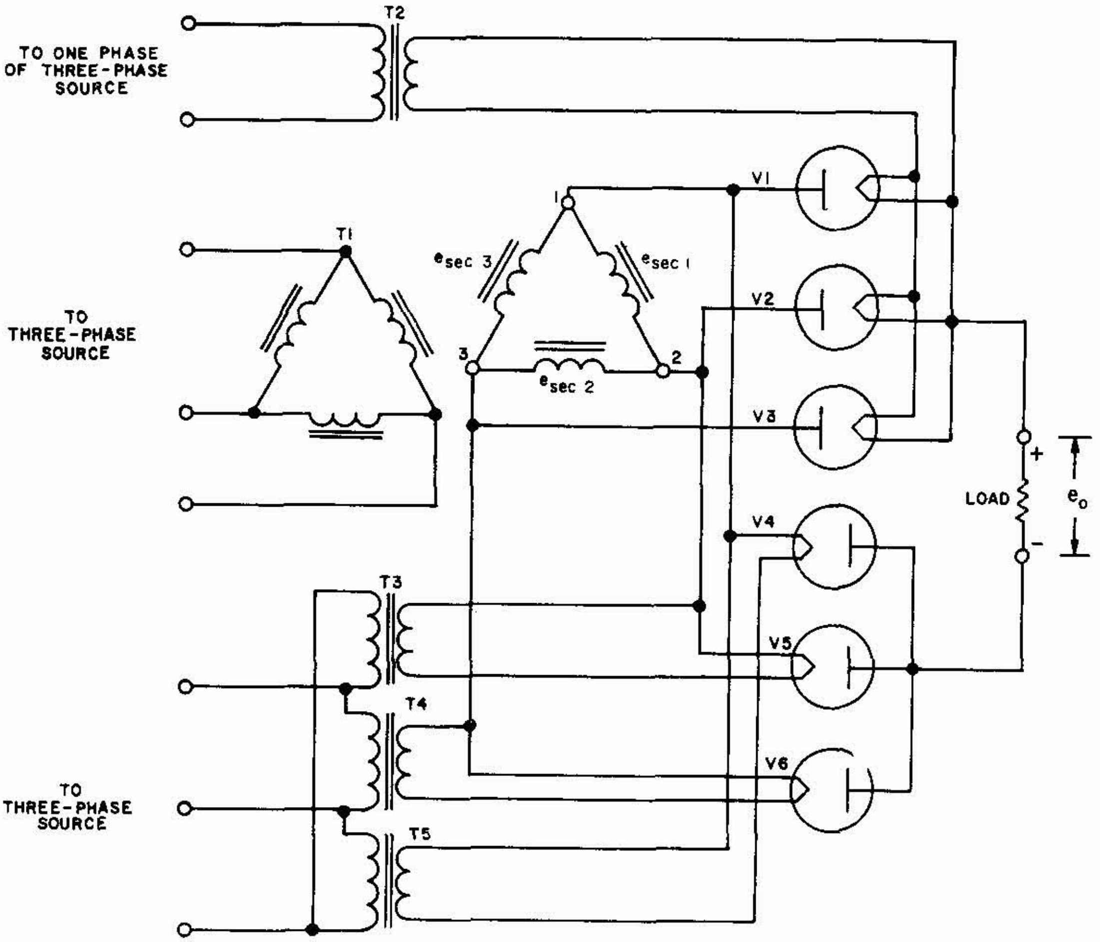
General. The three-phase, full-wave (delta-connected secondary) rectifier is a variation of the three-phase, full-wave (single-wye-connected secondary) rectifier, previously described in this section. The full-wave rectifier with delta secondary is used where a large amount of power is required by the load, such as for large shipboard or shore electronic installations. The term **three-phase** refers to the primary a-c source, which is the equivalent of three single-phase sources, each source supplying a sine-wave voltage 120 degrees out of phase with the others.

Circuit Operation. The three-phase, full-wave (delta secondary) rectifier circuit is illustrated in the accompanying circuit schematic. The circuit uses a three-phase power transformer, T1, to step up the alternating source voltage to a high value in the delta-connected secondaries. Each secondary winding is connected to the other in proper phase relationship so that the currents through the windings are balanced. Damage can result to the transformer windings if improperly connected; for this reason, the windings are usually connected internally in the proper phase to prevent the possibility of making wrong connections, and only the three secondary terminals are brought out of the case.

The primary windings of transformer T1 are shown delta-connected, although in some instances they may be wye-connected (as for a three- or four-wire system).

The plate of rectifier V1 and the filament (cathode) of rectifier V4 are connected to secondary terminal No. 1 of transformer T1; the plate of rectifier V2 and the filament of rectifier V5 are connected to secondary terminal No. 2; the plate of rectifier V3 and the filament of rectifier V6 are connected to secondary terminal No. 3.

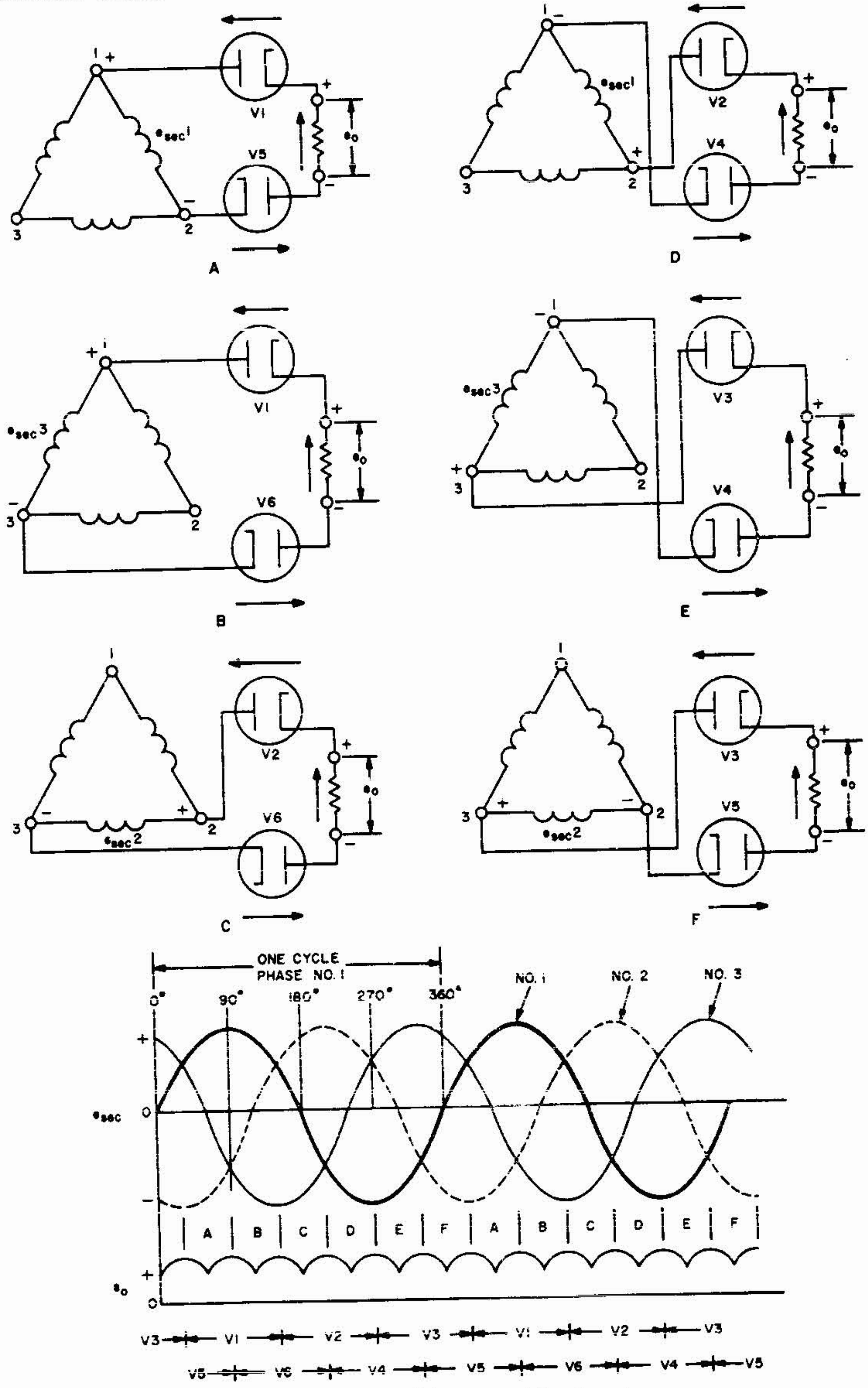
One filament transformer, T2, is used to supply the filament voltage to rectifiers V1, V2, and V3, since the filaments of these rectifiers are all at the same potential. However, since the filaments of rectifiers V4, V5, and V6 have a high potential difference existing between them, three separate filament transformers (T3, T4, and T5) are used. A single filament transformer may be used for this



Basic Three-Phase, Full-Wave (Delta Secondary) Rectifier Circuit

purpose, provided that it incorporates three separate filament windings that are well insulated from each other and ground (chassis). The primary windings of filament transformers T3, T4, and T5 are connected to different phases of the three-phase source and may be considered to be delta-connected although they are three separate transformers. The a-c voltage for the primaries of the filament transformers is applied independent of and prior to, the primary voltage to the three-phase power transformer, T1. A time-delay arrangement, either manually operated or automatic, normally permits the rectifier filaments to be preheated to the normal operating temperature before the high-voltage ac can be applied to the rectifier circuit.

The circuit arrangement given in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). The circuit is typical of high-voltage d-c supplies designed for use in radar sets, communication



Simplified Circuit Schematics and Waveforms for Three-Phase, Full-Wave Rectifier transmitters, or other equipment for which the d-c power requirement is several kilowatts or more.

The operation of the three-phase, full-wave rectifier circuit can be understood from the simplified circuit schematics (parts A through F) and the waveforms given in the accompanying illustration. The basic three-phase, full-wave rectifier schematic, given earlier in this discussion, has been simplified to show the circuit action throughout the electrical cycle; the reference designations used correspond to those assigned in the basic circuit schematic.

The operation of the delta-secondary rectifier circuit is similar to that of the wye-secondary rectifier circuit (previously described); however, the a-c voltage across an individual delta-connected secondary winding is 0.742 E_{av}, whereas the voltage across an individual wye-connected secondary winding is 0.428 E_{av} (E_{av} is the unfiltered d-c output across the load). The voltages developed across the secondary windings of transformer T1 are 120 degrees out of phase with relation to each other and are constantly changing in polarity. In the delta-connected secondary, at any given instant the voltage in one phase is equal to the vector sum of the voltages in the other two phases. The polarities indicated for the secondary windings in the simplified circuit schematics (parts A through F) of the accompanying illustration represent the instantaneous polarity of the induced voltages in the secondary. Although the instantaneous polarity shown in the schematic is given for only one secondary winding, the sum of the instantaneous voltages in the other two windings is equal to the voltage of the first winding. The arrows on the schematics are used to indicate the directions of electron flow in the circuit.

The plates of rectifiers V1, V2, and V3 are connected to secondary terminals No. 1, No. 2, and No. 3, respectively; the filaments (cathode) of rectifiers V4, V5, and V6 are connected to secondary terminals No. 1, No. 2, and No. 3, respectively. When the plates of V1, V2, and V3 are positive with respect to their filaments, the tubes will conduct; when the filaments of V4, V5, and V6 are negative with respect to their plates, these tubes will conduct.

At any given instant of time in the three-phase, full-wave rectifier circuit, a rectifier, the load, and a second rectifier are in series across two terminals of the delta-connected secondaries and, therefore, two rectifiers are conducting. Each of the six rectifiers conducts for 120 degrees of an electrical cycle; however, there is an overlap of conduction periods, and the rectifiers conduct in a sequence which is determined by the phasing of the instantaneous secondary voltages of the power transformer. In the circuit described, two rectifiers are conducting at any instant of time, with the rectifier conduction periods occurring in the following order: V1 and V6, V6 and V2, V2 and V4, V4 and V3, V3 and V5, V5 and V1, V1 and V6, etc.

Refer to the secondary-voltage waveform, e_{sec}, shown in the accompanying illustration. Assume that the a-c voltage induced in secondary No. 1, transformer terminals No. 1 and No. 2, is approaching its maximum positive value (at 90 degrees); also, the voltage induced in secondary No. 2, transformer secondary terminals No. 2 and No. 3, has reached its maximum negative value (at 30 degrees) and is decreasing. (The voltage induced in secondary No. 3, terminals No. 1 and No. 3, is passing through zero.) This condition is shown by the simplified schematic of part A in the accompanying illustration. The plate of rectifier V1 is positive with respect to its filament (cathode), and the filament of rectifier V5 is negative with respect to its plate; therefore, both tubes conduct, and electrons flow through V5, the load, and V1 for 60 degrees of the electrical cycle.

In part B, the a-c voltage induced in secondary No. 1 has reached its maximum positive value (at 90 degrees) and starts to decrease during the next 60 degrees of the cycle; the voltage induced in secondary No. 3 is approaching its maximum negative value. The plate of V1 remains positive with respect to its filament, and the filament of V6 becomes negative with respect to its plate; therefore, V1 continues to conduct and V6 takes over conduction from V5, with V1 and V6 conducting in series with the load. Electrons flow through V6, the load, and V1 for another 60 degrees of the cycle.

In part C, the a-c voltage induced in secondary No. 3 has reached its maximum negative value and starts to decrease; the voltage induced in secondary No. 2 is approaching its maximum positive value. The filament of V6 remains negative with respect to its plate, and the plate of V2 becomes positive with respect to its filament; therefore, V6 continues to conduct and V2 takes over conduction from V1, with V2 and V6 conducting in series with the load. Electrons flow through V6, the load, and V2 for another 60 degrees of the cycle.

In part D, the a-c voltage induced in secondary No. 2 has reached its maximum positive value and starts to decrease; the voltage induced in secondary No. 1 is approaching its maximum negative value. The plate of V2 remains positive with respect to its filament, and the filament of V4 becomes negative with respect to its plate; therefore, V2 continues to conduct and V4 takes over conduction from V6, with V2 and V4 conducting in series with the load. Electrons flow through V4, the load, and V2 for another 60 degrees of the cycle.

In part E, the a-c voltage induced in secondary No. 3 approaches its maximum positive value, and the negative voltage in secondary No. 1 is decreasing. The filament of V4 remains negative with respect to its plate, and the plate of V3 becomes positive with respect to its filament; therefore, V4 continues to conduct and V3 takes over conduction from V2 with V3 and V4 conducting in series with the load. Electrons flow through V4, the load, and V3 for another 60 degrees of the cycle.

In part F, the a-c voltage induced in secondary No. 2 approaches its maximum negative value, and the positive voltage in secondary No. 3 is decreasing. The plate of V3 remains positive with respect to its filament, and the filament of V5 becomes negative with respect to its plate; therefore, V3 continues to conduct and V5 takes over conduction from V4, with V3 and V5 conducting in series with the load. Electrons flow through V5, the load, and V3 for another 60 degrees of the cycle.

The cycle of operation is repeated, as shown in part A, when the a-c voltage induced in secondary No. 2 has reached its maximum negative value and the positive voltage in secondary No. 1 is increasing. The filament of V5 remains negative with respect to its plate, and the plate of V1 becomes positive with respect to its filament; therefore, V5 continues to conduct and V1 takes over conduction from V3, with V1 and V5 conducting in series with the load. Electrons flow through V5, the load, and V1, to initiate another complete cycle.

Thus, from the action described above, it can be seen that each positive and negative peak in each of the three phases produces a current pulse in the load. Because of the nature of the rectifier conduction periods, each rectifier tube conducts for 120 degrees of the cycle and carries one third of the total load current. The output voltage, e_o, produced across the load resistance is determined by the instantaneous current flowing through the load; therefore, the output voltage has a pulsating waveform, which results in an irregularly shaped ripple voltage, because the output current and voltage are not continuous. The frequency of the ripple voltage is six times the frequency of the a-c source. Since this ripple frequency is higher than the ripple frequency of a single-phase, full-wave rectifier circuit or a three-phase, half-wave rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage.

The three-phase, full-wave rectifier circuit makes continuous use of the transformer secondaries, with the d-c load current passing through the delta-connected secondary windings first in one direction and then in the other; thus, there is no tendency for the transformer core to become permanently magnetized. Since little d-c core saturation occurs, the effective inductance of the transformer, and therefore the efficiency, is relatively high.

The three-phase, full-wave rectifier with delta-connected secondaries produces across the load a pulsating (unfiltered) d-c output voltage, E_{av}, as follows:

$$E_{av} = 1.35\ E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of three-phase delta-connected transformer

The **peak inverse voltage** across an individual rectifier in the three-phase, full-wave circuit during the period of time the tube is nonconducting is approximately 1.42 times the rms voltage across the secondary winding of one phase. Some pulsating d-c voltage is always present across the load, and this voltage is in series with the applied a-c secondary voltage; therefore, the sum of the instantaneous pulsating d-c load voltage and the instantaneous peak peak secondary voltage represents the peak inverse voltage across the rectifier tube. The peak inverse voltage **per tube** can be expressed as:

$$E_{inv}\ (\text{per tube}) = 1.42\ E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of three-phase delta-connected transformer

The output of the three-phase, full-wave rectifier circuit is connected to a suitable filter circuit, to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in part D of this section.)

FAILURE ANALYSIS.

No Output. In the three-phase, full-wave (delta secondary) rectifier circuit, the no-output condition is likely to be limited to the following possible causes: the lack of a-c filament or filament-transformer primary supply voltage, the lack of applied a-c high voltage, or a shorted load circuit (including shorted filter components).

Checks for rectifier tube and filament transformer operation and for a shorted load circuit are the same as those given for the three-phase, full-wave (single "Y" secondary) rectifier circuit, previously described in this section.

With the primary voltage removed from the circuit, continuity (resistance) measurements should be made of the secondary and primary windings to determine whether one or more windings are open. Since the three windings of the delta-secondary circuit are sometimes connected internally and only three terminals are brought out of the case, voltage and resistance measurements are made between the terminals of the delta-connected secondaries. When making measurements (voltage or resistance) of the secondary circuit, it should be remembered that the windings form a delta configuration, with two windings in series and this combination in parallel with the winding under measurement. In other instances, the secondary windings are connected to six individual terminals, and these terminals are connected together to form a delta configuration. Thus, in this instance, the terminal connections may be removed to enable measurements to be made on individual secondary windings independent of other windings. If necessary, the a-c secondary voltage at each of the three high-voltage secondaries may be measured between the terminals of the delta-connected secondaries, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage to determine whether it is present and of the corret value.

Low Output. Except for the voltage and resistance measurements of the delta-secondary circuit, the checks for low-output condition are the same as those given for the three-phase, full-wave (single "Y" secondary) rectifier circuit, previously discussed in this section. Also, refer to the paragraph above for information concerning procedures to be used when making voltage and resistance measurements on delta-connected secondary windings.

THREE-PHASE, HALF-WAVE (DOUBLE "Y" SECONDARY) RECTIFIER.

APPLICATION.

The three-phase, half-wave rectifier with double-wye secondary and interphase reactor is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses six high-vacuum or gas-filled electron-tube diodes as rectifiers.

Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Requires only one filament-voltage supply.

Uses multiphase power transformer with two parallel sets of wye-connected secondaries operating 180 degrees out of phase with each other. The center points of the wye-connected secondaries are connected through an interphase reactor or balance coil to the load. The primary windings are generally delta-connected.

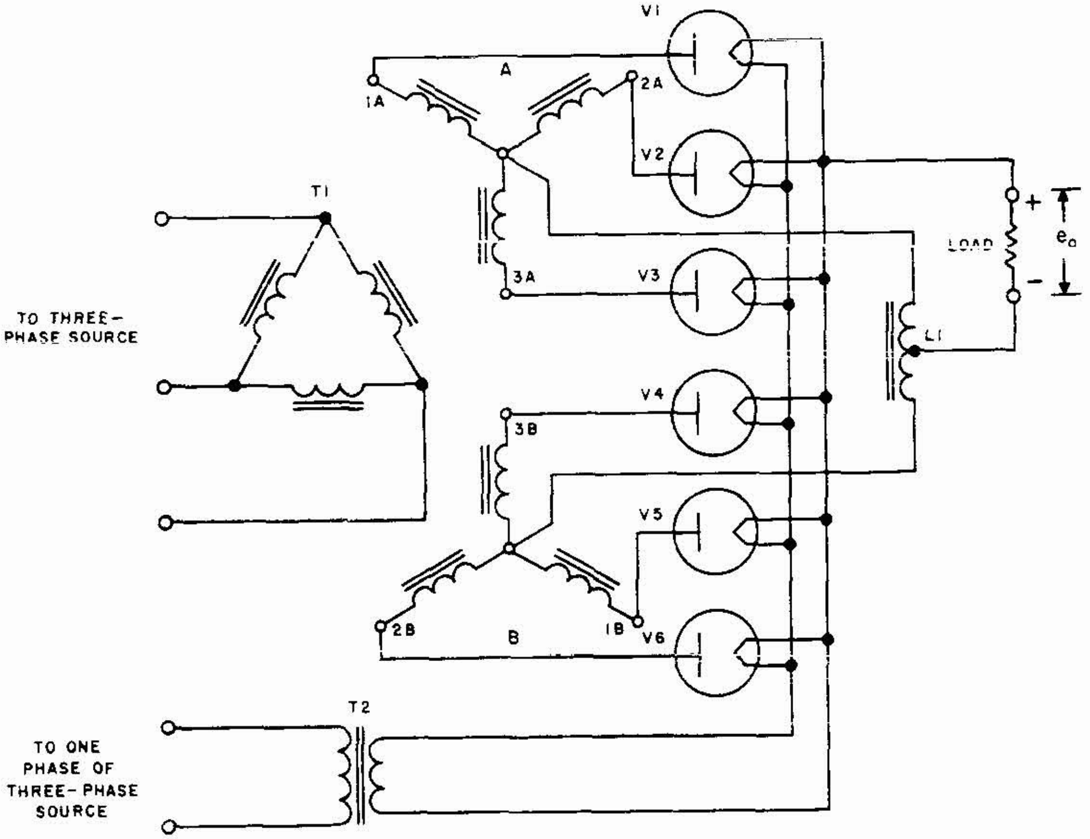
CIRCUIT ANALYSIS.

General. Fundamentally, this rectifier circuit resembles two half-wave (three-phase star) rectifiers in parallel, each rectifier circuit operating from a common delta-connected primary, and sharing a common load through an interphase reactor or balance coil. (The three-phase, half-wave rectifier circuit was previously described in this section.) The three-phase, half-wave (double-wye secondary) rectifier circuit uses a power transformer with two sets of wye-connected secondaries, the windings of one set being connected 180 degrees out of phase with respect to the corresponding windings of the other set. For this reason, the circuit is sometimes referred to as a **six-phase** rectifier. The junction point of each wye-connected secondary is, in turn, connected to a center-tapped inductance, called an **interphase reactor** or **balance coil**. The center tap of the interphase reactor is the common negative terminal for the load.

Circuit Operation. The three-phase, half-wave (double-wye secondary) rectifier circuit is illustrated in the accompanying circuit schematic. The circuit used a three-phase power transformer, T1, to step up the alternating source voltage to a high value in the wye-connected secondaries. The primary windings of transformer T1 are shown delta-connected; the delta primary is common to both wye-connected secondaries. The plates of rectifiers V1, V2, and V3 are connected to one set of secondary ("A") windings at terminals 1A, 2A, and 3A, respectively. The plates of rectifiers V4, V5, and V6 are connected to the other set of secondary ("B") windings at terminals 3B, 1B, and 2B, respectively.

One filament transformer, T2, is used to supply the filament voltage to all rectifiers, since the filament of the rectifiers are all at the same potential. Although a single filament transformer is shown on the schematic, as many as three identical filament transformers are sometimes used as the filament supply, with each filament transformer supplying two (or more) rectifier tubes; in this case the primary of each single-phase filament transformer is connected to a different phase of the three-phase source. Voltage is applied to the primaries of the filament transformers before it is applied to the primary of the three-phase power transformer T1. A time-delay arrangement, either manually operated or automatic, normally permits the rectifier filaments to be preheated to the normal operating temperature before the high-voltage ac can be applied to the rectifier circuit.

The center-tapped inductance, L1, is an interphase reactor or balance coil. The common terminal of each wye-connected secondary is connected to one end of L1; the



Basic Three-Phase, Half-Wave (Double "Y" Secondary) Rectifier Circuit

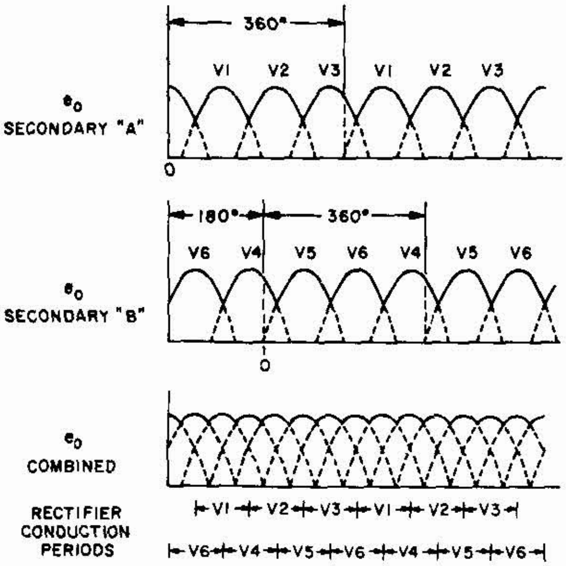
center tap of the interphase reactor is connected to the load. Thus, the output-load current of each three-phase, half-wave rectifier circuit passes through one half of the interphase reactor, and these two currents are then combined in the load. For satisfactory operation, interphase reactor L1 must have sufficient inductance to maintain continuous current flow through each half of the coil. In effect, this reactor constitutes a choke-input filter arrangement, and exhibits the regulation characteristics of such a filter.

The circuit arrangement given in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). The circuit is typical of high-voltage d-c supplies designed for use in large communication transmitters or other equipment for which the d-c power requirement is several kilowatts or more.

The operation of the three-phase, half-wave (double-wye secondary) rectifier circuit can be understood by reference to the circuit schematic and the waveforms given in the accompanying illustration. The operation of each individual half-wave rectifier is the same as that given for the three-phase, half-wave (three-phase star) rectifier circuit previously described in this section. Although the voltages induced in the three transformer secondary windings differ in phase by 120 degrees, the voltages induced in corresponding windings of the two sets of wye-connected secondaries ("A" and "B") are 180 degrees out of phase with respect to each other.

The output resulting from the conduction of rectifiers V1, V2, and V3 in conjunction with secondary "A" is shown on the accompanying illustration; the output resulting from the conduction of rectifiers V4, V5, and V6 in conjunction with secondary "B", the resulting combined d-c output voltage, e_o, and the corresponding rectifier conduction periods are also given.

At any instant of time, two rectifier tubes are conducting to deliver current to the load, but their currents are not in phase and an overlap in conduction periods of the six rectifiers occurs. Each rectifier conducts for 120 degrees of the input cycle and contributues one sixth of the total d-c current supplied to the load. In the circuit described, two rectifiers are conducting at any instant of time, with the rectifier conduction periods occurring in the following order: V6 and V1, V1 and V4, V4 and V2, V2 and V5, V5 and V3, V3 and V6, V6 and V1, etc.



Waveforms for Three-Phase, Half-Wave (Double "Y" Secondary) Rectifier Circuit

The main component of the ripple frequency present across the interphase reactor is three times the frequency of the a-c source. Electrons flow through the load in pulses, one pulse for each positive half cycle of the impressed voltage in each of the three phases of the two sets of secondaries. As mentioned previously, the secondaries are 180 degrees out of phase with respect to each other; therefore, the output voltage has a ripple frequency which is six times the frequency of the a-c source. Since this ripple frequency is higher than that of a single-phase, full-wave rectifier circuit or a single three-phase, half-wave rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage.

In order to keep d-c core saturation to a minimum (because of current flowing in one direction only in each secondary winding) and to keep the efficiency relatively high, it is necessary to use a single three-phase transformer with multiple secondaries, rather than six individual single-phase transformers.

The three-phase, half-wave (double-wye secondary) rectifier circuit produces across the load a pulsating (unfiltered) d-c output voltage, E_{av}, as follows:

$$E_{av} = 1.17\ E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of the three-phase transformer

The **peak inverse voltage** across an individual rectifier in the three-phase, half-wave rectifier circuit during the period of time the tube is nonconducting is approximately 2.45 times the rms voltage across the secondary winding of one phase. The peak inverse voltage **per tube** can be expressed as:

$$E_{inv}\ \text{(per tube)} = 2.45\ E_{rms}$$

where: E_{rms} = rms voltage across one secondary winding of the three-phase transformer

The output of the three-phase, half-wave (double-wye secondary) rectifier circuit is connected to a suitable filter circuit, to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in the latter part of this section.)

A variation of the three-phase, half-wave (double-wye secondary) rectifier circuit omits the use of an interphase reactor or balance coil. If the interphase reactor (L1) is not used in the circuit and the common terminal of each wye-connected secondary is connected to the negative terminal of the load, the circuit is classified as a **six-phase star.** However, the six-phase star, half-wave rectifier circuit is considered less desirable than the three-phase, half-wave (double-wye secondary) rectifier circuit, because it requires the use of tubes with higher peak current ratings and a transformer with a higher kva rating to obtain an equivalent d-c output. Therefore, the circuit is seldom used.

FAILURE ANALYSIS.

No Output. In the three-phase, half-wave (double-wye secondary) rectifier circuit, the no-output condition is likely to be limited to the following possible causes: the lack of a-c filament or filament-transformer primary supply voltage, the lack of applied a-c high voltage, or a shorted load circuit (including shorted filter components).

A visual check of the glass-envelope rectifier tubes can easily be made to determine whether the filaments are lit; if they are not lit, there can be no d-c output. The filament voltage should be measured at the secondary terminals of transformer T2 to determine whether it is present; if necessary, check the primary voltage to T2 to determine whether it is present and of the correct value. When the circuit employs more than one filament transformer (for example, three transformers each operating from one phase of the three-phase source), if none of the rectifier filaments are lit the primary voltage source for the filament transformers should be checked for the presence of voltage.

With the primary voltage removed from the circuit, continuity (resistance) measurements should be made of the secondary and primary windings, to determine whether one or more windings are open and whether the common terminals of the wye-connected secondaries are connected to the load circuit through the interphase reactor or balance coil. If necessary, the secondary voltage may be measured at one (or more) of the high-voltage secondaries between the common terminal of the wye-connected secondaries and a secondary terminal or corresponding rectifier plate, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage to determine whether it is present and of the correct value.

With primary voltage removed from the rectifier circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. A short in the components of the filter circuit or in the load circuit will cause an excessive load current to flow, and the full output voltage will be developed across each half of the interphase reactor, L1. If the rectifier tubes are of the high-vacuum type, the heavy load current will cause the plates of the rectifiers to become heated and emit a reddish glow when the plate dissipation is exceeded and, if allowed to continue, may result in permanent damage to the tubes. If gas-filled rectifiers are used in the circuit, excessive load current will result in permanent damage to the tubes because gas-filled rectifiers are very susceptible to damage from current overload. Therefore, once the difficulty in the load circuit has been located and corrected, the gas-filled rectifiers will require replacement as a result of the overload condition.

Low Output. The rectifier tubes should be checked to determine whether all filaments are lit; however, because of the normal overlap in rectifier conduction periods, the failure of one or two rectifiers in the circuit will not greatly affect the output voltage but may increase the ripple amplitude. If only one rectifier is not lit, the tube filament should be checked for continuity. If the circuit employs more than one filament transformer and one or more tubes are not lit, the corresponding filament transformer (s) should be checked. Measure the secondary voltage to determine whether the correct filament voltage is present; the primary voltage should be measured at the transformer terminals, to determine whether voltage is applied and of the correct value. If necessary, continuity measurements of the transformer windings should be made to determine whether the transformer is defective.

The continuity of each half of the interphase reactor, L1, should be measured to determine whether one half of the winding is open. An open circuit in one half of this reactor will disconnect its associated three-phase, wye-connected secondary; the output voltage will decrease as a result, and the rectifier circuit will continue to operate as a three-phase, half-wave rectifier with single-wye secondary.

With the three-phase primary voltage removed from the circuit, continuity measurements should be made of the primary (and secondary) windings, to determine whether one (or more) of the windings is open. If necessary, the a-c voltage of each secondary winding in each set of secondaries may be measured between the common terminal of the wye connection and the individual secondary terminal or the corresponding rectifier plate, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage at each phase, to determine whether voltage is present and of the correct value, since a low applied primary voltage can result in a low secondary voltage.

Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. Disconnect all secondary leads from the transformer, and measure the current in each leg of the three-phase primary with the transformer unloaded; excessive primary current is an indication of shorted turns. A secondary winding which is shorted to the core can also cause a low output voltage indication; to determine whether a winding is shorted to the core, all leads should be disconnected from the transformer and a measurement made between each winding and the core, using an ohmmeter or a Megger (insulation tester).

Since a decrease in load resistance can cause an increase in load current and possibly result in a low-output condition, the rectifier-output current (to the filter circuit and to the load) should be checked, to make sure that it is within tolerance and is not excessive.

HALF-WAVE VOLTAGE DOUBLER.

APPLICATION.

The half-wave voltage-doubler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional half-wave rectifier circuit. This voltage doubler is normally used in "transformerless" circuits where the load current is small and voltage regulation is not critical. The circuit is frequently employed as the power supply in small portable receivers and audio amplifiers and, in some transmitter applications, as a bias supply.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-c output voltage is approximately twice that obtained from equivalent half-wave rectifier circuit; output current is relatively small.

Output requires filtering; d-c output ripple frequency is equal to a-c source frequency.

Has poor regulation characteristics; output voltage available is a function of load current.

Depending upon circuit applications, may be used with or without a power isolation transformer.

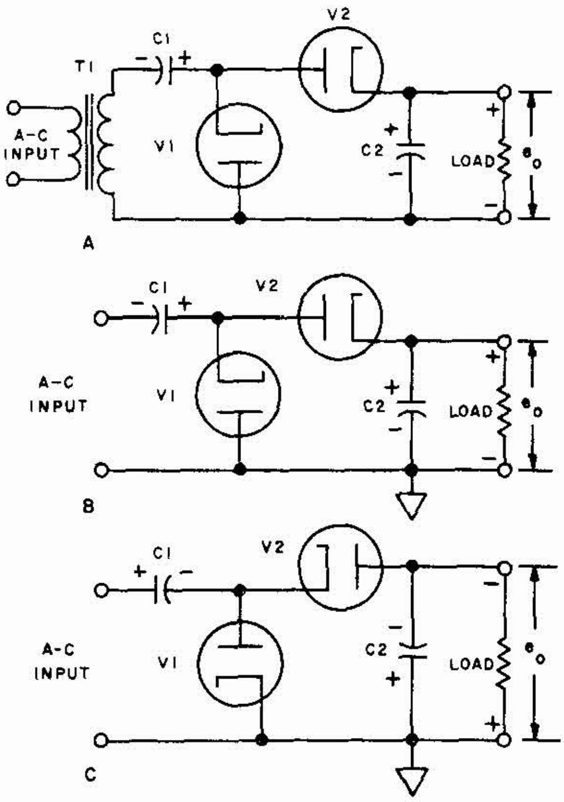
Uses indirectly heated cathode-type rectifiers.

CIRCUIT ANALYSIS.

General. The half-wave voltage-doubler circuit is used with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage doubler** implies, the output voltage is approximately twice the input voltage. The half-wave voltage doubler derives its name from the fact that the output charging capacitor (C2) across the load receives a charge once for each complete cycle of the applied voltage. The half-wave voltage doubler is sometimes called a **cascade** voltage doubler. The voltage regulation of the circuit is poor and, therefore, its use is generally restricted to applications in which the load current is small and relatively constant.

Circuit Operation. In the accompanying circuit schematics, parts A, B, and C illustrate basic half-wave voltage-doubler circuits. The circuit shown in part A uses a transformer, T1, which can be either a step-up transformer to obtain a high value of voltage in the secondary circuit, or an isolation transformer to permit either d-c output terminal to placed at ground (chassis) potential. The circuits shown in parts B and C do not use a transformer, and operate directly from the a-c source. In the circuit illustrated in part A, either output terminal may be placed at ground (chassis) potential. The circuit illustrated in part B places one side of the a-c source at a negative d-c potential, and thus restricts the circuit to use as a positive d-c supply. A variation of this circuit is illustrated in part C; this variation provides a negative output voltage.

The rectifiers, V1 and V2, are of the indirectly heated cathode type, and are identical-type diodes. Although the circuit schematic illustrates two separate rectifiers, a twin-diode is generally used in the circuit. Typical twin-diode electron tubes designed specifically for use in voltage-doubler circuits are: 25Z6, 50Y6, and 117Z6. As indicated by the tube-type numbers, these tubes require nominal filament-supply voltages of 25, 50, and 117 volts, respectively. Because there are several possible circuit combinations, the actual filament circuits for V1 and V2 are not shown on the circuit schematics. The filament voltage for the rectifiers is usually obtained directly from the a-c source if the filament is rated at the source voltage, by use of a voltage-dropping resistance in series with the rectifier filament (s) to reduce the a-c source voltage to the correct value, or from a transformer secondary winding of the correct value. In some equipments, the filaments of other tubes within the equipment are connected in series (or series-parallel), and this combination is then placed in series with the rectifier filament (s) across the a-c source; when this is done, a voltage-dropping resistor may be required.

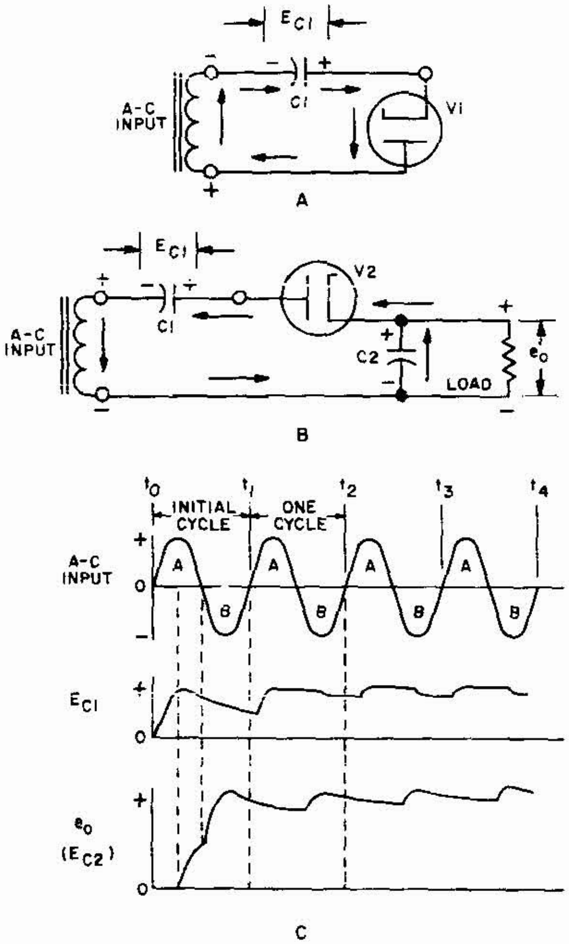


Basic Half-Wave Voltage-Doubler Circuits

In the three circuits illustrated, the functions of rectifiers V1 and V2, and of charging capacitors C1 and C2, are the same for each of the circuits.

The operation of a half-wave voltage-doubler circuit can be understood from the simplified circuits, parts A and B, and the waveforms, part C, shown in the accompanying illustration.

Assume that the a-c input to the voltage doubler during the initial half-cycle is of the polarity indicated in part A of the illustration. Electrons flow in the direction indicated by the small arrows from the positive plate of charging capacitor C1, through rectifier tube V1 (cathode to plate),



Typical Half-Wave Voltage-Doubler Circuit Operation and Waveforms

and to the a-c source. The left-hand (negative) plate of capacitor C1 now has a surplus of electrons, while the right-hand (positive) plate lacks electrons. Thus, during initial half-cycle, capacitor C1 assumes a charge (E_{C1}) of the polarity indicated, which is equal to approximately the peak value of the applied a-c voltage.

During the next half-cycle the polarity of the applied a-c input to the voltage doubler is as indicated in part B of the illustration. The charge (E_{C1}) existing across capacitor C1 is in series with the applied ac and will therefore add its potential to the peak value of the input voltage. Electrons flow in the direction indicated by the small arrows from the positive plate of capacitor C2, through rectifier tube V2 (cathode to plate), and to the positive plate of capacitor C1. Thus, during the second half-cycle capacitor C2 assumes a charge (E_{C2}) of the polarity indicated which is equal to the peak value of the applied a-c voltage plus the value of the charge (E_{C1}) existing across charging capacitor C1. Thus the value of the voltage (E_{C2}) across capacitor C2 is equal to approximately twice the peak voltage of the applied ac, provided that charging capacitor C1 does not lose any initial charge.

In a practical circuit, the value of capacitors C1 and C2 is at least 16 μf; therefore, with such a large value of capacitance in the circuit and because there is always some resistance (rectifier-tube plate resistance and a-c source impedance) in the circuit, each capacitor may not immediately attain its maximum charge until several input cycles have occurred. Capacitor C2 is charged only on alternate half-cycles of the applied a-c voltage, and is always attempting to discharge through the load resistance; therefore, the resulting waveform of the output voltage, e_o (or E_{C2}), varies as shown in part C of the illustration.

The output waveform contains some ripple voltage; therefore, additional filtering is required to obtain a steady d-c voltage. The frequency of the main component of the ripple voltage is the same as the frequency of the a-c source, because capacitor C2 is charged only once for each complete input cycle. The regulation of the voltage-doubler circuit is relatively poor; the value of output voltage obtained is determined largely by the resistance of the load and the resulting load current, since the load (and the filter circuit, if used) is in parallel with capacitor C2.

FAILURE ANALYSIS.

No Output. In the half-wave voltage-doubler circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of filament voltage or an open filament in the rectifier (s), the lack of applied a-c voltage, a shorted load circuit (including capacitor C2 and filter circuit components), or an open capacitor C1.

A visual check of a glass-envelope rectifier tube can be made to determine whether the filament (s) is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of voltage at the tube socket should be determined by measurement.

The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is present and is the correct value. If the circuit uses a step-up or isolation transformer (T1), measure the voltage at the secondary terminals to determine whether it is present and is the correct value. With the primary voltage removed from the transformer, continuity measurements of the primary and secondary windings should be made to determine whether one of the windings is open, since an open circuit in either winding will cause a lack of secondary voltage.

With the a-c supply voltage removed from the input to the circuit and with the load disconnected from capacitor

C2, resistance measurements can be made across the terminals of capacitor C2 and at the output terminals of the circuit (across load). These measurements will determine whether the capacitor (C2) or the load circuit (including filter components) is shorted. Because capacitor C2 and the filter-circuit capacitors are usually electrolytic capacitors, the resistance measurements may vary, depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the circuit test points for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value. Capacitor C1 may be checked in a similar manner.

A quick method which can be used to determine whether capacitor C1 or C2 is the source of trouble is to substitute a known good capacitor in the circuit for the suspected capacitor and measure the resulting output voltage.

Low Output. The rectifiers (V1 and V2) should be checked to determine whether the cause of low output is low cathode emission. The load current should be checked to make sure that it is not excessive, because the voltage-doubler circuit has poor regulation and an increase in load current (decrease in load resistance) can cause a decrease in output voltage.

One terminal of each capacitor, C1 and C2, should be disconnected from the circuit and each capacitor checked, using a capacitance analyzer, to determine the effective capacitance and leakage resistance of each capacitor. A decrease in effective capacitance or losses within either capacitor can cause the output of the voltage-doubler circuit to be below normal, since the defective capacitor will not charge to its normal operating value. If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter; the measurements are made with one terminal of the capacitor disconnected from the circuit and, using the ohmmeter procedure outlined in the previous paragraph, two measurements are made (with the test leads reversed at the capacitor terminals for one of the measurements). The larger of the two measurements should be greater than 1 megohm for a satisfactory capacitor.

A procedure which can be used to quickly determine whether the capacitors are the cause of low output is to substitute known good capacitors in the circuit and measure the resulting output voltage.

FULL-WAVE VOLTAGE DOUBLER.

APPLICATION.

The full-wave voltage-doubler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional rectifier circuit utilizing the same input voltage. This voltage doubler is normally used where the load current is small and voltage regulation is not too critical; however, the regulation of the full-wave voltage doubler is better than that of the half-wave voltage doubler. The circuit is frequently employed as the power supply in small portable receivers and audio amplifiers and, in some transmitter applications, as a bias supply.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-c output voltage is approximately twice that obtained from half-wave rectifier circuit utilizing the same input voltage; output current is relatively small.

Output requires filtering; d-c output ripple frequency is equal to twice the a-c source frequency.

Has relatively poor regulation characteristics; output voltage available is a function of load current.

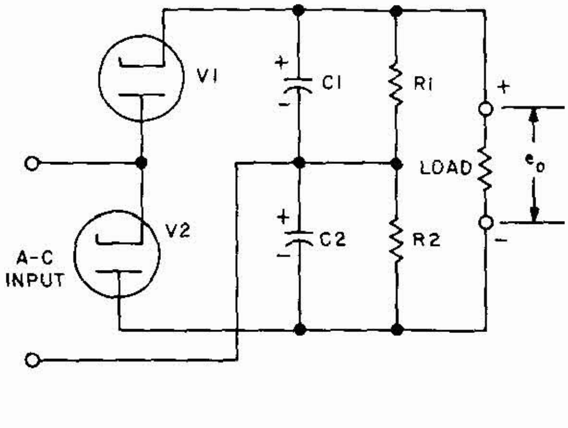
Depending upon circuit application, may be used with or without a power or isolation transformer.

Uses indirectly heated cathode-type rectifiers.

CIRCUIT ANALYSIS.

General. The full-wave voltage-doubler circuit is used either with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage doubler** implies, the output voltage is approximately twice the input voltage. The full-wave voltage doubler derives its name from the fact that the charging capacitors (C1 and C2) are in series across the load, and each capacitor receives a charge on alternate half-cycles of the applied voltage; therefore, two pulses are present in the load circuit for each complete cycle of the applied voltage. Although the voltage regulation of the full-wave voltage doubler is better than that of the half-wave voltage doubler, it is nevertheless considered poor as compared with conventional rectifier circuits. Therefore, use of the circuit is generally restricted to applications in which the load current is small and relatively constant.

Circuit Operation. A basic full-wave voltage-doubler circuit is shown in the accompanying circuit schematic. Fundamentally, the circuit consists of two half-wave rectifiers, V1 and V2, and two charging capacitors, C1 and C2, arranged so that each capacitor receives a charge on alternate half-cycles of the applied voltage. The voltage developed across one capacitor is in series with the



Basic Full-Wave Voltage-Doubler Circuit

voltage developed across the other; thus, the output voltage developed across the load resistance is approximately twice the applied voltage.

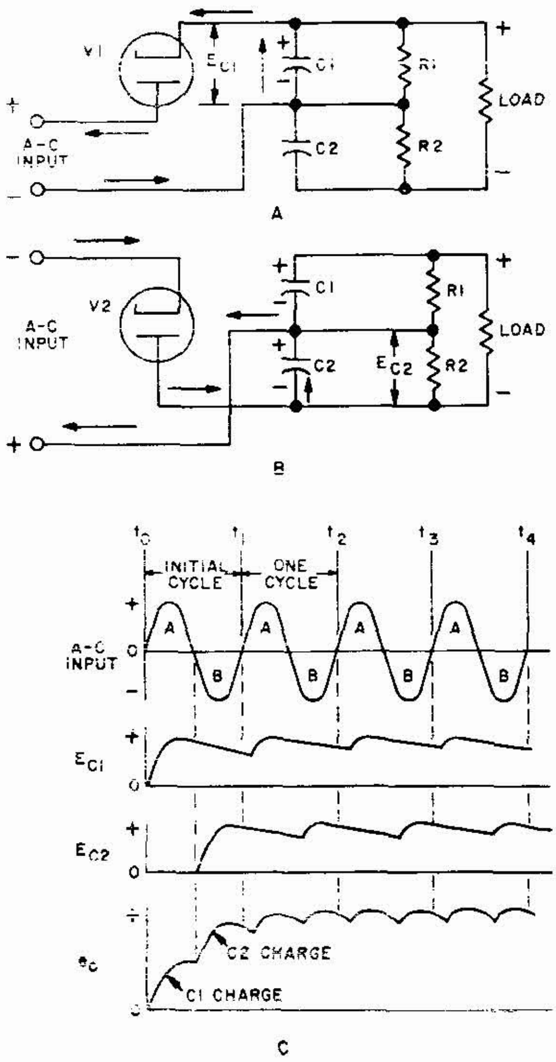
The rectifiers, V1 and V2, are of the indirectly heated cathode type, and are identical-type diodes. Although the circuit schematic illustrates two separate rectifiers, a twin-diode is generally used in the circuit. Typical twin-diode electron tubes designed specifically for use in voltage-doubler circuits are: 25Z6, 50Y6, and 117Z6. As indicated by the tube-type numbers, these tubes require nominal filament-supply voltages of 25, 50, and 117 volts, respectively. Because there are several possible filament circuit combinations, the actual filament circuit for V1 and V2 is not shown on the circuit schematic. The filament voltage is usually obtained directly from the a-c source if the filament is rated at the source voltage, by use of a voltage-dropping resistance in series with the rectifier filament (s) to reduce the a-c source voltage to the correct value, or from a transformer secondary winding of the correct value. In some equipments, the filaments of other tubes within the equipment are connected in series (or series-parallel), and this combination is then placed in series with the rectifier filament (s) across the a-c source; when this is done, a voltage-dropping resistor may be required.

The charging capacitors, C1 and C2, are of equal capacitance value and are usually relatively large (10 to 16 μf). Equalizing resistors R1 and R2, are connected across charging capacitors C1 and C2, respectively; they are of equal value and are generally greater than 2 megohms. Resistors R1 and R2 are not necessary for circuit operation; however, when included in the circuit, they have a dual purpose in that they tend to equalize the voltages across the charging capacitors and also act as bleeder resistors to discharge the associated capacitors when the circuit is de-energized. When capacitors C1 and C2 are large, the peak charge current, during the period of time the rectifier conducts, may be excessive. To limit the charge current and offer protection to the rectifiers, a protective "surge" resistor is placed in series with the a-c source. The value of the surge resistor is relatively small, generally 50 to 1000 ohms.

One disadvantage of the full-wave voltage-doubler circuit is that neither d-c output terminal can be directly connected to ground or to one side of the a-c source; however, when a step-up or isolation transformer is used to supply the input to the voltage doubler, either output terminal may be connected to ground or to the chassis.

The operation of the full-wave voltage-doubler circuit can be understood from the simplified circuits, parts A and B, and the waveforms, part C, shown in the accompanying illustration.

Assume that the a-c input to the voltage doubler during the initial half-cycle is of the polarity indicated in part A of the illustration. Electrons flow in the direction indicated by the arrows from the positive plate of charging capacitor C1, through rectifier tube V1 (cathode to plate), through the a-c source, and to the negative plate of charging capacitor C1. The upper (positive) plate of capacitor C1 lacks electrons, while the lower (negative) plate has a surplus of electrons. Thus, during the initial half cycle, capacitor C1 assumes a charge (E_{C1}) of the polarity indicated, which is equal to approximately the peak value of the applied a-c voltage. The voltage (E_{C1}) developed across charging capacitor C1 does not remain constant, as shown by waveform E_{C1}, but tends to vary somewhat because of a small discharge current flowing through the parallel equalizing resistor (R1) and because there is a tendency to discharge



Typical Full-Wave Voltage-Doubler Circuit Operation and Waveforms

VOLTAGE TRIPLER.

APPLICATION.

The voltage-tripler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional rectifier circuit utilizing the same input voltage. It is normally used in "transformerless" circuits where the load current is small and voltage regulation is not critical.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

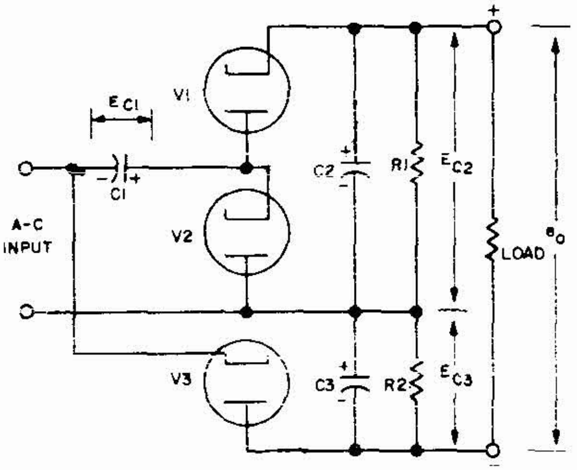
D-c output voltage is approximately three times the voltage obtained from a half-wave rectifier circuit utilizing the same input voltage; output current is relatively small.

Output requires filtering; d-c output ripple frequency is either twice or equal to a-c source frequency, depending upon tripler circuit arrangement.

Has poor regulation characteristics; output voltage available is a function of load current.

Depending upon circuit application, may be used with or without a power or isolation transformer.

Uses *indirectly heated cathode-type rectifiers.*



Basic Voltage-Tripler Circuit

CIRCUIT ANALYSIS.

General. The voltage-tripler circuit is used with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage tripler** implies, the output voltage is approximately three times the input voltage. The voltage regulation of the voltage tripler is relatively poor as compared with the regulation of either the half-wave or the full-wave voltage doubler circuit. Assuming that a given voltage-multiplier (doubler, tripler, or quadrupler) circuit uses the same value of capacitors in each instance, the greater the voltage-multiplication factor of the circuit, the poorer is the regulation characteristics. However, the regulation characteristics can be improved somewhat by increasing the value of the individual capacitors used in the voltage-multiplier circuit. Because of the regulation characteristics of the voltage tripler, the use of the circuit is generally restricted to applications in which the load current is small and relatively constant.

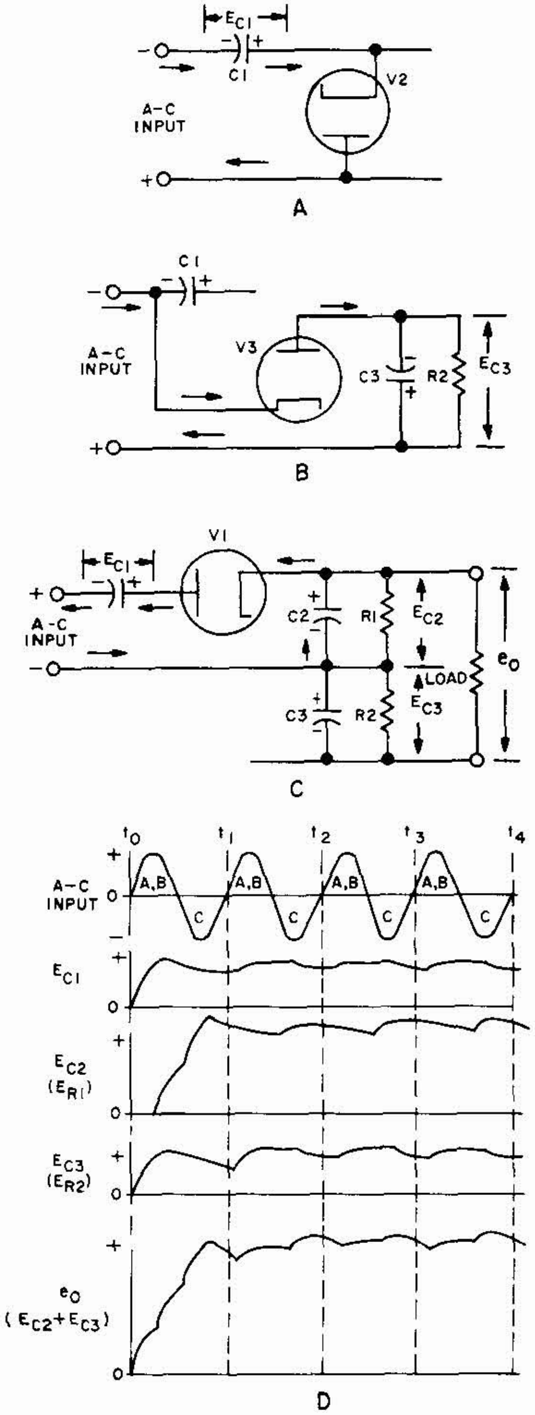
Circuit Operation. A basic voltage-tripler circuit is shown in the accompanying circuit schematic. Fundamentally, this circuit consists of a half-wave voltage-doubler circuit *and a half-wave* rectifier circuit arranged so that the output voltage of one circuit is in series with the output voltage of the other; thus, the total output voltage developed across the load resistance is approximately three times the applied voltage.

Rectifiers V1 and V2, charging capacitors C1 and C2, and resistor R1 form a half-wave voltage-doubler circuit (the operation of the voltage-doubler circuit was previously described in this section). Rectifier V3, charging capacitor C3, and resistor R2 form a simple half-wave rectifier circuit. Rectifiers V1, V2, and V3 are all identical-type diodes with indirectly heated cathodes. Because there are several possible filament circuit arrangements, the actual filament circuit for V1, V2, and V3 is not shown on the circuit schematic. It is usually necessary to isolate the filament circuits from each other and supply the filament (heater) voltages from independent sources because of heater-to-cathode breakdown voltage limitations imposed by the rectifier tubes themselves.

Charging capacitors C1, C2, and C3 are of equal capacitance value and are usually rather large (10 to 20 μf) for 50- to 60-cycle a-c input. Resistors R1 and R2 are connected *across charging capacitors C2 and C3,* respectively; they are generally greater than 2 megohms. Resistors R1 and R2 are not necessary for circuit operation; however, when included in the circuit, they act as *bleeder resistors* to discharge the associated capacitors when the circuit is de-energized.

One disadvantage of the basic voltage-tripler circuit illustrated is that neither d-c output terminal can be directly connected to ground or to one side of the a-c source; however, when a step-up or isolation transformer is used to supply the input to the voltage tripler, either output terminal may be connected to ground or to the chassis.

The operation of the basic voltage-tripler circuit can be understood from the simplified circuits, parts A, B, and C, and the waveforms, part D, shown in the accompanying illustration.



Typical Voltage-Tripler Circuit Operation and Waveforms

Assume that the a-c input to the voltage-tripler circuit (during the initial half-cycle) has the polarity indicated by the signs adjacent to the input terminals in part A of the illustration. Electrons flow in the direction indicated by the arrows from the right-hand (positive) plate of charging capacitor C1, through rectifier tube V2 (cathode to plate), through the a-c source, and to the left-hand (negative) plate of charging capacitor C1. (The positive plate of capacitor C1 lacks electrons, while the negative plate has a surplus of electrons.)

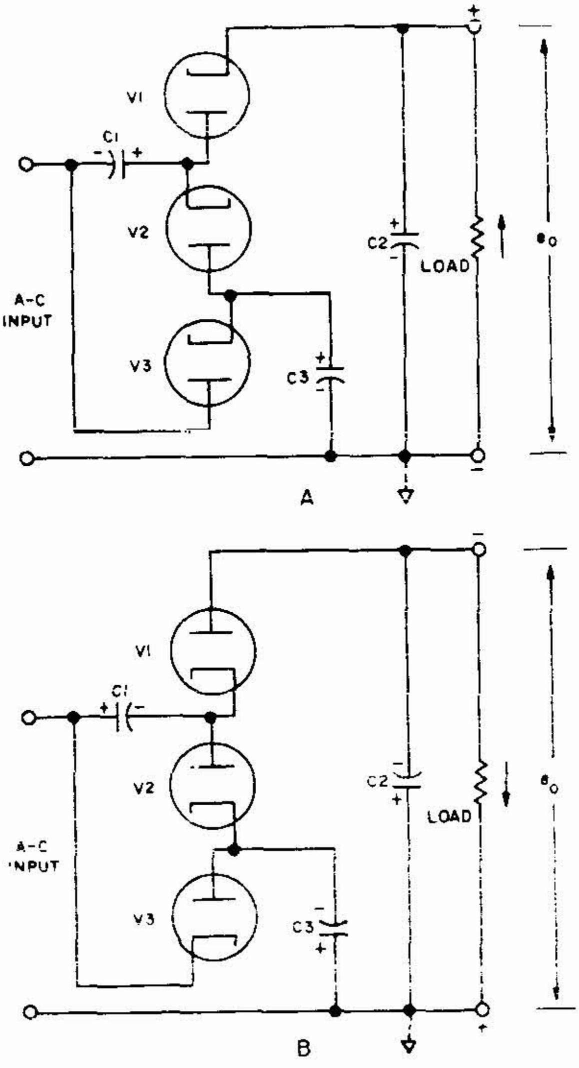
While the action described above for the simplified circuit of part A is taking place, a similar action occurs (during the initial half-cycle) for the simplified half-wave circuit given in part B. (Note that in part B, the a-c input has the polarity indicated by the signs adjacent to the input terminals, and, since these two circuits operate simultaneously, the input polarity is the same as that shown in part A.) Electrons flow in the direction indicated by the arrows from the upper (positive) plate of charging capacitor C3, through the a-c source, through rectifier tube V3 (cathode to plate), and to the lower (negative) plate of charging capacitor C3. Thus, during the initial half-cycle, charging capacitor C1 assumes a charge (E_{C1}) of the polarity indicated in part A, and this voltage is equal to approximately the peak value of the applied a-c voltage; also, charging capacitor C3 assumes a charge (E_{C3}) of the polarity indicated in part B, and this voltage is equal to approximately the peak value of the applied a-c voltage.

During the next half-cycle, the applied a-c input to the voltage tripler has the polarity indicated by the signs adjacent to the input terminals in part C of the illustration. The charge (E_{C1}) existing across charging capacitor C1 is in series with the applied ac and will therefore add its potential to the peak value of the input voltage. Electrons flow in the direction indicated by the arrows from the upper (positive) plate of capacitor C2, through rectifier tube V1 (cathode to plate), through charging capacitor C1 and the a-c source in series, and to the lower (negative) plate of charging capacitor C2. Thus, during the second half-cycle, charging capacitor C2 assumes a charge (E_{C2}) of the polarity indicated which is equal to the peak value of the applied a-c voltage plus the value of the charge (E_{C1}) existing across charging capacitor C1. As a result, the value of the voltage (E_{C2}) across capacitor C2 is equal to approximately twice the peak voltage of the applied ac, provided that charging capacitor C1 does not lose any of its initial charge.

Charging capacitors C2 and C3 are connected in series across the load resistance; therefore, the d-c voltage delivered to the load is the sum of the voltages ($E_{C2} + E_{C3}$) developed across charging capacitors C2 and C3. The value of the d-c output voltage, e_o, is approximately three times the peak voltage applied to the input of the voltage-tripler circuit.

The output waveform, e_o, contains a ripple component; therefore, filtering is required to obtain a steady d-c voltage. The frequency of the main component of the ripple voltage is equal to twice the frequency of the a-c source because charging capacitors C2 and C3 receive charges on alternate half-cycles of the applied voltage. The value of the output voltage obtained from the voltage tripler is determined largely by the resistance of the load and the resulting load current. Assuming the same value for each of the *charging capacitors in either rectifier circuit*, the regulation of the voltage-tripler circuit is poor as compared with that of a typical voltage-doubler circuit.

Two possible arrangements for a modified voltage-tripler circuit are given in the accompanying illustration; part A shows a modified tripler circuit arranged for positive output with the negative output terminal common to one side of the a-c source, and part B shows the circuit arranged for negative output with the positive output terminal common to one side of the a-c source.



Modified Voltage-Tripler Circuits

In these two circuit variations, the basic half-wave rectifier circuit, represented by V3 and C3, has a voltage doubler circuit connected to it in such a manner that the full output voltage is developed across charging capacitor C2. The operation of either tripler circuit (part A or part B) is briefly described in the following paragraph.

During the initial half-cycle of the applied voltage, rectifier V3 conducts to charge capacitor C3. During the next half-cycle, the voltage across capacitor C3 is in series with the applied voltage, and rectifier V2 conducts to charge capacitor C1 to approximately twice the value of the peak input voltage. On the next half-cycle, rectifier V3 again conducts to charge capacitor C3; at the same time, since the voltage across capacitor C1 is in series with the applied voltage, rectifier V1 also conducts to charge capacitor C2 to approximately *three times the peak* value of the input voltage. Thus, the voltage developed across capacitor C2 is the d-c output delivered to the load.

The output of the tripler circuits illustrated in parts A and B requires filtering to obtain a steady d-c voltage. The frequency of the ripple voltage for either circuit arrangement *is equal to the frequency* of the a-c source because charging capacitor C2 receives a charge only once for each complete cycle of the applied voltage. For this reason, *the regulation* is not as good as the regulation of the basic voltage-tripler circuit described earlier.

FAILURE ANALYSIS.

No Output. In the basic voltage-tripler circuit, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage to all rectifiers, the lack of applied a-c voltage, or a shorted load circuit (including filter circuit components).

A visual check of the glass-envelope rectifier tubes can be made to determine whether the filaments are lit; if the filaments are not lit, the presence of voltage should be determined by measurement.

The a-c supply voltage should be measured at the input to the circuit to determine whether the voltage is present and is the correct value. If the circuit uses a step-up or isolation transformer, measure the voltage at the secondary terminals to determine whether it is present and is the correct value. If necessary, the primary voltage should be removed from the transformer and continuity measurements of the primary and secondary windings made to determine whether one of the windings is open, since an open circuit in either winding will cause a lack of secondary voltage.

With the a-c supply voltage removed from the input to the circuit and with the load (including filter circuit) disconnected *from the terminal of capacitor C2*, resistance measurements can be made across the load to determine whether the load circuit (including filter components) is *shorted. Measurements should be* made across the terminals of charging capacitors C2 and C3 in the basic tripler circuit, or across charging capacitor C2 in the *modified tripler circuit*, to determine whether the no-output condition is caused by shorted capacitors. The basic tripler circuit includes resistors R1 and R2; therefore, the resistance measured across capacitors C2 and C3 will normally be something less than the value of the associated bleeder resistor. Since the charging capacitors are electrolytic capacitors, the resistance measurements may vary, depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the capacitor terminals for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value.

Low Output. The rectifiers (V1, V2, and V3) should be checked to determine whether the cause of low output is low cathode emission. The load current should be checked to make sure that it is not excessive, because the voltage-tripler circuit has poor regulation and an increase in load current (decrease in load resistance) can cause a decrease in output voltage.

One terminal of each charging capacitor (C1, C2, and C3) should be disconnected from the circuit and each capacitor checked, using a capacitance analyzer, to determine its effective capacitance and leakage resistance. A decrease in effective capacitance or losses within the capacitor can cause the output of the voltage-tripler circuit to be below normal, since the defective capacitor will not charge to its normal operating value. If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter. First, disconnect one terminal of the capacitor from the circuit; then, using the ohmmeter procedure outlined for the no-output condition, make two measurements (reverse the test leads at the capacitor terminals for one of the measurements). The larger of the two measurements should be greater than 1 megohm for a satisfactory capacitor.

A procedure which can be used to quickly determine whether the capacitors are the cause of low output is to substitute known good capacitors of the same value in the voltage-tripler circuit and measure the resulting output voltage.

VOLTAGE QUADRUPLER.

APPLICATION.

The voltage-quadrupler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional rectifier circuit utilizing the same input voltage. It is normally used in "transformerless" circuits where the load current is small and voltage regulation is not critical.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-c output voltage is approximately four times the voltage obtained from a half-wave rectifier circuit utilizing the same input voltage; output current is relatively small.

Output requires filtering; d-c output ripple frequency is either equal to or twice the a-c source frequency, depending upon quadrupler circuit arrangement.

Has poor regulation characteristics; output voltage available is a function of load current.

Depending upon circuit application, may be used with or without a power or isolation transformer.

Uses indirectly heated cathode-type rectifiers.

CIRCUIT ANALYSIS.

General. The voltage-quadrupler circuit is used with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage quadrupler** implies, the output voltage is approximately four times the input voltage. The voltage regulation of the voltage quadrupler is very poor as compared with the regulation of either the half-wave or the full-wave voltage doubler circuit. Assuming that a given voltage-multiplier (doubler, tripler, or quadrupler) circuit uses the same value of capacitors in each instance, the greater the voltage-multiplication factor of the circuit, the poorer will be the regulation characteristics. Because of the poor regulation characteristics of the voltage quadrupler, the use of the circuit is generally restricted to applications in which the load current is small and relatively constant.

Circuit Operation. Two basic voltage-quadrupler circuits are shown in the accompanying circuit schematic. Each circuit (part A or part B of the illustration) consists of two half-wave voltage doublers arranged so that the output of one doubler circuit is in series with the output of the other; thus, the total output voltage developed across the load resistance is approximately four times the applied voltage.

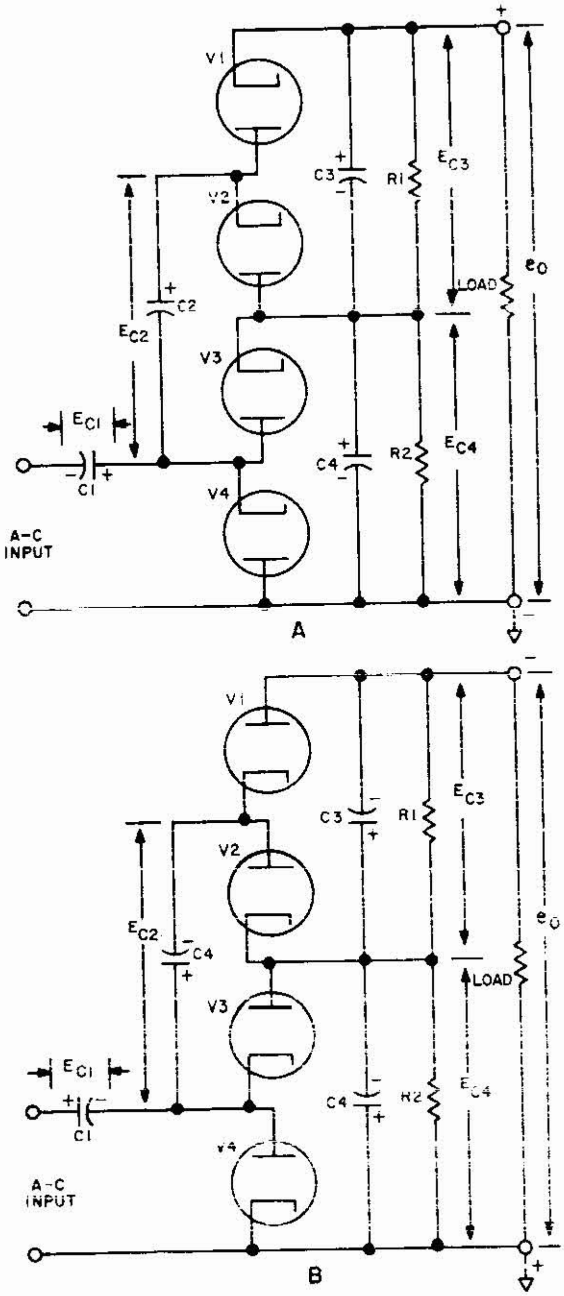
Rectifiers V3 and V4 and charging capacitors C1 and C4 form a conventional half-wave voltage-doubler circuit (the operation of the voltage-doubler circuit was previously described in this section). Rectifiers V1 and V2 and charging capacitors C2 and C3 form a second half-wave voltage-doubler circuit; however, this voltage-doubler circuit operates in cascade with the first voltage-doubler circuit and obtains its input from the voltage available across the series combination of charging capacitor C1, the applied a-c input voltage, and charging capacitor C4.

Rectifiers V1, V2, V3, and V4 are identical-type diodes with indirectly heated cathodes. Because there are several possible filament circuit arrangements, the actual filament circuits are not shown on the schematic. It is necessary to isolate the rectifier filament circuits from each other because of the heater-to-cathode breakdown voltage limitation imposed by the rectifier tubes themselves; therefore, a filament transformer with separate well-insulated secondary windings, or a single transformer for each rectifier tube, is required. This requirement for an independent filament (heater) voltage source for each rectifier tube places a practical limitation on the use of electron tubes in voltage-multiplier circuits; for this reason, the voltage-quadrupler circuit and other voltage-multiplier circuits generally employ semiconductor diodes as rectifiers in lieu of electron-tube diodes.

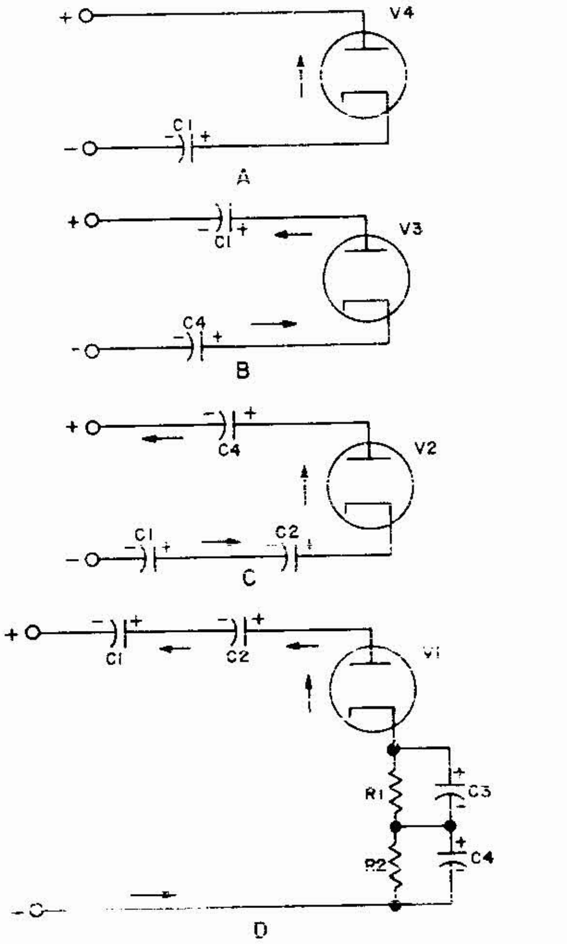
Charging capacitors C1, C2, C3, and C4 are of equal capacitance and are usually relatively large (10 to 20 μf) for 50- to 60-cycle a-c input; however, for some high-voltage, low-current applications, such as in the high-voltage supply for cathode-ray tube indicators, the charging capacitors may be relatively small (0.01 to 0.1 μf), especially if the a-c input frequency is much higher than the normal 50- to 60-cycle input frequency.

Resistors R1 and R2 are equalizing resistors for charging capacitors C3 and C4, respectively; they are of equal value and are generally greater than 2 megohms. Resistors R1 and R2 are not necessary for circuit operation; however, when included in the circuit, they have a dual purpose—they tend to equalize the voltages across charging capacitors C3 and C4, and they also act as bleeder resistors to discharge the capacitors when the circuit is de-energized.

The operation of the basic voltage-quadrupler circuit can be understood from the simplified circuits, parts A, B, C, and D, given in the accompanying illustration. These simplified circuits are based upon the basic voltage-quadrupler circuit schematic (part A) given earlier in this discussion. The operation of a typical half-wave voltage-doubler circuit was described earlier in this section of the handbook; therefore, the discussion which follows will only briefly describe the circuit operation when two voltage-doubler circuits are arranged in cascade to obtain voltage-quadrupler action.



Basic Cascade Voltage-Quadrupler Circuits



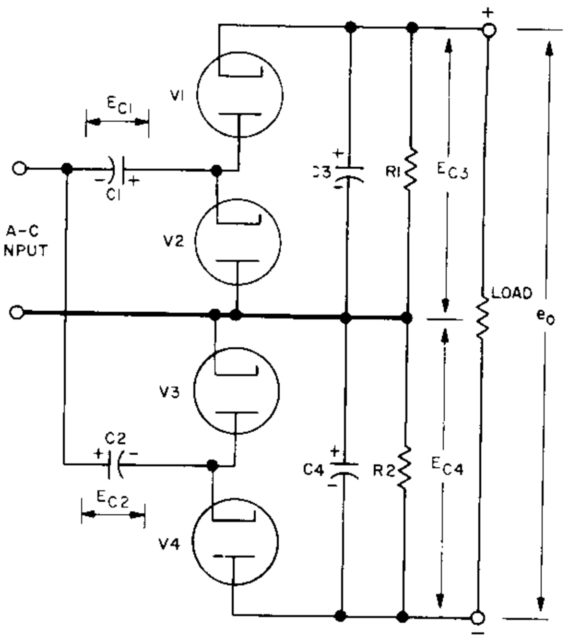
Voltage-Quadrupler Operation

Assume that the a-c input to the voltage quadrupler circuit (during the initial half-cycle) has the polarity indicated by the signs adjacent to the input terminals in part A of the accompanying illustration. Rectifier V4 conducts to charge capacitor C1 to the peak value of the applied a-c input voltage. In part B of the illustration (during the next half-cycle) the applied voltage has the polarity indicated by the signs at the input terminals and is in series with the charge on capacitor C1 (E_{C1}); hence, rectifier V3 conducts to charge capacitor C4 to twice the peak value of the applied voltage and thereby discharge capacitor C1. In part C of the illustration, the applied voltage has the polarity indicated and is in series with the charge on capacitor C4 (E_{C4}) which causes rectifier V2 to conduct. This action charges capacitor C2 to twice the peak value of the input voltage, capacitor C1 to the peak value of the input voltage, and discharges capacitor C4 to zero. In part D of the illustration, the applied voltage has the polarity indicated and is in series with the charge on capacitor C1 (E_{C1}) and capacitor C2 (E_{C2}). At this time rectifier V1 conducts charging capacitors C3 and C4. Capacitors C3 and C4 are equal value capacitors and each will charge to twice the peak value of the applied voltage (a-c input plus EC_1 and EC_2.) Since C3 and C4 are in series, the d-c voltage delivered to the load resistance is the sum of the voltage (EC_3 plus EC_4) developed across capacitors C3 and C4. Because the voltage across each of these capacitors is equal to twice the applied voltage, the value of the d-c output voltage is approximately four times the peak voltage of the a-c input to the voltage-quadrupler circuit.

The d-c output contains a ripple component; therefore, filtering is required to obtain a steady d-c voltage. The frequency of the main component of the ripple voltage is equal to the frequency of the a-c source because capacitors C3 and C4 simultaneously receive a charge, once for each complete cycle of the applied voltage. The value of the output voltage obtained from the voltage quadrupler is determined largely by the resistance of the load and the resulting load current. The regulation of the circuit is very poor; for this reason, if the output voltage is to be maintained at a high level, the load current must be kept small.

The voltage-quadrupler circuit given in the accompanying circuit schematic is a variation of the basic cascade voltage-quadrupler circuits given earlier.

In this circuit, two basic half-wave voltage-doubler circuits are arranged back-to-back; each doubler-circuit input is connected to the common a-c source, and the two output voltages, E_{C3} and E_{C4}, are in series to produce the total output voltage, e_o. Rectifiers V1 and V2 and charging capacitors C1 and C3 form one doubler circuit; rectifiers V3 and V4 and charging capacitors C2 and C4 form the other doubler circuit. Each doubler circuit operates to charge its associated output capacitor (C3 or C4) to a value which is twice the peak value of the applied input voltage; as a result, the voltage produced across capacitors C3 and C4, in series, is four times the value of the applied input voltage. Because charging capacitors C3 and C4 receive a charge on alternate half-cycles of the applied input voltage, the ripple frequency for this quadrupler circuit is equal to twice the frequency of the a-c source.



Two Half-Wave Voltage-Doublers Connected Back-to-Back To Form a Voltage-Quadrupler Circuit

Once it is recognized that this quadrupler circuit consists of two complete half-wave voltage-doublers connected back-to-back sharing a common input source and that measurements on each doubler circuit may be made as though they were two independent circuits, then failure analysis becomes relatively simple. The circuit operation and failure analysis for each doubler circuit is identical to that given for the basic half-wave voltage-doubler circuit described earlier in this section of the handbook and, therefore, will not be discussed here.

FAILURE ANALYSIS.

No Output. In the voltage-quadrupler circuit, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage or an open filament in two or more rectifiers, the lack of applied a-c voltage, a shorted load circuit (including filter circuit components), or an open in one or both of the charging capacitors, C1 and C2.

The failure analysis procedures for the no-output condition are esentially the same as those given for the voltage-tripler and half-wave voltage-doubler circuits described previously in this section of the handbook.

Low Output. The failure analysis for the low-output condition is esentially the same as that given for the voltage-tripler circuit described previously and is somewhat similar to that given for the half-wave voltage-doubler circuit described earlier in this section of the handbook. The procedure for substituting known good capacitors of the same value in the voltage-quadrupler circuit and measuring the resulting output voltage may be used to quickly determine whether the charging capacitors are the cause of low output.

HIGH-VOLTAGE (CRT) SUPPLY, AUDIO-OSCILLATOR TYPE.

APPLICATION.

The audio-oscillator type high-voltage supply is used in electronic equipment for applications requiring extremely high-voltage dc at a small load current. The output circuit can be arranged to furnish negative or positive high voltage to the load. The supply is commonly used to provide the high voltage for accelerating and final anodes, ultor, and other similar electrodes of cathode-ray tubes used in indicators. It is sometimes used as a keep-alive voltage source in radar equipment.

CHARACTERISTICS.

Uses a self-excited oscillator circuit combined with a rectifier circuit.

Typical operating frequency is between 400 to 3000 cycles.

Output is high-voltage dc at low current.

Regulation is fair; may be improved by regulating oscillator d-c supply voltage.

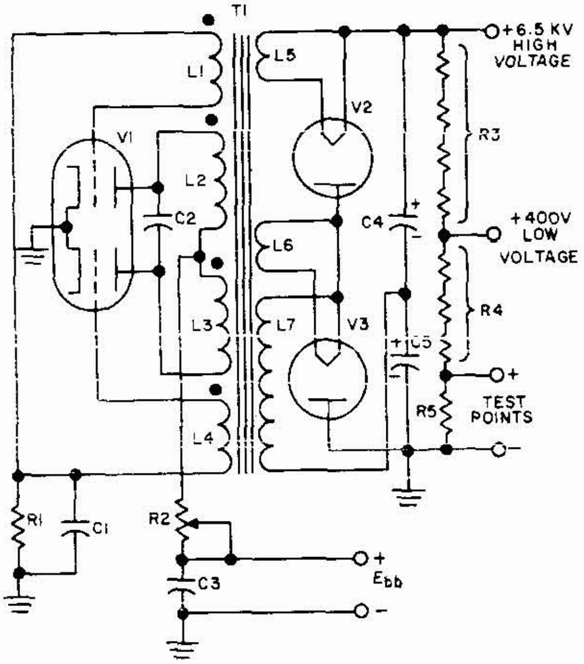
The rectifier circuit can be arranged to provide either positive- or negative-polarity output voltage.

CIRCUIT ANALYSIS.

General. The audio-oscillator type high-voltage supply is a self-excited oscillator operating in the audio-frequency range. The oscillator generates a voltage which is either *sinusoidal or square wave in form*, depending upon the circuit design. The rectifier circuit used in conjunction with the oscillator circuit is commonly a half-wave rectifier or a full-wave voltage-doubler circuit and uses either electron tubes or semiconductor diodes as rectifiers. The d-c output filter component values are determined by the desired output impedance of the high-voltage supply and by the frequency of the applied a-c generated by the oscillator circuit. In most cases, the output impedance is given first consideration in the design of the filter circuit, rather than the reduction or elimination of the ripple-frequency component from the d-c output.

The d-c output of a self-excited oscillator supply under a given load, such as the load offered by a cathode-ray tube circuit, can be maintained nearly as constant as the d-c source supplying the oscillator circuit. For this reason, it is desirable to provide the oscillator circuit with a regulated supply voltage which approaches ±1 percent so that the output voltage can be maintained reasonably constant for a given load current.

Circuit Operation. The accompanying circuit schematic illustrates a push-pull, self-excited oscillator circuit used in conjunction with a full-wave voltage-doubler circuit to obtain high-voltage output. The operation of the self-excited, push-pull oscillator is essentially the same as that described under OSCILLATORS in Section 7 of this handbook; the operation of a typical full-wave voltage-doubler circuit has already been described in this section of the handbook. For these reasons, the discussion which follows will be somewhat limited because the circuit is a combination of two basic circuits discussed elsewhere in this handbook.



High-Voltage Supply, Audio-Oscillator Type Using Twin-Triode Tube

Electron tube V1 is a twin-triode, such as the type 5670 or 6J6; if desired, two identical-type triode tubes may be used in this circuit in lieu of the single twin-triode. Electron tubes V2 and V3 are identical diodes using directly-heated cathodes, such as the type 1B3, 1V2, or 1X2, and are specifically designed for high-voltage applications. The parallel combination of resistor R1 and capacitor C1 is used to obtain operating (grid-leak) bias for the self-excited oscillator circuit. Transformer T1 is the oscillator and high-voltage transformer; in the schematic the dots adjacent to windings L1, L2, L3, and L4 are used to indicate similar winding polarities. Windings L1 and L4 are the push-pull oscillator grid windings, and windings L2 and L3 are plate windings. Capacitor C2 forms a resonant circuit with the inductance of windings L2 and L3 to determine the frequency of oscillation. Transformer windings L5 and L6 supply the filament current to the diodes, V2 and V3, respectively. Although windings L5 and L6 are shown as part of transformer T1, a separate filament transformer with independent, well-insulated windings is sometimes used as the filament supply. (A filament supply is not necessary when semiconductor diodes are used in the rectifier circuit, and windings L5 and L6 may be omitted.) Transformer winding L7 is the high-voltage (step-up) winding and is the a-c source for the rectifier circuit. Depending upon the design of the transformer and the circuit constants used, the oscillator circuit generates a sinusoidal waveform at the high-voltage winding, or, if the circuit operates in a switching mode, it generates a square wave.

Capacitor C3 and variable resistor R2 form a decoupling filter to prevent interaction between the oscillator circuit and the d-c supply. Resistor R2 is also used to vary the d-c potential applied to the oscillator circuit. A change in the applied voltage affects the amplitude of the voltage across winding L7 which is applied to the rectifier circuit; therefore, the setting of resistor R2 determines the high-voltage output within certain limits and may be adjusted to obtain a predetermined output voltage.

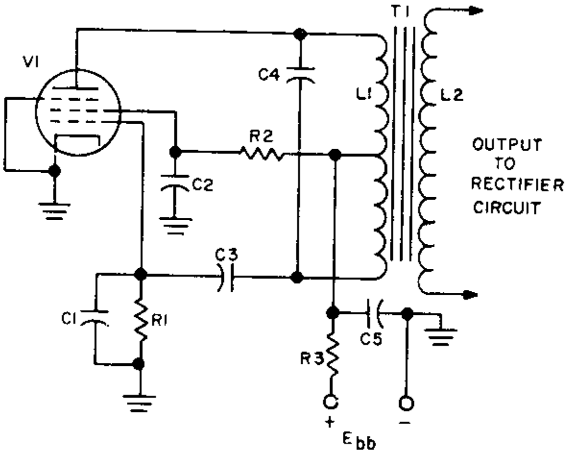
Capacitors C4 and C5 are the charging capacitors of the voltage-doubler circuit. Since the frequency of the applied voltage is in the audio range and the load current is small, the value of these capacitors is relatively small. Resistors R3, R4, and R5 in series form a bleeder and a voltage-divider resistance for the output of the doubler circuit. The tap at the junction of resistors R3 and R4 enables a lower voltage to be supplied to a low-current load, such as the lower-voltage electrodes of a cathode-ray tube. In actual practice, resistors R3 and R4 are made up of a number of resistors in series to obtain the desired value of total resistance for each portion of the bleeder (R3 and R4). To prevent failure, the voltage drop across each resistor must be less than the maximum terminal-voltage rating of the resistor.

Resistor R5 is used for test metering purposes, to permit measurement of the high-voltage d-c output without the requirement for a special voltmeter or high-voltage probe. A precalculated voltage drop across R5, when read with a high-resistance voltmeter, will indicate the presence of the correct value of high voltage.

In general, the output-voltage regulation of this supply is sufficient for most cathode-ray-tube circuit applications since the stability of the output voltage can be held to ± 1 percent by regulating the d-c supply voltage applied to the oscillator circuit.

The oscillator circuit using a twin-triode tube offers several advantages; its efficiency is relatively high and it requires fewer parts than does a comparable circuit which uses a single pentode. Furthermore, the reliability of the twin-triode oscillator circuit is better than that of a comparable pentode circuit, because it has the ability to oscillate even after failure of one triode section of the tube. If a failure of this nature should occur at a time when continued operation is vital to the mission, sufficient voltage will normally be available to sustain emergency operation with reduced efficiency until corrective maintenance can be performed.

The accompanying circuit schematic illustrates a single pentode used in a self-excited oscillator circuit to produce a sinusoidal voltage. The oscillator is fundamentally a series-fed Hartley oscillator with grid stabilization; the operation of this circuit is similar to that of the conventional Hartley oscillator described elsewhere in this handbook. The rectifier circuit commonly used with the pentode oscillator is a full-wave voltage doubler and employs either electron tubes or semiconductor diodes as rectifiers; however, the schematic does not show the associated rectifier circuit because it can be the same as that illustrated for the twin-triode oscillator given earlier in this discussion.



High-Voltage Supply, Audio-Oscillator Type Using Pentode Tube

Electron tube V1 is a pentode such as the type 5763. The parallel combination of resistor R1 and capacitor C1 is used to obtain operating bias for the self-excited oscillator circuit. Transformer T1 is the oscillator and high-voltage transformer. In this transformer, winding L1 is tapped for the series-fed oscillator circuit and is in parallel with capacitor C4 to determine the resonant frequency of the oscillator. Winding L2 is the high-voltage winding and is the a-c source for the rectifier circuit. (The pentode oscillator circuit generates a sinusoidal waveform.) Although not shown, if electron-tube diodes are used in the rectifier circuit, additional windings may be required to supply the rectifier filament current. Capacitor C3 couples the grid of V1 to the grid-winding portion of L1 and also acts as a d-c blocking capacitor. Capacitor C2 is the screen bypass, and resistor R2 is the screen-dropping resistor. Capacitor C5 and resistor R3 form a decoupling filter; capacitor C5 also returns the tap of winding L1 to signal ground (cathode) potential.

The pentode oscillator circuit found in various equipments may differ somewhat from the circuit given in the accompanying schematic. Several typical variations are as follows: A small capacitor may be connected between the control grid and the plate of V1 to increase the grid-to-plate capacitance and thus provide additional feedback to sustain oscillation; a resistance may be placed in series with capacitor C3 to help stabilize the circuit and limit the amplitude of oscillations; and a variable resistor may be placed in series with either screen-dropping resistor R2 or decoupling resistor R3 to permit adjustment of the screen voltage or both the plate and screen voltages. A change in the applied oscillator voltage(s) will affect the output amplitude of the oscillator and will therefore affect the high-voltage output of the supply.

FAILURE ANALYSIS

General. The audio-oscillator type high-voltage supply consists of two basic circuits—an oscillator and a rectifier. It must be determined initially whether the oscillator or the rectifier portion of the power-supply circuit is at fault. Tests must be made to determine whether the oscillator is performing satisfactorily; if it is, the trouble is then assumed to be located within the associated rectifier circuit. The failure analysis outlined in the following paragraphs is somewhat brief because the subject of electron-tube oscillators is discussed in another section of this handbook; furthermore, the particular high-voltage rectifier circuit may be the same as one of the rectifier circuits described earlier in this section. Since the audio-oscillator type high-voltage supply is a combination of two basic circuits, information concerning failure analysis for either portion of the high-voltage supply can be obtained by reference to the applicable basic circuit given elsewhere in this handbook.

No Output. When the oscillator is in a nonoscillating condition, negative grid voltage will not be developed across R1C1, and the measured plate (and screen) voltage of oscillator tube V1 will be below normal. The applied filament and plate (and screen) voltages should be measured to determine whether these voltages are present and of the correct value. The oscillator tube, V1, may be replaced with one known to be good to determine whether it is defective. Excessive losses in the L-C resonant circuit formed by the transformer and its associated capacitor will prevent sustained oscillation; the transformer windings should be checked for continuity, and the associated capacitor should be checked to determine whether it is open or shorted. Shorted capacitor in the circuit will prevent oscillation; therefore, all capacitors should be checked with a suitable capacitance analyzer to determine whether they are satisfactory. An open transformer winding would normally prevent sustained oscillations, however, in the twin triode oscillator circuit, there is a possibility that one coil could resonate with stray capacity and oscillate (at a higher frequency) and produce a low output.

If the oscillator circuit is found to be functioning normally, then it must be assumed that the trouble is associated with the rectifier circuit or its load, and a check of the rectifier circuit must be made in accordance with the procedures outlined earlier in this section for the applicable rectifier circuit.

Low Output. A relative indication of oscillator output can be obtained by measuring the amount of bias voltage developed across R1C1. A value of bias which is below normal is an indication of low oscillator output. Also, if the applied plate (and screen) voltage is below normal, a reduction in output will occur. The applied filament and plate (also screen) voltages should be measured to determine whether they are within tolerance; a 10-percent variation in applied filament voltage will not appreciably affect the output of the supply, but a small change in applied plate voltage will produce a noticeable change in output.

In the twin-triode oscillator circuit, trouble in one triode section (such as low cathode emission, low transconductance, or an open tube element) or an open winding in transformer T1 will cause a reduction in output. The tube may be replaced with one known to be good and the checks repeated; continuity measurements of the windings of transformer T1 can be made to determine whether any of the windings are open. In the pentode oscillator circuit, a leaky screen bypass (C2) will form a voltage divider with the screen-dropping resistor (R2) and result in a decreased screen voltage; thus, the output of the supply will be low.

If the oscillator is found to be operating normally, a defect within the rectifier circuit or associated load must be suspected as the cause of low output. For example, because of the relatively high-impedance rectifier and filter circuits, an excessive load current can cause the output voltage to be low. Failure analysis procedures for typical rectifier circuits used in high-voltage supplies are outlined earlier in this section.

HIGH-VOLTAGE (CRT) SUPPLY, R-F OSCILLATOR TYPE.

APPLICATION.

The r-f oscillator type high-voltage supply is used in electronic equipment for applications requiring extremely high-voltage dc at a small load current. The output circuit can be arranged to furnish negative or positive high voltage to the load. The supply is commonly used to provide the high voltage for the accelerating and final anodes, the ultor, and other similar electrodes of cathode-ray tubes used in video indicators.

CHARACTERISTICS.

Uses a self-excited r-f oscillator circuit combined with a rectifier circuit.

Typical operating frequency is between 40 and 600 kilocycles.

Output is high-voltage dc at low current.

Regulation is poor; may be improved considerably by additional circuitry to control the oscillator output.

The rectifier circuit can be arranged to provide either positive- or negative-polarity output voltage.

Circuit may require shielding to prevent undesirable radiation from interfering with other equipments.

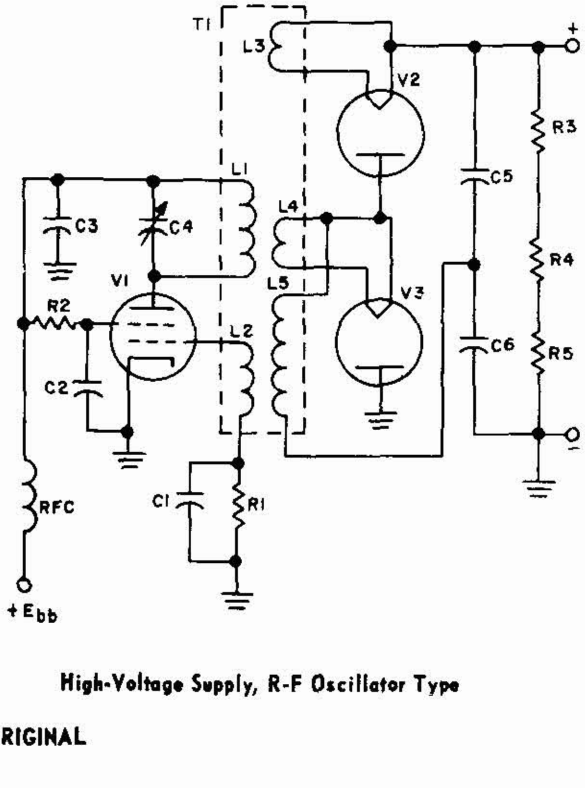
CIRCUIT ANALYSIS.

General. The r-f oscillator type high-voltage supply is a self-excited oscillator operating in the low- and medium-frequency range. The oscillator generates a sinusoidal output which is coupled through the air-core step-up transformer to the high-voltage rectifier circuit. Sometimes two identical oscillator tubes are connected in parallel to increase the current output capability of the supply over that obtainable with single-tube operation. The rectifier circuit used in conjunction with the oscillator circuit is commonly a half-wave rectifier or a voltage-doubler circuit. The rectifier circuit may employ either electron-tubes or semiconductor diodes as rectifiers.

The d-c output from the r-f oscillator high-voltage supply is subject to considerable variation with a change in load current, and, therefore, because of its poor regulation characteristics, the use of this circuit is usually limited to applications where the load is constant. Although the regulation characteristics of the supply can be improved considerably by the addition of regulator circuits to control the oscillator output, the additional circuitry required in some cases makes it impracticable to do so because of the added space, weight, number of components, etc.

Circuit Operation. The accompanying circuit schematic illustrates a self-excited pentode power oscillator used in conjunction with a full-wave voltage-doubler circuit to obtain high-voltage dc output. The oscillator is fundamentally a series-fed tuned-plate, untuned-grid (tickler) oscillator circuit. The operation of the oscillator is essentially the same as that described, under OSCILLATORS, in Section 7 of this handbook, for the Tuned-Plate Armstrong Oscillator circuit; the operation of a typical full-wave voltage-doubler circuit has already been described in this section (Section 4) of the handbook. For these reasons, the discussion which follows will be somewhat limited.

Electron tube V1 is a pentode tube, such as type 6V6 or 6Y6. Electron tubes V2 and V3 are identical directly-heated diodes, such as type 1B3, 1V2, or 1X2. The parallel combination of resistor R1 and capacitor C1 is used to obtain operating (grid-leak) bias for the self-excited oscillator circuit. The air-core transformer, T1, is the oscillator tank circuit and high-voltage transformer. Winding L1 is the primary winding of the transformer, and is resonated by tuning capacitor C4 to determine the frequency of oscillation. Winding L2 is the untuned-grid (tickler) coil, which supplies the necessary feedback to the grid of V1 to sustain oscillations. (The ratio of the relative reactances of L1 and L2 determines the exciting voltage for the oscillator grid.) Windings L3 and L4 supply the filament current to the rectifier diodes, V2 and V3, respectively. Winding L5 is the high-voltage (step-up) winding, and is the a-c source for the rectifier circuit.



High-Voltage Supply, R-F Oscillator Type

Capacitor C2 is the screen bypass capacitor, and resistor R2 is the screen dropping resistor. Bypass capacitor C3 returns the series-fed primary winding, L1, to r-f ground potential, and the r-f choke (RFC) prevents any radio-frequency currents from entering the plate-voltage source, E_{bb}.

Capacitors C5 and C6 are the charging capacitors of the voltage-doubler circuit. Since the frequency of the applied voltage is between 40 and 600 kilocycles, and the load current is a low value, the value of these capacitors is relatively small, generally about 1000 $\mu\mu$f. Furthermore, because the ripple-frequency component is also in the radio-frequency range, there is little need for large-value filter components. Resistors R3, R4, and R5 in series form a bleeder and voltage-divider resistance for the output of the doubler circuit.

As previously mentioned, primary winding L1 is tuned to resonance by capacitor C4. The resonant frequency of the high-voltage winding, L5, is determined primarily by the shunting capacitances of rectifier V3 and capacitor C6 in series, as well as stray circuit capacitance resulting from wiring and the physical placement of other circuit components. The r-f oscillator power supply is normally designed so that the maximum output voltage obtainable is greater than the output voltage required to be delivered to the load. Maximum output voltage is developed when the oscillator frequency is equal to the natural resonant frequency of L5 in parallel with its shunting capacitance; therefore, the desired value of output voltage is obtained by adjusting tuning capacitor C4 to set the oscillator frequency near the natural resonant frequency of L5 and its shunting capacitance. The voltage produced across winding L5 is applied to the voltage-doubler circuit, and, since the d-c output voltage contains a ripple-frequency component which is twice the frequency of the applied a-c voltage, the output requires very little filtering.

The use of grid-leak bias (R1C1) tends to make the oscillator self-regulating with respect to its power output, because the oscillator operates as a Class C stage, the efficiency is fairly high. The regulation of the supply is considered adequate for most cathode-ray-tube circuit applications where the load current is always constant; however, any change in the voltages applied to the oscillator circuit, a change in the oscillator frequency, or a change in the load current will affect the output voltage and thus cause poor regulation. Therefore, if good regulation is required, a voltage regulator circuit must be added. Another disadvantage of the r-f oscillator power supply is that it must be well shielded to prevent the oscillator fundamental frequency or its harmonics from being radiated as an undesired signal, causing interference within the associated equipment or perhaps affecting nearby electronic equipments.

FAILURE ANALYSIS.

General. The r-f oscillator type high-voltage supply consists of two basic circuits—an oscillator and a rectifier. It must be determined initially whether the oscillator or the rectifier portion of the power-supply circuit is at fault. Tests must be made to determine whether the oscillator is performing satisfactorily; if it is, the trouble is then assumed to be located within the associated rectifier circuit or its load circuit. The failure analysis outlined in the following paragraphs is somewhat brief because the subject of electron-tube oscillators is discussed in another section of this handbook; furthermore, the particular high-voltage-rectifier circuit may be the same as one of the rectifier circuits described earlier in this section. Since the r-f oscillator high-voltage supply is a combination of two basic circuits, information concerning failure analysis for either portion of the high-voltage supply can be obtained by reference to the applicable basic circuit given elsewhere in this handbook.

No Output. When the oscillator is in a nonoscillating condition, negative grid voltage will not be developed across R1C1, and the measured plate and screen voltages of oscillator tube V1 will be below normal. The applied filament, plate, and screen voltages should be measured to determine whether these voltages are present and are of the correct value. To determine whether the oscillator tube, V1, is defective, it may be replaced with a tube known to be good.

Excessive losses in the air-core transformer, T1, or shorted capacitor C1, C2, C3, or C4 will prevent the oscillator from operating. Also, defective components in the rectifier circuit associated with the high-voltage winding, L5, may introduce losses into the oscillator circuit which will prevent oscillator operation. With all voltages removed from the circuit, disconnect one lead from winding L5, or remove rectifiers V2 and V3 from their sockets; then reapply the voltages and again perform tests on the oscillator to determine whether the oscillator will operate under no-load conditions.

If the oscillator circuit is found to be functioning normally, it must be assumed that the trouble is associated with the rectifier circuit or its load, and a check of the rectifier circuit must be made in accordance with the procedures outlined in this section for the applicable rectifier circuit.

Low Output. A relative indication of oscillator output can be obtained by measuring the amount of bias voltage developed across R1C1. A value of bias which is below normal is an indication of low oscillator output. Also, if the applied plate and screen voltages are below normal, a reduction in output will occur. A leaky screen bypass capacitor, C2, will form a voltage divider with screen dropping resistor R2 and result in a decreased screen voltage; thus, the output of the supply will be low.

To determine whether the oscillator tube, V1, is the cause of low output, it may be replaced with a tube known to be good. Where the oscillator circuit employs two tubes in parallel, one or both tubes may be suspected as causing low output.

It is possible that the low output condition may be caused by a change in oscillator frequency away from the resonant frequency of the high-voltage winding L5. (A change in the oscillator frequency toward the resonant frequency of L5 will ordinarily cause a higher than normal output.) An adjustment of tuning capacitor C4 can be made in this case in an attempt to obtain the normal output voltage.

If the oscillator is found to be operating normally, a defect within the rectifier circuit or the associated load must be suspected as the cause of low output. For example, because of the relatively high-impedance rectifier and filter circuits and the generally poor regulation characteristics of this type of supply, an excessive load current can cause the output voltage to be low. Failure analysis procedures for typical rectifier circuits used in high-voltage supplies are outlined earlier in this section.

PART B. SEMICONDUCTOR CIRCUITS

SEMICONDUCTOR RECTIFIERS.

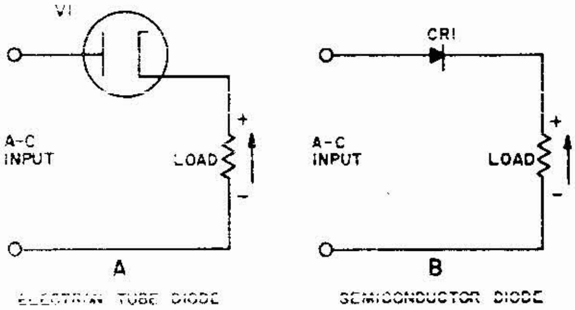
General. The application of semiconductor rectifiers in the design of power supplies for electronic equipment is increasing. The characteristics which have caused this increase are: no requirement for filament (cathode) power, immediate operation without need for warm-up time, low internal voltage drop substantially independent of load current, low operating temperature, and generally small physical size.

Formerly, metallic or dry-disc rectifiers, such as copper-oxide, copper-sulfide, and selenium rectifiers, were used primarily in low-voltage applications and were limited in use to the lower frequencies (25 to 800 cycles). Additional design improvements have allowed these rectifiers to be used with higher input voltages, and today they are widely used as power rectifiers. The newer silicon-type rectifier is now used in many power-supply circuits where other types were formerly used. The small physical size of semiconductor rectifiers, especially the silicon types, makes it practical to place these units in series to handle the higher input voltages.

The semiconductor rectifier is utilized as a diode in power-supply circuits in much the same manner as the electron-tube diode. A semiconductor rectifier can be substituted for each electron-tube diode in almost every basic power supply circuit given in Part A of this handbook section; furthermore, many power-supply circuits which were originally designed to use tubes and were formerly considered impracticable can now be used to advantage by incorporating semiconductor rectifiers in lieu of electron-tube diodes. For example, a voltage-multiplier circuit with many stages to obtain an extremely high-voltage output becomes practicable when semiconductor-type rectifiers are used because the need for an independent filament-voltage source for each stage (to operate directly-heated diodes) is eliminated.

Semiconductor rectifiers are particularly well-adapted for use in the power supplies of portable and small electronic equipment where weight and space are important considerations. Many of these smaller power supplies use very practical bridge and voltage-doubler circuits which require a transformer having only a single high-voltage secondary winding; thus, there is no requirement for a large, expensive transformer which has a center-tapped secondary winding (or an extremely high-voltage secondary winding).

Semiconductor Diode Symbol. The rectifying action of semiconductor diodes is essentially the same as that discussed for electron-tube diodes in Part A of this section. The accompanying illustration shows two equivalent rectifier circuits for the purpose of comparison and to establish the correct use of the semiconductor-diode symbol. (The small arrow adjacent to the load resistance indicates the direction of electron flow in the circuit.)



Equivalent Rectifier Circuits

The terminal of the semiconductor diode (CR1), shown in part B, which corresponds to the cathode (or filament) of the electron-tube diode (V1), shown in part A, is usually identified by a colored dot or band, or by a plus (+) sign, the letter "K", the schematic symbol, or other similar means of identification stencilled on the rectifier itself. The power supply circuits described in this section of the handbook and their associated schematics will use the semiconductor-diode symbol in the same manner as shown in the circuit (part B) above.

Rectifier Ratings. The use of one or a combination of several particular type semiconductor rectifiers in any given circuit is based upon the voltage and current requirements of the circuit. All semiconductor rectifiers are subject to certain voltage breakdown and current limitations; for these reasons the rectifier is usually rated in accordance with its ability to withstand a given peak-inverse voltage, its ability to conduct in terms of a maximum d-c load current, or its working rms (applied a-c input) voltage.

The semiconductor rectifier has an extremely low forward resistance, and precautions are generally taken in the circuit design to ensure that the peak-current rating of the rectifier is not exceeded, especially if the rectifier is used with a capacitance-input filter. For this reason, a small value resistor, called a **surge resistor,** is frequently placed in series with the rectifier to limit the peak current through the rectifier; however, if there is sufficient resistance in the transformer winding (or the a-c source), the series resistor is usually omitted. The series resistor, if used, can also be made to act as a fuse in the circuit. Typical values for the series resistor range from approximately 5 ohms for high-current rectifiers (200 milliamperes or greater) to approximately 50 ohms for low-current rectifiers (50 milliamperes or less). The series resistor is normally not necessary when the rectifier is used with a choke-input filter.

An ideal rectifier would have no (zero) resistance in the forward direction and infinite resistance in the reverse direction. (The electron tube approaches an ideal diode.) In commercially available semiconductor rectifiers, the forward resistance is very small and almost constant, but the reverse resistance is not as great as that of an electron-tube diode; however, the reverse resistance of the semiconductor rectifier can normally be neglected because it is

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generally so much greater than the associated load resistance. Under normal operating conditions, as long as the rectifier is not subjected to severe overload or otherwise abused, the rectifying action is very stable. The only effect of long use is a gradual increase in the forward resistance with age and, depending upon the rectifier type, a gradual increase in the amount of heat developed. An individual rectifier cell (or element) can withstand only a given peak-inverse voltage without breakdown or rupture of the cell; therefore, if higher peak-inverse voltages are to be sustained, a number of cells must be connected in series. Therefore, it is common practice to place many individual cells in series, or to "stack" several complete rectifier units, to obtain the desired characteristics and ratings necessary to withstand the peak-inverse voltage of the circuit without breakdown.

When rectifiers are placed in series (or stacked) to meet the voltage requirements of the circuit, the total forward resistance is increased accordingly. It is normal for this forward resistance to develop some heat; for this reason, many types of rectifiers are equipped with cooling fins or are mounted on "heat sinks" to dissipate the heat. These rectifiers are cooled by convection air currents or by forced-air. In some special applications, a large number of rectifiers may be incased in an oil-filled container to help dissipate heat. Similarly, just as rectifiers are placed in series to meet certain voltage requirements, they may also be placed in parallel to meet power (current) requirements; however, when rectifiers are operated in parallel to provide for an increased current output, precautions are usually taken to ensure that the parallel rectifiers have reasonably similar electrical characteristics.

Semiconductor Rectifier Circuit Analysis. As mentioned before, the rectifying action of a semiconductor diode is the same as that of an electron-tube diode; for this reason, the various power-supply circuits in this part of the handbook are described only briefly, especially where the basic circuit is the counterpart of the electron-tube circuit. Since many of the power-supply circuits are similar, much of the detailed theory of circuit operation can be omitted for the semiconductor version, because the rectifier action is identical with that given for the corresponding electron-tube circuit described in Part A of this section.

Semiconductor Rectifier Failure Analysis. Depending upon the semiconductor type, materials, and construction, a visual check of rectifier appearance may or may not reveal a defective rectifier. Since rectifier failure is not always accompanied by a change in physical appearance, an ohmmeter check or an electrical test may be necessary to determine whether the rectifier is damaged or defective. Improper rectifier operation may result from a change in the rectifier characteristics; that is, the rectifier can be open or shorted, its forward resistance can increase, or its reverse resistance can decrease.

An ohmmeter can be used to make a quick, relative check of rectifier condition. To make this check, disconnect one of the rectifier terminals from the circuit wiring, and make resistance measurements across the terminals of the rectifier. The resistance measurements obtained depend upon the test-lead polarity of the ohmmeter; therefore, two measurements must be made, with the test leads reversed at the rectifier terminals for one of the measurements. The larger resistance value is assumed to be the reverse resistance of the rectifier, and the smaller resistance value is assumed to be the forward resistance. Measurements can be made for comparison purposes using another identical-type rectifier, known to be good, as a standard. Two high-value resistance measurements indicate that the rectifier is open or has a high forward resistance; two low-value resistance measurements indicate that the rectifier is shorted or has a low reverse resistance. An apparently normal set of measurements, with one high value and one low value, does not necessarily indicate satisfactory or efficient rectifier operation, but merely shows that the rectifier is capable of rectification. The rectifier efficiency is determined by how low the forward resistance is as compared with the reverse resistance; that is, it is desirable to have as great a ratio as possible between the reverse and forward resistance measurements. However, the only valid check of rectifier condition is a dynamic electrical test which determines the rectifier forward current (resistance) and reverse current (resistance) parameters.

SINGLE-PHASE, HALF-WAVE RECTIFIER.

APPLICATION.

The single-phase, half-wave rectifier is sometimes used in electronic equipment for applications requiring a d-c output voltage from an a-c source. It is frequently used in "transformerless" circuits where the load current is small and voltage regulation is not critical and also where small space, light weight, high efficiency, ruggedness, and long life are important considerations. The circuit is often employed as the power supply in small receivers and audio amplifiers. It is also used in low-voltage battery chargers and in some equipment applications, as a bias supply. The rectifier circuit can be arranged to furnish either negative or positive d-c output to the load.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

Uses semiconductor diode as rectifier.

Output requires filtering; d-c output ripple frequency is equal to a-c source frequency.

Has relatively poor regulation characteristics.

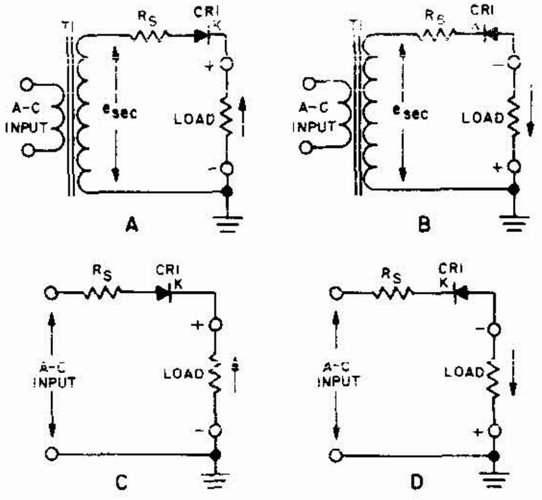
Depending upon circuit application, may be used with or without a power or isolation transformer.

Circuit provides either positive- or negative-polarity output voltage.

CIRCUIT ANALYSIS.

General. The single-phase, half-wave rectifier is the simplest type of rectifier circuit. It consists of a semiconductor rectifier (diode) in series with the alternating source and the load. Since the rectifier conducts in only one direction, electrons flow through the load and through the rectifier once during each complete cycle of the impressed voltage. Thus, the electrons flow through the load in pulses, one pulse for every other half cycle of the impressed voltage.

Circuit Operation. In the accompanying circuit schematic, parts A and B illustrate a semiconductor diode, CR1, used in two variations of a basic single-phase, half-wave rectifier circuit. These two circuit variations use a transformer, T1, as an isolation transformer or to step up the alternating-source voltage to a higher value in the secondary. The use of a transformer in this circuit permits either d-c output terminal to be placed at ground (chassis) potential. The two circuit variations shown in parts C and D do not use a transformer, but operate directly from the a-c source. Both circuits shown in parts C and D place one side of the a-c source at a d-c potential, and thus restricts the output of the supply to either a positive d-c potential (part C) or a negative d-c potential (part D).



Basic Half-Wave Rectifier Circuits

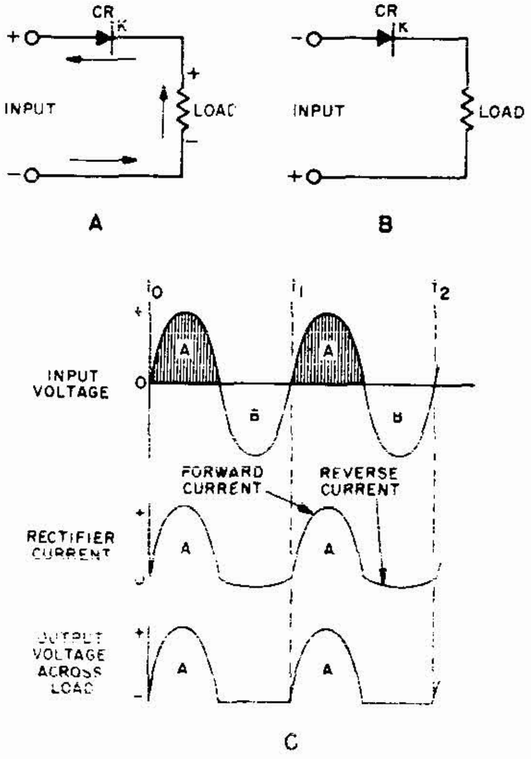
In the four circuits illustrated, the function of semiconductor diode CR1 is the same for each circuit. However, because of the manner in which the diode is placed in the circuit, electrons flow through the load in the direction indicated by the arrow adjacent to the load resistance. The d-c output polarity for each circuit is indicated by the signs associated with the load resistance. The triangle in the graphic symbol for diode CR1 points in the direction of current flow according to conventional (positive-to-negative) current theory; electron flow is in the opposite direction. The letter "K" assigned to one terminal of the graphic symbol for CR1 indicates that this terminal corresponds to the cathode (filament) of a electron-tube diode. Therefore, the terminal represented by the solid-arrow portion of the graphic symbol corresponds to the plate of an electron-tube diode.

Each of the four circuits shows a resistor, Rs, in series with the semiconductor diode. This resistor, called the **surge resistor,** limits the peak current through the rectifier to a safe value. The value of resistor Rs is influenced by the circuit design; determination of its value includes the consideration of several other factors, such as the applied a-c voltage, the resistance of the load circuit, the filter-circuit input capacitance, and the peak current rating of the semiconductor diode. If there is sufficient resistance in the secondary winding of transformer T1 (shown in parts A and B) or in the a-c source (parts C and D), the resistor may be omitted; also, if the load circuit of the supply includes a choke-input filter, the resistor may be omitted.

The operation of the half-wave rectifier circuit can be understood from the simplified circuits, parts A and B, and the waveforms, part C, shown in the accompanying illustration.

Assume that the a-c voltage applied to the input terminals of the rectifier circuit during the initial half-cycle has the polarity indicated in part A of the illustration. Electrons flow in the direction indicated by the small arrows from the lower (negative) input terminal, through the load, through rectifier CR, and to the upper (positive) input terminal. Thus, during the initial half-cycle, rectifier CR passes maximum current in the forward direction, and an output voltage is developed across the load resistance. In other words, when the rectifier conducts, electrons pass through the load to develop a corresponding output-voltage pulse, as shown in part C of the illustration.

During the next half-cycle, the polarity of the applied a-c input is as indicated in part B of the illustration. Except for possibly a very small value of reverse current, the



Typical Half-Wave Rectifier Circuit Operation and Waveforms rectifier does not conduct, the reverse resistance remains high, and the small current which flows can be neglected. (Normally, the reverse resistance of the rectifier is extremely high as compared with the circuit load resistance.) Thus, during the second half-cycle, no voltage is developed across the load resistance. In other words, because the rectifier is nonconducting and no electrons pass through the load, there is no output from the circuit.

The waveforms given in part C show that, on positive half cycles of the applied voltage, current passes through the rectifier and the load resistance, producing an output voltage across the load resistance. The output voltage has a pulsating waveform, which results in an irregularly shaped ripple voltage; the frequency of the ripple voltage is the same as the frequency of the a-c source. Since the output voltage and current are not continuous, the half-wave rectifier circuit requires considerable filtering to smooth out the ripple and produce a steady d-c voltage.

The **peak inverse voltage** of the semiconductor rectifier is defined as the maximum instantaneous voltage in the direction opposite to that in which the rectifier is designed to pass current. Assuming the output of the supply to be filtered, the peak inverse voltage across the rectifier in a half-wave rectifier circuit during the period of time the rectifier is nonconducting is approximately 2.83 times the rms value of the applied (or transformer secondary) voltage.

The output of the half-wave rectifier circuit is connected to a suitable filter circuit, to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in Part D of this section of the handbook.) Because of the very low forward resistance of the semiconductor rectifier and its associated low internal-voltage drop which is practically independent of load current, the half-wave power supply (including filter and load) using a semiconductor diode will have somewhat better regulation characteristics than the equivalent electron-tube circuit; however, the regulation is still considered to be relatively poor.

FAILURE ANALYSIS.

No Output. In the half-wave rectifier circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of an open series resistor Rs or a defective transformer), a defective rectifier, or a shorted load circuit (including shorted filter-circuit components).

The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is present and is the correct value. If the circuit uses a step-up (or isolation) transformer, measure the voltage at the secondary terminals to determine whether it is present and is the correct value. If necessary, the primary voltage should be removed from the transformer and continuity measurements of the primary and secondary windings made to determine whether one of the windings is open, since an open circuit in either winding will cause a lack of secondary voltage.

If the circuit includes a series resistor (Rs), a resistance measurement can be made to determine whether the resistor is open. However, if the resistor is found to be open, the rectifier and load circuit should be checked further to determine whether excessive load current or a defective rectifier has caused the resistor to act as a fuse and to open.

With the a-c supply voltage removed from the input of the circuit and with the load disconnected from the rectifier, resistance measurements can be made across the load to determine whether the load circuit (including filter components) is shorted.

Although physical appearance is not a positive indication of condition, the rectifier may be given a visual check for a change in physical appearance which can indicate rectifier failure. A relative check of the rectifier condition can be made using an ohmmeter, as outlined in a previous paragraph of this section. However, failure of the rectifier may be the result of other causes; therefore, additional tests of the filter and load circuit are necessary. Once the filter components and load circuit have been determined to be satisfactory, a procedure which can be used to quickly determine whether the rectifier is defective is to substitute a known good rectifier in the circuit and measure the output voltage.

Low Output. The rectifier should be checked to determine whether the low output is due to normal rectifier aging. A relative check of the rectifier condition can be made using an ohmmeter, as outlined in a previous paragraph of this section. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease, and the amplitude of the ripple voltage will become excessive.

The load current should be checked to make sure that it is not excessive, because the circuit has relatively poor regulation and an appreciable increase in load current (decrease in load resistance) can cause a decrease in output voltage. Also, the filter circuit components should be suspected as a possible cause of low output. Once the load circuit and filter components have been determined to be satisfactory, a procedure which can be used to quickly determine whether the rectifier is at fault is to substitute a known good rectifier in the circuit and measure the output voltage under normal load conditions.

SINGLE-PHASE, FULL-WAVE RECTIFIER.

APPLICATION.

The single-phase, full-wave rectifier is commonly used in all types of electronic equipment for applications requiring high- or low-voltage dc at a relatively high load current. The rectifier circuit can be arranged to furnish negative or positive output to the load.

CHARACTERISTICS.

Input to circuit is ac; output is dc.

Uses two semiconductor rectifiers.

Output requires filtering; d-c output ripple frequency is twice the primary line-voltage frequency.

Has good regulation characteristics.

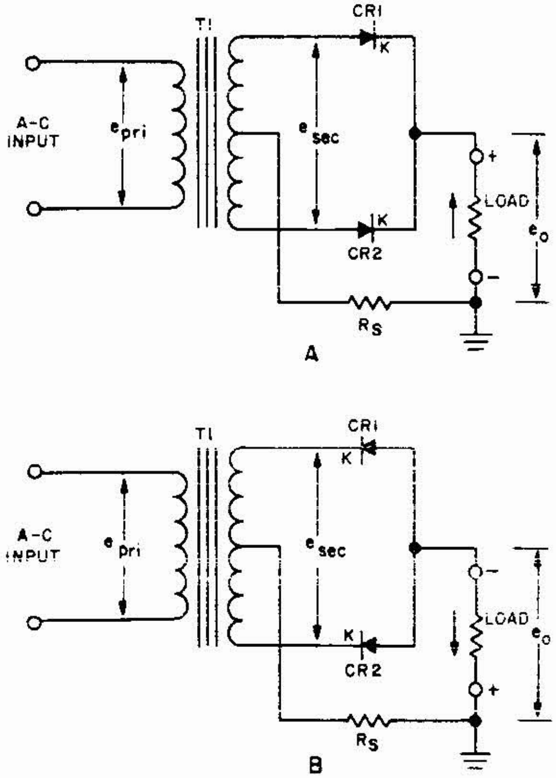
Circuit provides either positive- or negative-polarity output voltage.

Uses power transformer with center-tapped secondary winding.

CIRCUIT ANALYSIS.

General. The single-phase, full-wave rectifier is one of the most common types of rectifier circuits used in electronic equipment. It may be used as a low-voltage d-c supply for operation of relays, motors, electron-tube filaments, telephone and teletype circuits, and semiconductor circuits, or as a high-voltage d-c supply for operation of electron-tube circuits. The full-wave rectifier circuit consists of a transformer with a center-tapped secondary winding. At least two semiconductor diodes are used in the circuit; one diode is connected to one end of the transformer secondary, and the other diode is connected to the other end. The load is connected between the center tap of the secondary winding and the common junction of the two semiconductor diodes. Since the secondary winding is center-tapped, the voltages developed in the two halves of the secondary winding are in series with each other; therefore, only one rectifier is conducting at any instant. As a result, electrons flow through one half of the secondary winding, the load, and a rectifier on each half cycle of the impressed voltage, with first one diode conducting and then the other. Thus, the electrons flow through the load in pulses, one pulse for each half cycle of the impressed voltage.

Circuit Operation. In parts A and B of the accompanying circuit schematic, two semiconductor diodes, CR1 and CR2, are used in a basic single-phase, full-wave rectifier circuit. Although the schematic shows only two diodes in the circuit, in some instances for high-voltage operation each diode symbol represents two or more diodes in series to obtain the necessary peak-inverse characteristics.



Basic Single-Phase, Full-Wave Rectifier Circuits

The circuit uses a single transformer, T1, either to step up the alternating-source voltage to a higher value in each half of the secondary winding or to step down the voltage to a lower value. The circuit application and the values of the input and output voltages determine whether a step-up or step-down transformer is used.

The series, or surge, resistor (R_s) is generally required only in high-voltage supplies. Its function is to limit the peak current that can flow through the semiconductor rectifiers. When power is applied to the circuit, the input capacitor (in the filter circuit) is in a discharged condition. A very heavy current flows initially to establish the charge on this capacitor. The limiting action of R_s prevents any damage to the rectifiers, which would otherwise occur from the large surge of charging current. For 380-volt (peak inverse) rectifiers, the value of R_s is between 1 and 50 ohms, depending on the peak current rating of the unit. The resistor is common to both rectifiers since it is placed in the circuit between the transformer center tap and the load. A variation of this design practice uses two resistors, one resistor in series with each rectifier.

The circuit arrangement given in part A is typical of many plate- and low-voltage (positive) supplies. The circuit given in part B is typical for bias supply applications requiring a negative voltage. In the basic circuits illustrated, either terminal of the load may be placed at ground potential, depending upon whether a positive or negative d-c output is desired. When the d-c output terminal associated with the transformer center tap is grounded, the secondary-to-core insulation need not be as great as it would be if the secondary winding were above ground by the amount of the d-c output voltage. For this reason, the two circuits shown in parts A and B are the commonly used circuits, and do not require that special design consideration be given to the secondary-winding insulation.

In parts A and B of the accompanying illustration, the voltage induced in each half of the secondary of transformer T1 causes each diode to conduct on alternate half-cycles of the input voltage. Two d-c pulses are thus produced during each complete cycle of a-c input voltage. Hence, the output has a frequency which is twice the input frequency. Because of this, the full-wave circuit is more efficient, has better voltage regulation, and has an output which is easier to filter (with a higher average value than that of the half-wave circuit).

As an example of the peak and average voltages obtained from the full-wave rectifier circuit, assume that transformer T1 in part A of the illustration has a step-up ratio of 1 to 6. Then, with an applied input voltage of 115 volts, 690 volts will appear across the secondary winding, and 345 volts will be applied to each diode. Since only one-half of the secondary is used at a time, the peak voltage is found by using half of the voltage across the winding, or 345 volts. From the peak voltage formula:

$$\begin{aligned} E_{peak} &= 1.414 \times E_{rms} \\ &= 1.414 \times 345 \\ &= 488 \text{ volts (approx)} \end{aligned}$$

This is the peak value of the output voltage for half-wave (single-pulse) rectification. Since two pulses are produced for every cycle of a-c input voltage in full-wave rectification, the average value of the d-c output voltage will be greater than that for half-wave rectification; thus:

$$E_{av} = E_{peak} \times \frac{2}{\pi}$$

$$= 488 \times \frac{2}{3.14}$$

$$= 310 \text{ volts (approx)}$$

In a full-wave rectifier circuit designed to furnish high-voltage dc to the load, the peak-inverse voltage rating of the semiconductor rectifier is an important consideration.

The peak-inverse voltage across a semiconductor rectifier in a full-wave circuit during the period of time it is nonconducting is approximately 2.83 times the rms voltage across half of the transformer secondary $\left(\frac{e_{sec}}{2}\right)$, or approximately 1.41 times the rms voltage across the entire secondary (e_{sec}). For high-voltage applications, several identical-type rectifiers may be placed in series or stacked to withstand the peak-inverse voltage and avoid the possibility of rectifier breakdown. Generally, whenever a single rectifier unit is used in the full-wave circuit, it is chosen to have a peak-inverse voltage rating which is conservative and thus provide a safety factor.

Because of the very low forward resistance of the semiconductor rectifier and its low internal-voltage drop which is practically independent of load current, the full-wave power supply using semiconductor diodes has regulation characteristics which approach or equal those of the equivalent electron-tube circuit using mercury-vapor rectifiers. Hence, its regulation characteristics are somewhat better than those of the electron-tube circuit which uses high-vacuum rectifiers.

FAILURE ANALYSIS.

No Output. In the full-wave rectifier circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of a defective transformer), defective rectifiers, or a shorted load circuit (including shorted filter-circuit components).

The a-c voltage applied to each rectifier should be measured between the secondary center tap and each rectifier to determine whether voltage is present and of the correct value. If the circuit includes a series resistor (Rs), an additional measurement should be made between the load connection at the resistor and the rectifier to determine whether the resistor is open. (With primary voltage removed from the input, a resistance measurement can be made to determine whether the resistor is open.)

If necessary, measure the applied primary voltage to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, a continuity measurement of the primary winding should be made to determine whether the winding is open, since an open winding will cause lack of secondary voltage.

If the circuit includes a series (surge) resistor common to both rectifiers and the resistor is found to be open, each rectifier and the load circuit should be checked further to determine whether excessive load current or a defective rectifier(s) has caused the resistor to act as a fuse and to open. With the a-c supply voltage removed from the input of the circuit and with the load disconnected from the rectifiers, resistance measurements can be made across the load to determine whether the load circuit (including filter components) is shorted.

Although physical appearance is not a positive indication of condition, the rectifier may be given a visual check for a change in physical appearance which can indicate rectifier failure. A relative check of the rectifier condition can be made using an ohmmeter, as outlined in a previous paragraph of this section. However, failure of the rectifier(s) may be the result of other causes; therefore, additional tests of the filter and load circuit are necessary. Once the filter components and load circuit have been determined to be satisfactory, a procedure which can be used to quickly determine whether the rectifiers are defective is to substitute known good rectifiers in the circuit and measure the output voltage.

Low Output. Each rectifier should be checked to determine whether the low output is due to normal rectifier aging or to one or more defective rectifiers. A relative check of rectifier condition can be made using an ohmmeter, as outlined in a previous paragraph of this section. (A comparison can be made by checking one rectifier against the other to determine whether they have similar characteristics.) If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease, and the amplitude of the ripple voltage will become excessive.

Since the full-wave rectifier circuit normally supplies current to the load on each half cycle, failure of either rectifier (or associated series resistor, if used) or an open in either half of the secondary winding will allow the circuit to act as a half-wave rectifier circuit, and the output voltage will be reduced accordingly. Furthermore, whenever this occurs, the ripple amplitude will also increase, and the ripple frequency will be that of the a-c source (instead of twice the source frequency). If one rectifier of the full-wave circuit is found to be defective, rather than replace the defective rectifier only, it is good practice to replace both rectifiers at the same time and to make certain that the replacement rectifiers have like, or matched, characteristics.

With the primary voltage removed from the circuit, resistance measurements can be made to check the continuity between the center tap and each rectifier terminal; this will determine whether one of the windings is open. As an alternative, the a-c secondary voltage applied to each rectifier can be measured between the center tap and each rectifier to determine whether both voltages are present and are of the correct value.

The primary voltage should be measured to determine whether it is of the correct value, since a low applied primary voltage can result in a low secondary voltage. Also, shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. (A check for shorted turns was outlined in the failure analysis described for the electron-tube full-wave rectifier circuit, given earlier in this section of the handbook).

The load current (to the filter circuit and to the load) should be checked to make sure that it is within tolerance and is not excessive. A low-output condition due to a decrease in load resistance would cause an increase in load current; for example, excessive leakage in the capacitors of the filter circuit would result in increased load current. Once the load circuit and filter components have been determined to be satisfactory, a procedure which can be used to quickly determine whether the rectifiers are at fault is to substitute known good rectifiers in the circuit and measure the output voltage under normal load conditions.

SINGLE-PHASE, FULL-WAVE BRIDGE RECTIFIER.

APPLICATION.

The single-phase, full-wave bridge rectifier is used in electronic equipment for applications requiring high- or low-voltage dc at a relatively high load current. The circuit can be arranged to furnish negative or positive voltage to the load. A variation of the basic bridge circuit can supply two output voltages simultaneously to separate loads.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

Uses four semiconductor rectifiers (single, multiple, or stacked units).

Output requires filtering; d-c output ripple frequency is twice the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Uses power transformer with single secondary winding; modified circuit to supply two output voltages simultaneously uses transformer with center-tapped secondary winding.

CIRCUIT ANALYSIS.

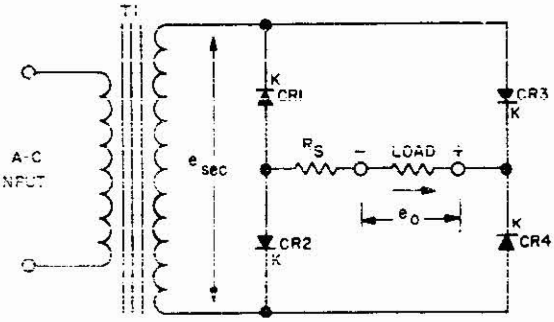
General. The single-phase, full-wave bridge rectifier circuit uses two semiconductor rectifiers in series on each side of a single transformer secondary winding (the secondary winding does not require a center tap); four rectifiers are used in the bridge circuit, one in each arm of the bridge. During each half cycle of the impressed a-c voltage, two rectifiers, one at each end of the secondary, conduct in series to produce an electron flow through the load. Thus, electrons flow through the load in pulses, one pulse for each half cycle of the impressed voltage. Since two d-c output pulses are produced for each complete input cycle, full-wave rectification is obtained, and the output is similar to that of the conventional full-wave rectifier circuit.

One advantage of the bridge rectifier circuit over a conventional full-wave rectifier is that for a given transformer total-secondary voltage the bridge circuit produces an output voltage which is nearly twice that of the full-wave circuit. Another advantage is that the peak-inverse voltage across an individual rectifier, during the period of time it is nonconducting, is approximately half the peak-inverse voltage across a rectifier in a conventional full-wave circuit designed to produce the same output voltage.

In many power-supply applications, it is desirable to provide two voltages simultaneously—one voltage for high-power stages and the other for low-power stages. For these applications the single-phase, full-wave bridge rectifier circuit can be modified to supply an additional output voltage which is equal to one half of the voltage provided by the full-wave bridge rectifier circuit.

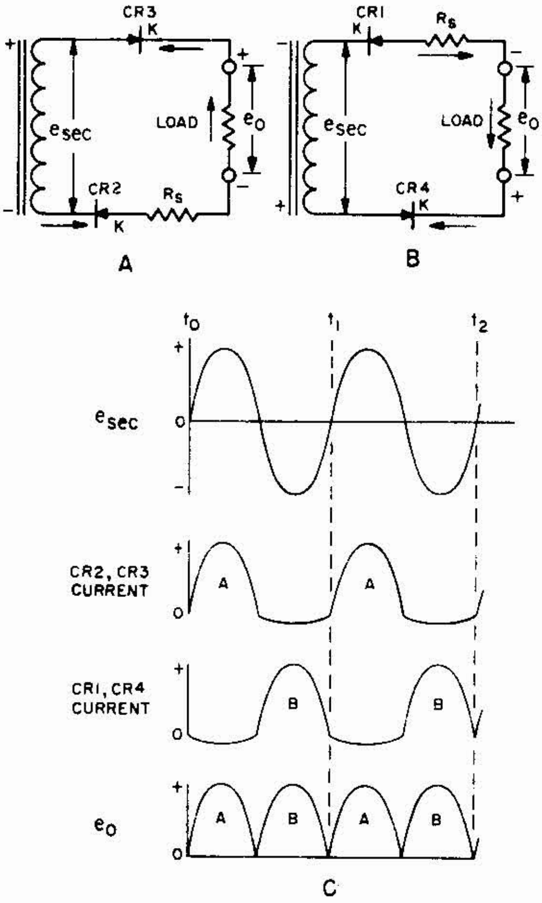
Circuit Operation. A single-phase, full-wave bridge rectifier using semiconductor diodes is shown in the accompanying circuit schematic. Four identical-type semiconductor rectifiers, CR1, CR2, CR3 and CR4, are connected in a bridge circuit across the secondary winding of transformer T1. Each rectifier forms one arm of the bridge circuit; the load is connected between the junction points of the balanced arms of the bridge. The circuit uses a single transformer, T1, either to step up the alternating-source voltage to a higher value in the secondary winding or to step down the voltage to a lower value. The circuit application and the values of the input and output voltages determine whether a step-up or step-down transformer is used. The series, or surge, resistor (Rs) is generally used only in high-voltage supplies and is not normally required in low-voltage supplies. The resistor is common to all rectifiers since it is placed in series with the load and filter circuit.

The circuit arrangement given in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired.



Basic Single-Phase, Full-Wave Bridge Rectifier Circuit

The operation of the full-wave bridge rectifier circuit can be understood from the simplified circuit schematic (parts A and B) and the waveforms (part C) shown in the accompanying illustration and by reference to the explanation given for the equivalent electron-tube bridge circuit found in part A of this handbook section. The basic bridge rectifier schematic, given previously in this discussion, has been simplified and redrawn to show the action which occurs on alternate half-cycles of the applied voltage. The



Simplified Full-Wave Bridge Rectifier Circuit and Waveforms

rectifier reference designations used correspond to those assigned in the basic bridge schematic.

During the first half-cycle the transformer secondary winding may be considered as a voltage source of the polarity given in part A of the illustration. As a result, electrons flow, in the direction indicated by the arrows, through the series circuit composed of rectifier CR2, resistor Rs, the load, and rectifier CR3. This electron flow produces an output pulse of the polarity indicated across the load resistance. Also, during this period, rectifiers CR1 and CR4 are nonconducting.

During the next half-cycle, a secondary voltage is produced of the polarity given in part B of the illustration. As a result, electrons flow, in the direction indicated by the arrows, through the series circuit composed of rectifier CR1, resistor Rs, the load, and rectifier CR4. The electrons flowing in the series circuit once again produce an output of the same polarity as before across the load resistance. During this period, rectifiers CR2 and CR3 are nonconducting.

From the waveforms given in part C, it can be seen that two rectifiers in series conduct at any instant of time; thus, on alternate half-cycles, electrons flow through the load resistance to produce a pulsating output voltage, e_o. This pulsating waveform results in an irregularly shaped ripple voltage because the output voltage and current are not continuous; the frequency of the ripple voltage is twice the frequency of the a-c source. The output of the full-wave bridge rectifier circuit requires filtering to smooth out the ripple and produce a steady d-c voltage.

The full-wave bridge rectifier circuit makes continuous use of the transformer secondary; therefore, there are two pulsations of current in the output for each complete cycle of the applied a-c voltage. The d-c load current passes through the entire secondary winding, flowing in one direction for one half-cycle of the applied voltage, and in the opposite direction for the other half-cycle; thus, there is no tendency for the transformer core to become permanently magnetized. Since little d-c core saturation occurs, the effective inductance of the transformer, and therefore the efficiency, is relatively high.

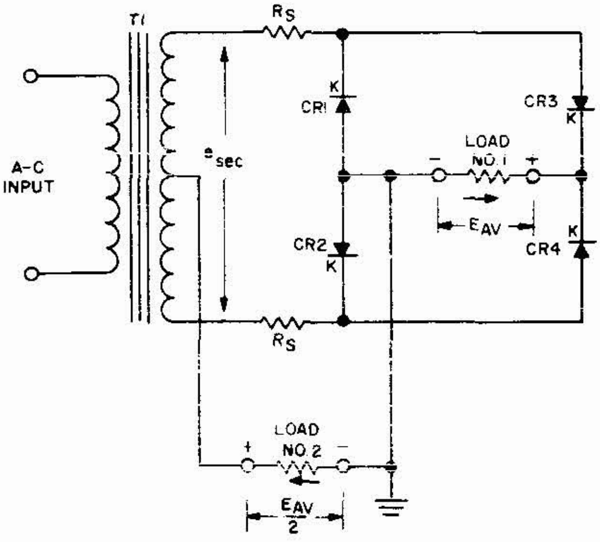
The peak-inverse voltage across an individual rectifier in a full-wave bridge rectifier circuit during the period of time the rectifier is nonconducting is approximately 1.41 times the rms voltage across the secondary winding. Since the secondary voltage, e_{sec}, is applied to two rectifiers in series, less peak-inverse voltage appears across each rectifier. Thus, the bridge circuit can be used to obtain a higher output voltage than can be obtained from a conventional full-wave rectifier circuit using identical rectifiers.

In bridge circuits designed to furnish high-voltage dc to the load, the peak-inverse voltage rating of the semiconductor rectifier is an important consideration. For such applications, several identical-type rectifiers may be placed in series or stacked to withstand the peak-inverse voltage and avoid the possibility of rectifier breakdown.

The output of the full-wave bridge rectifier is similar to that of the conventional full-wave rectifier circuit. For the same total transformer secondary voltage and d-c output current, the bridge rectifier provides twice as much output voltage as does the full-wave rectifier circuit using a center-tapped secondary.

The output of the bridge rectifier circuit is connected to a suitable filter circuit to smooth out the pulsating direct current for use in the load circuit. (Filter circuits are discussed in the latter part of this section.)

A variation of the full-wave bridge rectifier circuit uses a transformer with a center-tapped secondary winding to supply two output voltages simultaneously to two separate loads. The circuit is fundamentally the same as that given earlier; therefore, the reference designations previously assigned to the basic circuit remain unchanged. This modified circuit uses two series (surge) resistors which are common to both the full-wave center-tap rectifier circuit and the full-wave bridge rectifier circuit.



Full-Wave Center-Tap and Full-Wave Bridge Rectifier Circuit

One advantage of this circuit is that two voltages may be supplied from the same set of rectifiers. One output voltage (E_{av}) is obtained from the output of the bridge circuit; the other output voltage $\left(\frac{E_{av}}{2}\right)$, which is equal to one half of the bridge output voltage, is obtained by using two rectifiers, CR1 and CR2 of the bridge, and the center tap of the secondary winding as a conventional full-wave rectifier circuit. Although this circuit can supply two output voltages simultaneously to two separate loads, there is a limitation on the total current which can be safely carried by rectifiers CR1 and CR2.

FAILURE ANALYSIS.

No Output. In the full-wave bridge rectifier circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of a defective transformer), a shorted load circuit (including shorted filter-circuit components), or defective rectifiers.

The a-c secondary voltage, e_{sec}, should be measured at the transformer terminals to determine whether the voltage is present and of the correct value. If necessary, measure the applied primary voltage to determine whether it is present and of the correct value. With the input voltage removed from the circuit, continuity measurements of the windings can be made to determine whether one of the windings is open, since an open winding will cause a lack of secondary voltage.

If the circuit includes one or more series resistors (Rs), continuity measurements can be made to determine whether the resistors are open. When a series resistor is found to be open, the associated rectifiers and load circuit (including filter-circuit components) should be checked to determine whether excessive load current or defective rectifiers have caused the resistor to act as a fuse and to open.

With the a-c supply voltage removed from the input of the circuit and with the load disconnected from the rectifiers, resistance measurements can be made across the load to determine whether the load circuit (including filter components) is shorted.

Although physical appearance is not a positive indication of condition, the rectifiers may be given a visual check for a change in physical appearance which can indicate rectifier failure. A relative check of the rectifier condition can be made using an ohmmeter, as outlined in a previous paragraph of this section. However, failure of the rectifiers may be the result of other causes; for this reason, tests of the filter and load circuit are necessary.

Low Output. Each rectifier should be checked to determine whether the low output is due to normal rectifier aging or to one or more defective rectifiers. A relative check of rectifier condition can be made using an ohmmeter, as outlined in a previous paragraph of this section. A comparison can be made by checking all rectifiers and noting the results obtained to determine whether the rectifiers have similar characteristics. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease and the amplitude of the ripple voltage will become excessive.

Complete failure of only one rectifier in the bridge will allow the circuit to act as a half-wave rectifier with current supplied to the load on alternate half-cycles only, and the output voltage will be reduced accordingly. Furthermore, whenever this occurs, the ripple amplitude will also increase, and the ripple frequency will be that of the a-c source (instead of twice the source frequency).

The load current should be checked to make sure that it is not excessive, because a decrease in output voltage can be caused by an increase in load current (decrease in load resistance); for example, excessive leakage in the capacitors of the filter circuit would result in increased load current. Also, the a-c secondary voltage, e_{sec}, and the input (primary) voltage should be measured at the terminals of transformer T1 to determine whether these voltages are of the correct value. Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. (A check for shorted turns is outlined in the failure analysis described for the electron-tube full-wave bridge rectifier circuit given earlier in this section of the handbook.) Once the load circuit and filter components have been determined to be satisfactory, a procedure which can be used to quickly determine whether the rectifiers are at fault is to substitute known good rectifiers in the circuit and measure the output voltage under normal load conditions.

In the modified full-wave center-tap and full-wave bridge circuit, it is possible to have two definite conditions of low voltage caused by defective rectifiers: the output voltage (E_{av}) to load No. 1 can be low and the output voltage $\left(\frac{E_{av}}{2}\right)$ to load No. 2 normal, or both output voltages can be below normal. If the load currents are not excessive and the filter components have been checked as satisfactory, the defective rectifiers in the first case are assumed to be CR3 and CR4 of the bridge circuit, and those in the second case are assumed to be CR1 and CR2, which are common to both the full-wave center-tap and the bridge circuits. In a practical full-wave center-tap and full-wave bridge circuit, the two rectifiers designated in the schematic as CR1 and CR2 may have higher current ratings than the rectifiers designated as CR3 and CR4, because CR1 and CR2 must carry the combined currents of both output loads. For this reason, rectifiers CR1 and CR2 may not be directly interchangeable with rectifiers CR3 and CR4 of the bridge circuit.

THREE-PHASE, HALF-WAVE (THREE-PHASE STAR) RECTIFIER.

APPLICATION.

The three-phase, half-wave star- or wye-connected rectifier is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c power requirements exceed 1 kilowatt. The rectifier circuit can be arranged to furnish negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses three semiconductor rectifiers (single, multiple, or stacked units).

Output is relatively easy to filter; d-c output ripple frequency is equal to three times the primary line-voltage frequency.

Has good regulation characteristics.

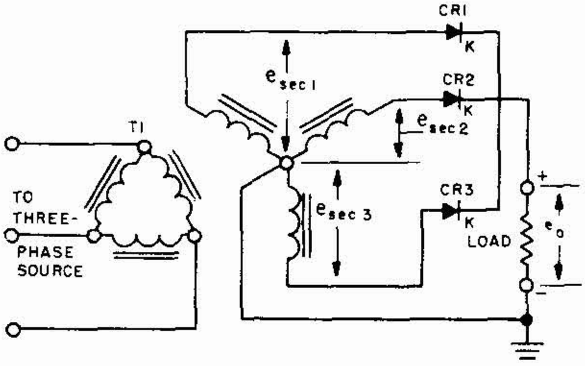
Circuit provides either positive- or negative-polarity output voltage.

Uses multiphase power transformer with star- or wye-connected secondary windings; primary windings may be either delta- or wye-connected.

CIRCUIT ANALYSIS.

General. The three-phase, half-wave (three-phase star) rectifier is the simplest type of three-phase rectifier circuit. Fundamentally, this rectifier circuit is three single-phase, half-wave rectifier circuits, each rectifier operating from one phase of a three-phase source and sharing a common load. The voltages induced in the transformer secondary windings differ in phase by 120 degrees; thus, each half-wave rectifier conducts for 120 degrees of the complete input cycle, and contributes one-third of the d-c current supplied to the load. Electrons flow through the load in pulses, one pulse for every other half-cycle of the impressed voltage in each of the three phases; therefore, the output voltage has a ripple frequency which is three times the frequency of the a-c source.

Circuit Operation. A basic three-phase, half-wave rectifier is illustrated in the accompanying circuit schematic. The circuit uses a three-phase transformer, T1, to step up the alternating source voltage to a high value in the star- or wye-connected secondaries. The primary windings of transformer T1 are shown delta-connected, although in some instances the primary windings may be wye-connected (as for a three- or four-wire system). Each rectifier, CR1, CR2, and CR3, is connected to a high-voltage secondary winding. The load is connected between the junction point of the wye-connected secondary windings and the common connection of the three rectifiers.



Basic Three-Phase, Half-Wave (Three-Phase Star) Rectifier Circuit

In the circuit illustrated, either terminal of the load can be placed at ground potential, depending upon whether a positive or negative d-c output is desired. However, it is good design practice for the d-c output terminal associated with the junction of the wye-connected secondaries to be grounded, in this case, the secondary-to-core insulation need not be as great as it would be if the secondary windings were above ground by the amount of the d-c output voltage. When a negative high-voltage d-c supply is required, it is common practice to keep the junction of the wye-connected secondaries at ground (chassis) potential and to reverse the connections to the rectifiers (CR1, CR2, and CR3); in this case, the output polarity across the load will be opposite that shown on the schematic.

The semiconductor rectifiers, CR1, CR2, and CR3, are made up of several rectifiers in series to safely withstand the peak inverse voltage of the circuit and to prevent rectifier breakdown. Since each individual rectifier cell in the series-connected arrangement (multiple or stacked units) has a maximum reverse-voltage rating, it is necessary for the series combination of rectifiers in any secondary leg to have a total reverse-voltage rating in excess of the maximum peak inverse voltage encountered in the circuit configuration. Although the voltage ratings for the commercially available silicon rectifiers are generally higher than for the selenium rectifiers, both selenium and silicon rectifiers are commonly used in high-voltage power supplies. Because a choke-input filter system is commonly employed with this circuit, series, or surge, resistors are not normally used, and for this reason are not shown in the schematic.

The operation of the three-phase, half-wave rectifier circuit can be readily understood from a study of the equivalent electron-tube circuit description and the associated waveforms given previously in this section of the handbook.

For this reason, an explanation of circuit operation is not given here.

The action of the semiconductor rectifiers in this circuit is essentially the same as that described for the equivalent electron-tube circuit. The rectifier in each secondary leg conducts for only one-third cycle, and this results in a series of d-c output voltage pulsations. The output voltage, e_o, across the load resistance is determined by the instantaneous currents flowing through the load; therefore, the output voltage never drops to zero because of the overlapping of applied three-phase secondary voltages and the resulting rectifier conduction in each secondary leg. Because the ripple voltage is equal to three times the frequency of the a-c source, the circuit requires less filtering to smooth out the ripple and produce a steady d-c voltage than does a single-phase rectifier circuit.

The peak inverse voltage across the rectifier (multiple or stacked units) in one secondary leg of the three-phase, half-wave circuit during the period of time the rectifier is nonconducting is approximately 2.45 times the rms voltage (e_{sec}) across the secondary winding of one phase.

The regulation of the circuit is considered to be very good, and is better than that of a single-phase rectifier circuit having equivalent power-output rating; the semiconductor rectifier characteristics and the three-phase input contribute greatly to the improved regulation characteristic of the supply. The output of the three-phase, half-wave rectifier circuit is connected to a suitable filter circuit, to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in Part D of this section of the handbook.)

FAILURE ANALYSIS.

No Output. In the three-phase, half-wave rectifier circuit, the no-output condition is likely to be limited to one of three possible causes: the lack of applied a-c voltage, a shorted load circuit (including shorted filter capacitors), or an open filter choke.

NOTE

> Most filter circuits used in Navy equipment employ two-section choke-input filters; thus, an open choke in either section will cause no output.

Measure the applied three-phase primary voltage to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings, to determine whether one or more than one winding is open and whether the common terminal(s) of the wye-connected secondaries is connected to the load circuit. If necessary, the a-c secondary voltage applied to the rectifiers may be measured between the common terminal(s) of the wye-connected secondaries and one or more rectifiers, to determine whether voltage is present and of the correct value.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. (As explained in the preceding note, an open choke in the filter circuit will also cause no output.) A short in the load circuit (including components in the filter circuit) will cause an excessive load current to flow and may result in permanent damage to the rectifiers. Therefore, once the difficulty in the load (including filter) circuit has been located and corrected, the rectifiers should be checked to determine whether they have been damaged as a result of the overload condition.

Low Output. If only one or two phases of the three-phase, half-wave rectifier circuit are operating normally, the output voltage will be lower than normal. For example, if only one secondary winding and associated rectifier is in operation, the effect is the same as though it were a single-phase, half-wave rectifier circuit; as a result, the output voltage is much lower than normal. When two phases are operating, the output voltage is somewhat higher, and when all three phases are operating, the output is normal. (Also, the percentage of ripple voltage will change for each of the conditions mentioned.) Thus, the low-output condition can be due to the fact that one (or more) of the secondary-phase circuits (including rectifiers) is not functioning normally.

The rectifiers should be checked to determine whether the low output is due to normal rectifier aging, or to one or more defective rectifiers. A relative check of rectifier condition can be made by using an ohmmeter, as outlined in a previous paragraph of this section. (A comparison can be made by checking one rectifier against each of the others to determine whether they have similar characteristics.) If the forward resistance of a rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease, and the amplitude of the ripple voltage will increase.

With the three-phase primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings, to determine whether one (or more) of the windings is open. If necessary, the a-c secondary voltage (e_{sec}) applied to each rectifier may be measured between the common terminal of the secondary wye connection and each rectifier, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase voltage at each of the phases, to determine whether each voltage is present and of the correct value, since low applied primary voltages can result in low secondary voltages.

Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. (A check for shorted turns is outlined in the failure analysis described for the electron-tube three-phase, half-wave rectifier circuit discussed earlier in this section of the handbook.)

The load current should be checked to make sure that it is not excessive, because a decrease in output voltage can be caused by an increase in load current (decrease in load resistance); for example, excessive leakage in the capacitors of the filter circuit will result in increased load current. Once it has been determined that the load circuit (including filter components) is satisfactory, a procedure which can be used to quickly determine whether the rectifiers are at fault is to substitute known good rectifiers in the circuit and measure the output voltage under normal load conditions.

THREE-PHASE, FULL-WAVE (SINGLE "Y" SECONDARY) RECTIFIER.

APPLICATION.

The three-phase, full-wave rectifier with single-wye secondary is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses six semiconductor rectifiers (multiple or stacked units).

Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

Has good regulation characteristics.

Circuit provides either positive- or negative-polarity output voltage.

Uses multiphase power transformer with wye-connected secondary windings; primary windings may be either delta- or wye-connected.

CIRCUIT ANALYSIS.

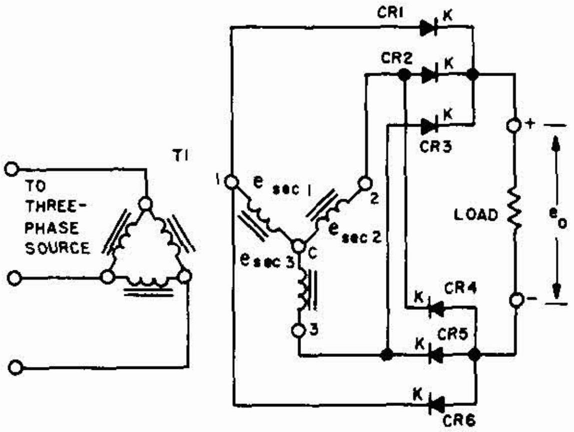
General. The three-phase, full-wave (single-wye secondary) rectifier is extensively used where a large amount of power is required by the load, such as for large shipboard or shore electronic installations. The rectifiers used in this circuit are generally forced-air-cooled or oil-cooled to dissipate heat developed during normal operation.

In many power-supply applications, it is desirable to provide two voltages simultaneously—one voltage for high-power stages and the other voltage for low-power stages. For these applications the three-phase, full-wave rectifier circuit can be modified to supply an additional output voltage, which is equal to one-half the voltage provided by the full-wave rectifier circuit.

Circuit Operation. The basic three-phase, full-wave rectifier circuit is illustrated in the accompanying circuit schematic. The circuit uses a conventional three-phase power transformer, T1, to step up the alternating source voltage to a high value in the wye-connected secondaries. The primary windings of T1 are shown delta-connected, although in some instances the primary windings may be wye-connected (as for a three- or four-wire system).

Semiconductor rectifiers CR1 and CR6 are connected to secondary terminal No. 1 of transformer T1; rectifiers CR2 and CR4 are connected to secondary terminal No. 2; rectifiers CR3 and CR5 are connected to secondary terminal No. 3. The rectifiers are identical-type semiconductor rectifiers. Although the schematic shows only six individual rectifiers in the circuit, each graphic diode symbol represents two or more diodes in series to obtain the necessary peak-inverse characteristics for high-voltage operation.

The circuit arrangement shown in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). Also, a choke-input filter system is commonly used with this circuit; therefore, series, or surge, resistors are not normally used.



Basic Three-Phase, Full-Wave (Single "Y" Secondary) Rectifier Circuit

The operation of the three-phase, full-wave rectifier circuit can be readily understood from a study of the equivalent electron-tube circuit description and the associated waveforms given previously in this section of the handbook. The reference designations used for semiconductor rectifiers CR1 through CR6 correspond directly to the reference designations used in the electron-tube circuit for rectifiers V1 through V6. Since the rectifier action which takes place in both circuits is the same, an explanation of circuit operation is not given here.

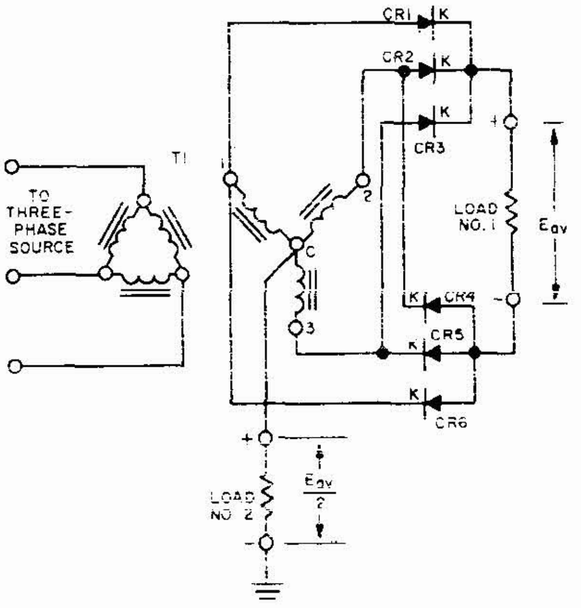
The voltages developed across the secondary windings of transformer T1 are 120 degrees out of phase with relation to each other, and are constantly changing in polarity. At any given instant of time in the three-phase, full-wave rectifier circuit, a rectifier, the load, and a second rectifier are in series across two of the wye-connected transformer secondaries. Each of the six rectifiers conducts for 120 degrees of an electrical cycle; however, there is an overlap of conduction periods, and the rectifiers conduct in a sequence which is determined by the phasing of the instantaneous secondary voltages. In the circuit given here (and in the electron-tube equivalent circuit), two rectifiers are conducting at any instant of time, with rectifier conduction occurring in the following order: CR1 and CR4, CR1 and CR5, CR2 and CR5, CR2 and CR6, CR3 and CR6, CR3 and CR4, CR1 and CR4, etc.

Each positive and negative peak in each of the three phases produces a current pulse in the load. Because of the nature of the rectifier conduction periods, each rectifier conducts for 120 degrees of the cycle, and carries one third of the total load current. The output voltage, e_o, produced across the load resistance is determined by the instantaneous currents flowing through the load; therefore, the output voltage has a pulsating waveform, which results in a ripple voltage, because the output current and voltage are not continuous. The frequency of the ripple voltage is six times the frequency of the a-c source. Since this ripple frequency is higher than the ripple frequency of a single-phase, full-wave rectifier circuit or a three-phase, half-wave rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage.

The peak inverse voltage across an individual rectifier (multiple or stacked units) in the three-phase, full-wave rectifier circuit during the period of time the rectifier is nonconducting is approximately 2.45 times the rms voltage across the secondary winding of one phase.

The regulation of the circuit is considered to be very good, and is better than that of a single-phase rectifier or of a three-phase, half-wave rectifier circuit having equivalent power-output rating. The output of the three-phase, full-wave rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in Part D of this section of the handbook.)

A variation of the three-phase, full-wave rectifier circuit uses the common terminal of the wye-connected secondaries and rectifiers CR4, CR5, and CR6 to form a three-phase, half-wave rectifier circuit. The circuit is fundamentally the same as that discussed earlier; therefore, the reference designations previously assigned to the basic circuit remain unchanged.



Three-Phase, Half-Wave and Three-Phase, Full-Wave Rectifier Circuit

One advantage of this circuit variation is that two voltages may be supplied from the same transformer and rectifier combination. One output voltage (E_{av}) is obtained from the full-wave circuit; the other voltage $\left(\frac{E_{av}}{2}\right)$, which is equal to one-half the full-wave output voltage, is obtained by using rectifiers CR4, CR5, and CR6 and the common terminal of the wye-connected secondaries as a conventional three-phase, half-wave rectifier circuit. Although this circuit can supply two output voltages simultaneously to two separate loads, there is a limitation on the total current which can be safely carried by the rectifiers (CR4, CR5, and CR6).

FAILURE ANALYSIS.

No Output. In the three-phase, full-wave rectifier circuit, the no-output condition is likely to be limited to one of three possible causes: the lack of applied a-c voltage, a shorted load circuit (including shorted filter capacitors), or an open filter choke.

NOTE

> Most filter circuits used in Navy equipment employ two-section choke-input filters; thus, an open choke in either section will cause no output.

Measure the applied three-phase primary voltage to determine whether it is present and of the correct value. With the primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings, to determine whether one or more than one winding is open and whether the common terminal(s) of the wye-connected secondaries is connected to the load circuit. If necessary, the a-c secondary voltage applied to the rectifiers may be measured between the common terminal(s) of the wye-connected secondaries and one or more rectifiers to determine whether voltage is present and of the correct value.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. (An open choke in the filter circuit will also cause no output. See note above.) A short in the load circuit (including components in the filter circuit) will cause an excessive load current to flow and may result in permanent damage to the rectifiers. Therefore, once the difficulty in the load (including filter) circuit has been located and corrected, the rectifiers should be checked to determine whether they have been *damaged as a result of the overload condition.*

Low Output. Failure of only one rectifier to conduct will cause a loss of current delivered to the load for approximately 120 degrees of the electrical cycle, and the output voltage will be reduced accordingly. (Also, breakdown of a rectifier will cause a shorting effect upon the windings of the transformer and subject other rectifiers to overload.) Furthermore, when one rectifier fails to conduct, the ripple *amplitude will increase.* Therefore, each rectifier should be checked to determine whether the low output is due to normal rectifier aging, or to one or more defective rectifiers. A relative check of rectifier condition can be made by using an ohmmeter, as *outlined in a previous paragraph* of this section. A comparison can be made by checking one rectifier against each of the others to determine whether the rectifiers have similar characteristics. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease, and the amplitude of the ripple voltage will increase.

The load current should be checked to make sure that it is not excessive, because a decrease in output voltage can be caused by an increase in load current (decrease in load resistance); for example, excessive leakage in the capacitors of the filter circuit will result in increased load current. Also, the a-c secondary voltage and the input (primary) voltage should be measured at the terminals of the transformer to determine whether these voltages are of the correct value. If necessary, and with the primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings, to determine whether one (or more) of the windings is open.

Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. (A check for shorted turns is outlined in the failure analysis described for the electron-tube equivalent circuit given earlier in this section of the handbook.) Once it has been determined that the load circuit (including filter components) is satisfactory, a procedure which can be used to quickly determine whether the rectifiers are at fault is to substitute known good rectifiers in the circuit and measure the output voltage under normal load conditions.

In the modified three-phase, half-wave and three-phase, full-wave rectifier circuit, it is possible to have two definite conditions of low voltage caused by one or more defective rectifiers; the output voltage (E_{av}) to load No. 1 can be low and the output voltage $\frac{(E_{av})}{2}$ to load No. 2 normal, or both output voltages can be below normal. If the load currents are not excessive and the filter components have been checked as satisfactory, the defective rectifier(s) in the first case is assumed to be CR1, CR2, or CR3, and in the second case, CR4, CR5, or CR6. When the modified circuit is used, rectifiers CR4, CR5, and CR6 will usually have higher current ratings than the other rectifiers (CR1, CR2, and CR3) because of the requirement to handle the combined currents of both output loads.

THREE-PHASE, FULL-WAVE (DELTA SECONDARY) RECTIFIER.

APPLICATION.

The three-phase, full-wave rectifier with delta secondary is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either negative or positive high-voltage output to the load.

CHARACTERISTICS.

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses six semiconductor rectifiers (multiple or stacked units).

Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

Has good regulation characteristics.

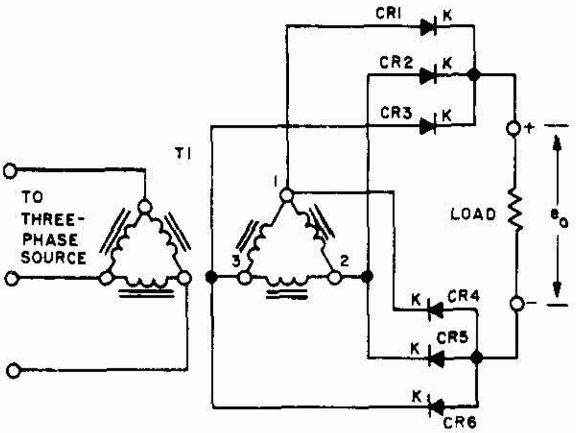
Circuit provides either positive- or negative-polarity output voltage.

Uses multiphase power transformer with delta-connected secondary windings; primary windings may be either delta- or wye-connected.

CIRCUIT ANALYSIS.

General. The three-phase, full-wave (delta secondary) rectifier is a variation of the three-phase, full-wave (single-wye-connected secondary) rectifier, previously described in this section. The full-wave rectifier with delta secondary is used where a large amount of power is required by the load, such as for large shipboard or shore electronic installations. The semiconductor rectifiers used in this circuit are generally forced-air-cooled or oil-cooled to dissipate heat developed during normal operation. Because of the three-phase, delta primary and secondary connections, the circuit is sometimes referred to as a full-wave **delta-delta** rectifier circuit. When the primary windings only are wye-connected, the circuit is sometimes referred to as a full-wave **wye-delta** rectifier circuit.

Circuit Operation. The three-phase, full-wave (delta secondary) rectifier circuit is illustrated in the accompanying circuit schematic. The circuit uses a three-phase power transformer, T1, to step up the alternating source voltage to a high value in the delta-connected secondaries. Each secondary winding is connected to the other in proper phase relationship so that the currents through the windings are balanced. Damage can result to the transformer windings if they are improperly connected; for this reason, the windings are usually connected internally in the proper phase to prevent the possibility of making wrong connections, and only three secondary terminals are brought out of the transformer case.



Basic Three-Phase, Full-Wave (Delta Secondary) Rectifier Circuit

The primary windings of transformer T1 are shown delta-connected, although in some instances they may be wye-connected (as for a three- or four-wire system).

Semiconductor rectifiers CR1 and CR4 are connected to secondary terminal No. 1 of transformer T1; rectifiers CR2 and CR5 are connected to secondary terminal No. 2; rectifiers CR3 and CR6 are connected to secondary terminal No. 3. The rectifiers are identical-type semiconductor rectifiers. Although the schematic shows only six individual rectifiers in the circuit, each graphic symbol represents two or more diodes in series to obtain the necessary peak-inverse characteristics for high-voltage operation.

The circuit arrangement shown in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). Also, a choke-input filter system is commonly used with this circuit.

The operation of the three-phase, full-wave (delta secondary) rectifier circuit can be readily understood from a study of the equivalent electron-tube circuit description and the associated waveforms given previously in this section of the handbook. The reference designations used for the semiconductor rectifiers CR1 through CR6 correspond directly to the reference designations used in the electron-tube circuit for rectifiers V1 through V6. Since the rectifier action which takes place in both circuits is the same, an explanation of circuit operation is not given here.

The operation of the delta-secondary rectifier circuit is similar to that of the wye-secondary rectifier circuit (previously described); however, the a-c voltage across an individual delta-connected secondary winding is approximately 1.73 times greater than the voltage across an individual wye-connected secondary winding for equal d-c output voltages from the two circuits. The voltages developed across the secondary windings of transformer T1 are 120 degrees out of phase with relation to one another, and are constantly changing in polarity. In the delta-connected secondary, at any given instant the voltage in one phase is equal to the vector sum of the voltages in the other two phases. At any given instant of time in the three-phase, full-wave rectifier circuit, a rectifier, the load, and a second rectifier are in series across two terminals of the delta-connected secondaries. Each of the six rectifiers conducts for 120 degrees of an electrical cycle; however, there is an overlap of conduction periods, and the rectifiers conduct in a sequence which is determined by the phasing of the instantaneous secondary voltages of the power transformer. In the circuit given here (and in the electron-tube equivalent circuit), two rectifiers are conducting at any instant of time, with rectifier conduction occurring in the following order: CR1 and CR6, CR6 and CR2, CR2 and CR4, CR4 and CR3, CR3 and CR5, CR5 and CR1, CR1 and CR6, etc.

Each positive and negative peak in each of the three phases produces a current pulse in the load. Because of the nature of the rectifier conduction periods, each rectifier conducts for 120 degrees of the cycle, and carries one third of the total load current. The output voltage, e_o, produced across the load resistance is determined by the instantaneous current flowing through the load; therefore, the output voltage has a pulsating waveform, which results in a ripple voltage, because the output current and voltage are not continuous. The frequency of the ripple voltage is six times the frequency of the a-c source. Since this ripple frequency is higher than the ripple frequency of a single-phase, full-wave rectifier circuit or a three-phase, half-wave rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage.

The peak inverse voltage across an individual rectifier (multiple or stacked units) in the three-phase, full-wave (delta secondary) rectifier circuit during the period of time the rectifier is nonconducting is approximately 1.42 times the rms voltage across the secondary winding of one phase.

The regulation of the circuit is considered to be very good, and is better than that of a single-phase rectifier or of a three-phase, half-wave rectifier circuit having equivalent power-output rating. The output of the three-phase, full wave rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in Part D of this section of the handbook.)

FAILURE ANALYSIS.

No Output. In the three-phase, full-wave (delta secondary) rectifier circuit, the no-output condition is likely to be limited to one of three possible causes: the lack of applied a-c voltage, a shorted load circuit (including shorted filter capacitors), or an open filter choke.

NOTE

> Most filter circuits used in Navy equipment employ two-section choke-input filters; thus, an open choke in either section will cause no output.

With the primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings to determine whether one or more than one winding is open. Since the three windings of the delta-secondary circuit are sometimes connected internally and only three terminals are brought out of the case, voltage and resistance measurements are made between the terminals of the delta-connected secondaries. When making measurements (voltage or resistance) of the secondary circuit, it should be remembered that the windings form a delta configuration, with two windings in series, and this combination in parallel with the winding under measurement. In other instances, the secondary windings are connected to six individual terminals, and these terminals are connected together to form a delta configuration. Thus, in this instance, the terminal connections may be removed to enable measurements to be made on individual secondary windings, independent of other windings. If necessary, the a-c voltage at each of the three high-voltage secondaries may be measured between the terminals of the delta-connected secondaries, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage to determine whether it is present and of the correct value.

With the primary voltage removed from the circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. (As explained in the preceding note, an open choke in the filter circuit will also cause no output.) A short in the components of the load circuit (including filter circuit) will cause an excess sive load current to flow and may result in permanent damage to the rectifiers. Therefore, once the difficulty in the load (including filter) circuit has been located and corrected, the rectifiers should be checked to determine whether they have been damaged as a result of the overload condition.

Low Output. Except for the voltage and resistance measurements of the delta-secondary circuit, the checks for a low-output condition are essentially the same as those given for the three-phase, full-wave (single "Y" secondary) rectifier circuit, previously discussed in this section. Also, refer to the paragraph above for information concerning procedures to be used when making voltage and resistance measurements on delta-connected secondary windings.

THREE-PHASE, HALF-WAVE (DOUBLE "Y" SECONDARY) RECTIFIER.

APPLICATION.

The three-phase, half-wave rectifier with double-wye secondary and interphase reactor is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either negative or positive high-voltage output to the load.

CHARACTERISTICS

Input to circuit is three-phase ac; output is dc with amplitude of ripple voltage less than that for a single-phase rectifier.

Uses six semiconductor rectifiers (multiple or stacked units).

Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

Has good regulation characteristics.

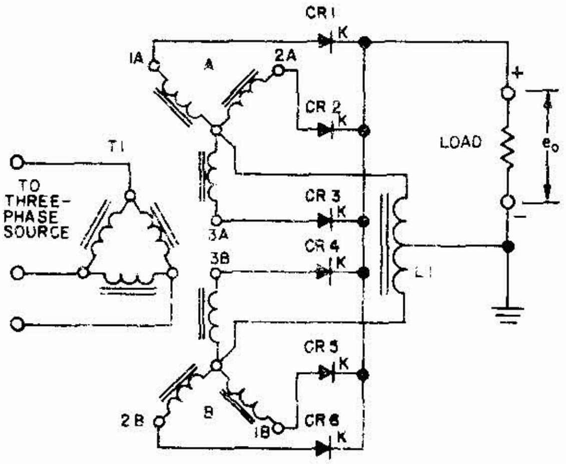
Circuit provides either positive- or negative-polarity output voltage.

Uses multiphase power transformer with two parallel sets of wye-connected secondaries operating 180 degrees out of phase with each other. The center points of the wye-connected secondaries are connected through an interphase reactor or balance coil to the load. The primary windings are generally delta-connected.

CIRCUIT ANALYSIS.

General. Fundamentally, this rectifier circuit resembles two half-wave (three-phase star) rectifiers in parallel, each rectifier circuit operating from a common delta-connected primary, and sharing a common load through an interphase reactor or balance coil. (The three-phase, half-wave rectifier circuit was previously described in this section.) The three-phase, half-wave (double-wye secondary) rectifier circuit uses a power transformer with two sets of wye-connected secondaries, the winding of one set being connected 180 degrees out of phase with respect to the corresponding windings of the other set. For this reason, the circuit is sometimes referred to as a **six-phase, half-wave** or a **delta-double-wye with balance coil** rectifier circuit. The junction point of each wye-connected secondary is, in turn, connected to a center-tapped inductance, called an **interphase reactor** or **balance coil**. The center tap of the interphase reactor is the common output terminal for the load.

Circuit Operation. The three-phase, half-wave (double-wye secondary) rectifier circuit is illustrated in the accompanying schematic. The circuit uses a three-phase power transformer, T1, to step up the alternating source voltage to a high value in the wye-connected secondaries. The primary windings of the transformer are shown delta-connected; the delta primary is common to both wye-connected secondaries.



Basic Three-Phase, Half-Wave (Double "Y" Secondary) Rectifier Circuit

Semiconductor rectifiers CR1, CR2, and CR3 are connected to secondary terminals 1A, 2A, and 3A, respectively. Rectifiers CR4, CR5, and CR6 are connected to secondary terminals 3B, 1B, and 2B, respectively. The rectifiers are identical-type semiconductor rectifiers. Although the schematic shows only six individual rectifiers in the circuit, each graphic symbol represents two or more diodes in series to obtain the necessary peak-inverse characteristics for high-voltage operation.

The center-tapped inductance, L1, is an interphase reactor or balance coil. The common terminal of each wye-connected secondary is connected to one end of L1; the center tap of the interphase reactor is connected to the load. Thus, the output-load current of each three-phase, half-wave rectifier circuit passes through one half of the interphase reactor, and these two currents are then combined in the load. For satisfactory operation, interphase reactor L1 must have sufficient inductance to maintain continuous current flow through each half of the coil. In effect, this reactor constitutes a choke-input filter arrangement, and exhibits the regulation characteristics of such a filter.

The circuit arrangement shown in the illustration permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). It is good design practice for the d-c output terminal associated with the center tap of the inductance, L1, to be grounded; therefore, the secondary-to-core insulation of transformer T1 need not be as great as it would be if the secondary windings were above ground by the amount of the d-c output voltage. When a negative high-voltage d-c supply is required, it is common practice to keep the center tap of inductor L1 at ground (chassis) potential and to reverse the rectifiers (CR1 through CR6); thus, the output polarity across the load will be opposite that shown in the schematic.

The operation of the three-phase, half-wave (double-wye secondary) rectifier circuit can be readily understood from a study of the equivalent electron-tube circuit description and the associated waveforms given previously in this section of the handbook. The reference designations used for semiconductor rectifiers CR1 through CR6 correspond directly to the reference designations used in the electron-tube circuit for rectifiers V1 through V6. Since the rectifier action which takes place in both circuits is the same, an explanation of circuit operation is not given here.

The operation of each half-wave rectifier circuit associated with a three-phase secondary ("A" or "B") is the same as that given for the three-phase, half-wave (three-phase star) rectifier circuit previously described in this section. Although the voltages induced in the three secondary windings differ in phase by 120 degrees, the voltages induced in corresponding windings of the two sets of wye-connected secondaries ("A" and "B") are 180 degrees out of phase with respect to each other.

At any instant of time, two rectifiers are conducting to deliver current to the load, but their currents are not in phase and an overlap in conduction periods of the six rectifiers occurs. Each rectifier conducts for 120 degrees of the input cycle and contributes one sixth of the total current supplied to the load. In this circuit, two rectifiers are conducting at any instant of time, with the rectifier conduction periods occurring in the following order: CR1 and CR4, CR4 and CR2, CR2 and CR5, CR5 and CR3, CR3 and CR6, CR6 and CR1, CR1 and CR4, etc.

The main component of the ripple frequency present across the interphase reactor (L1) is three times the frequency of the a-c source. Electrons flow through the load in pulses, one pulse for each positive half-cycle of the impressed voltage in each of the three phases of the two sets of secondaries. As mentioned previously, the secondaries are 180 degrees out of phase with respect to each other; therefore, the output voltage has a ripple frequency which is six times the frequency of the a-c source. Since this ripple frequency is higher that that of a single-phase, full-wave rectifier circuit or a three-phase, half-wave (three-phase star) rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage.

The peak inverse voltage across a rectifier (multiple or stacked units) in a secondary leg of the three-phase, half-wave (double-wye secondary) rectifier circuit during the period of time the rectifier is non-conducting is approximately 2.45 times the rms voltage across the secondary winding of one phase.

The regulation of the circuit is considered to be very good, and is better than that of a single-phase rectifier or of a three-phase, half-wave (three-phase star) rectifier circuit having equivalent power-output rating. The output of the three-phase, half-wave (double-wye secondary) rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. (Filter circuits are discussed in Part D of this section of the handbook.)

FAILURE ANALYSIS.

No Output. In the three-phase, half-wave (double-wye secondary) rectifier circuit, the no-output condition is likely to be limited to one of three possible causes: the lack of applied a-c voltage, a shorted load circuit (including shorted filter capacitors), or an open input choke

NOTE

Most filter circuits used in Navy equipment employ two-section choke-input filters; thus, an open choke in either section will cause no output.

With the primary voltage removed from the circuit, continuity measurements should be made of the secondary and primary windings, to determine whether one or more than one winding is open, and whether the common terminals of the wye-connected secondaries are connected to the load circuit through the interphase reactor or balance coil. If necessary, the a-c secondary voltage may be measured at one (or more) of the high-voltage secondaries (between the common terminal of the wye-connected secondaries and one or more rectifiers), to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage to determine whether it is present and of the correct value.

With primary voltage removed from the rectifier circuit, resistance measurements can be made at the output terminals of the rectifier circuit (across load) to determine whether the load circuit, including the filter, is shorted. A short in the components of the load circuit (including filter circuit) will cause an excessive load current to flow, and considerable output voltage will be developed across each half of the interphase reactor, L1. If an open should develop in both halves or in the center-tap lead of the interphase reactor, no output will be developed. Likewise, an open choke in the filter circuit will cause no output. (See note above.) An excessive load current caused by shorted components in the circuit may result in permanent damage to the rectifiers. Therefore, once the difficulty in the load (including filter) circuit has been located and corrected, the rectifiers should be checked to determine whether they have been damaged as a result of the overload condition.

Low Output. An open circuit in one half of the interphase reactor will disconnect its associated three-phase, wye-connected secondary; the output voltage will decrease as a result, and the rectifier circuit will continue to operate as a three-phase, half-wave rectifier with single-wye secondary. Therefore, the continuity of each half of the interphase reactor (L1) should be checked to determine whether one half of the winding is open.

With the three-phase primary voltage removed from the circuit, continuity measurements should be made of the

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primary and secondary windings, to determine whether one (or more) of the windings is open. If necessary, the a-c voltage of each secondary winding in each set of secondaries may be measured between the common terminal of the wye connection and the individual secondary terminal of the corresponding rectifier, to determine whether voltage is present and of the correct value. Also, if necessary, measure the applied three-phase primary voltage at each phase, to determine whether voltage is present and of the correct value, since a low applied primary voltage can result in a low secondary voltage.

Shorted turns in either the primary or secondary windings will cause the secondary voltage to measure below normal. (A check for shorted turns is outlined in the failure analysis described for the electron-tube equivalent circuit given earlier in this section of the handbook.)

The load current should be checked to make sure that it is not excessive, because a decrease in output voltage can be caused by an increase in load current (decrease in load resistance); for example, excessive leakage in the capacitors of the filter circuit will result in increased load current.

Failure of a rectifier to conduct will cause a loss of current delivered to the load, and the output voltage will be reduced accordingly. Therefore, each rectifier should be checked to determine whether the low output is due to normal rectifier aging, or to one or more defective rectifiers. A relative check of rectifier condition can be made by using an ohmmeter, as outlined in a previous paragraph of this section. A comparison can be made by checking one rectifier against each of the others to determine whether the rectifiers have similar characteristics. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease and the amplitude of the ripple voltage will also increase. Once it has been determined that the load circuit (including filter components) is satisfactory, a procedure which can be used to quickly determine whether the rectifiers are at fault is to substitute known good rectifiers in the circuit and measure the output voltage under normal load conditions.

HALF-WAVE VOLTAGE DOUBLER.

APPLICATION.

The half-wave voltage-doubler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional half-wave rectifier circuit. This voltage doubler is normally used in "transformerless" circuits where the load current is small and voltage regulation is not critical. The circuit is frequently employed as the plate voltage supply in small portable receivers and audio amplifiers and, in some equipment applications, as a bias supply.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-C output voltage is approximately twice that obtained from half-wave rectifier circuit; output current is relatively small.

Output requires filtering; d-c output ripple frequency is equal to a-c source frequency.

Has poor regulation characteristics; output voltage available is a function of load current.

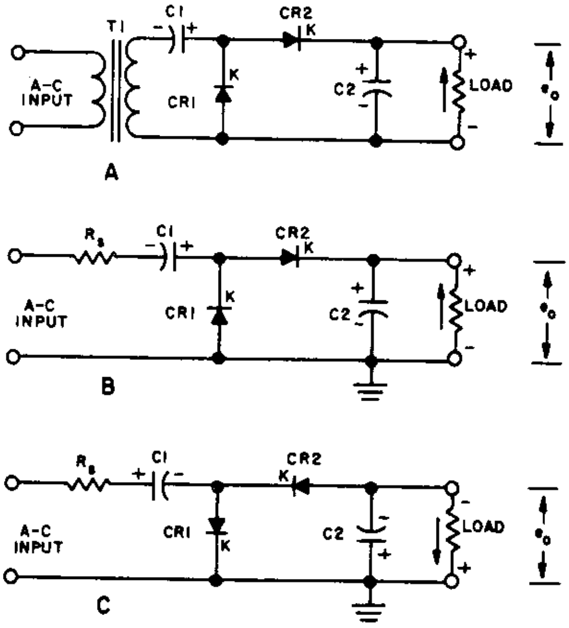
Uses two semiconductor rectifiers (single, multiple or stacked units).

Depending upon circuit application, may be used with or without a power or isolation transformer.

CIRCUIT ANALYSIS.

General. The half-wave voltage-doubler circuit is used with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage doubler** implies, the output voltage is approximately twice the input voltage. The half-wave voltage doubler derives its name from the fact that the output charging capacitor (C2) across the load receives a charge once for each complete cycle of the applied voltage. The half-wave voltage doubler is sometimes called a **cascade** voltage doubler. The voltage regulation of the circuit is poor, and, therefore, its use is generally restricted to applications in which the load current is small and relatively constant.

Circuit Operation. In the accompanying circuit schematics, parts A, B, and C illustrate basic half-wave voltage-doubler circuits. The circuit shown in part A uses a transformer, T1, which can be either a step-up transformer to obtain a high value of voltage in the secondary circuit, or an isolation transformer. The circuits shown in parts B and C do not use a transformer, and operate directly from the a-c source. In the circuit illustrated in part A, the use of transformer T1 permits either output terminal to be placed at ground (chassis) potential. The circuit illustrated in part B places one side of the a-c source at a negative d-c potential, and thus restricts the circuit to use as a positive



Basic Half-Wave Voltage-Doubler Circuits d-c supply. A variation of this circuit is illustrated in part C; this variation provides a negative output voltage.

The rectifiers, CR1 and CR2, are identical-type semiconductor diodes. In the three circuits illustrated, the functions of rectifiers CR1 and CR2, and of charging capacitors C1 and C2, are the same for each of the circuits. Electrons flow through the load in the direction indicated by the arrow adjacent to the load resistance. The d-c output polarity for each circuit is indicated by the signs associated with the load resistance.

The circuits shown in parts B and C have a resistor, Rs, in series with the a-c source. This resistor, called the **surge resistor**, limits the peak current through each rectifier to a safe value. The value of resistor Rs is influenced by the circuit design; determination of its value includes the consideration of several other factors, such as the applied a-c voltage, the resistance of the load circuit, the capacitance value of the charging capacitors, and the peak current rating of the semiconductor diodes. In the circuit shown in part A, the resistor has been omitted since there is normally sufficient resistance in the secondary winding of transformer T1 to limit the peak current through each rectifier; however, some circuits may include a resistor (Rs) between the charging capacitor (C1) and the transformer secondary winding.

The operation of the half-wave voltage-doubler circuit can be readily understood from a study of the equivalent electron-tube circuit description, simplified circuits, and associated waveforms given previously in this section of the handbook. The action of the semiconductor rectifiers in this voltage-doubler circuit is essentially the same as that described for the equivalent electron-tube circuit. Semiconductor rectifiers CR1 and CR2 correspond directly to rectifiers V1 and V2 in the electron-tube circuit description. For these reasons, an explanation of circuit operation is not given here.

Charging capacitor C2 is charged only on alternate half-cycles of the applied a-c voltage, and is always attempting to discharge through the load resistance; therefore, the output voltage, e_o, contains some voltage variation, or ripple. The frequency of the ripple voltage is the same as the frequency of the a-c source, because capacitor C2 is charged only once for each complete input cycle: thus, additional filtering is necessary to obtain a steady d-c voltage. (Filter circuits are discussed in Part D of this section of the handbook.)

The regulation of the voltage-doubler circuit is relatively poor; the value of output voltage obtained is determined largely by the resistance of the load and the resulting load circuit, since the load (and the filter circuit, if used) is in parallel with capacitor C2.

FAILURE ANALYSIS.

No Output. In the half-wave voltage-doubler circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of a defective transformer or an open surge resistor Rs), an open capacitor C1, a shorted load circuit (including capacitor C2 and filter circuit capacitor), an open filter choke, or defective rectifiers.

The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is present and is the correct value. If the circuit uses a step-up or isolation transformer (T1), measure the voltage at the secondary terminals to determine whether it is present and is the correct value. With the primary voltage removed from the transformer, continuity measurements of the primary and secondary windings should be made to determine whether one of the windings is open, since an open circuit in either winding will cause a lack of secondary voltage.

If the circuit includes a surge resistor (Rs), a resistance measurement can be made to determine whether the resistor is open. If the resistor is found to be open, the voltage-doubler and load circuit should be checked further to determine whether excessive load current, a defective rectifier, or a shorted capacitor has caused the resistor to act as a fuse and to open.

With the a-c supply voltage removed from the input to the circuit and with the load disconnected from capacitor C2, resistance measurements can be made across the terminals of capacitor C2 and at the output terminals of the circuit (across the load). These measurements will determine whether capacitor C2 or the load circuit (including filter components) is shorted. Because capacitor C2 and the filter-circuit capacitors are electrolytic capacitors, the resistance measurements may vary, depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the circuit test points for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value. Capacitor C1 may be checked in a similar manner.

A quick method which can be used to determine whether capacitor C1 or C2 is the source of trouble is to substitute a known good capacitor in the circuit for the suspected capacitor, and then measure the resulting output voltage.

The rectifiers should be checked to determine whether they are open or otherwise defective. A relative check of the rectifier condition can be made by use of an ohmmeter, as outlined in a previous paragraph of this section. However, failure of one or both rectifiers may be the result of other causes; therefore, tests of the filter and load circuit are necessary. Once it is determined that the filter components and load circuit are satisfactory, a procedure which can be used to quickly determine whether the rectifiers are defective is to substitute known good rectifiers in the circuit and measure the output voltage.

Low Output. The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is the correct value, since a low applied voltage can result in a low output voltage.

Each rectifier should be checked to determine whether the low output is due to normal rectifier aging. A relative check of rectifier condition can be made by use of an ohmmeter, as outlined in a previous paragraph of this section. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease, and the amplitude of the ripple voltage will increase.

The load current should be checked to make sure that it is not excessive, because the voltage doubler circuit has poor regulation and an increase in load current (decrease in load resistance) can cause a decrease in output voltage.

One terminal of each charging capacitor, C1 and C2, should be disconnected from the circuit and each capacitor checked, using a capacitance analyzer, to determine the effective capacitance and leakage resistance of each capacitor. A decrease in effective capacitance or losses within either capacitor can cause the output of the voltage-doubler circuit to be below normal, since the defective capacitor will not charge to its normal operating value. If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by use of an ohmmeter; the measurements are made with one terminal of the capacitor disconnected from the circuit. Using the ohmmeter procedure outlined in a previous paragraph for the no-output condition, two measurements are made (with the test leads reversed at the capacitor terminals for one of the measurements). The larger of the two measurements should be greater than 1 megohm for a satisfactory capacitor. A procedure which can be used to quickly determine whether the capacitors are the cause of low output is to substitute known good capacitors in the circuit and measure the resulting output voltage under normal load conditions.

FULL-WAVE VOLTAGE DOUBLER.

APPLICATION.

The full-wave voltage-doubler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional rectifier circuit utilizing the same input voltage. This voltage doubler is normally used where the load current is small and voltage regulation is not too critical; however, the regulation of the full-wave voltage doubler is better than that of the half-wave voltage doubler. The circuit is frequently employed as the power supply in small portable receivers and audio amplifiers and, in some equipment applications, as a bias supply.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-c output voltage is approximately twice that obtained from half-wave rectifier circuit; output current is relatively small.

Output requires filtering; d-c output ripple frequency is equal to twice the a-c source frequency.

Has relatively poor regulation characteristics; output voltage available is a function of load current.

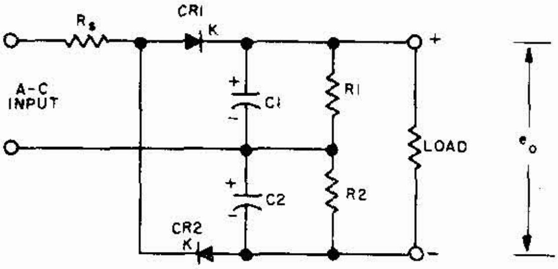
Uses two semiconductor rectifiers (single, multiple, or stacked units).

Depending upon circuit application, may be used with or without a power or isolation transformer.

CIRCUIT ANALYSIS.

General. The full-wave voltage-doubler circuit is used either with or without a transformer to obtain a d-c voltage from a-c source. As the term **voltage doubler** implies, the output voltage is approximately twice the input voltage. The full-wave voltage doubler derives its name from the fact that the charging capacitors (C1 and C2) are in series across the load, and each capacitor receives a charge on alternate half-cycles of the applied voltage; therefore, two pulses are present in the load circuit for each complete cycle of the applied voltage. Although the voltage regulation of the full-wave voltage doubler is better than that of the half-wave voltage doubler, it is nevertheless considered poor as compared with conventional rectifier circuits. Therefore, use of the circuit is generally restricted to applications in which the load current is small and relatively constant.

Circuit Operation. A basic full-wave voltage-doubler circuit is shown in the accompanying circuit schematic. Fundamentally, the circuit consists of two half-wave rectifiers, CR1 and CR2, and two charging capacitors, C1 and C2, arranged so that each capacitor receives a charge on alternate half-cycles of the applied voltage. The voltage developed across one capacitor is in series with the voltage developed across the other; thus, the output voltage developed across the load resistance is approximately twice the applied voltage.



Basic Full-Wave Voltage-Doubler Circuit

The rectifiers, CR1 and CR2, are identical-type semiconductor diodes, and the charging capacitors, C1 and C2, are of equal value. Equalizing resistors R1 and R2 are connected across charging capacitors C1 and C2, respectively; they are of equal value and are generally greater than 2 megohms. Resistors R1 and R2 are not necessary for circuit operation; however, when included in the circuit, they have a dual purpose in that they tend to equalize the voltages across the charging capacitors and also act as bleeder resistors to discharge the associated capacitors when the circuit is de-energized. When capacitors C1 and C2 are large, the peak charge current, during the period of time the rectifier conducts, may be excessive. To limit the charge current and offer protection to the rectifiers, a protective "surge" resistor, Rs, is placed in series with the a-c source; however, if a transformer is used and if there is sufficient resistance in the secondary winding, the series resistor is usually omitted.

One disadvantage of the full-wave voltage-doubler circuit is that neither d-c output terminal can be directly connected to ground or to one side of the a-c source; however, when a step-up or isolation transformer is used to supply the input to the voltage doubler, either output terminal may be connected to ground or to the chassis.

The operation of the full-wave voltage-doubler circuit can be readily understood from a study of the equivalent electron-tube circuit description, simplified circuits, and associated waveforms given previously in this section of the handbook. The action of the semiconductor rectifiers in this voltage-doubler circuit is essentially the same as that described for the equivalent electron-tube circuit. Semiconductor rectifiers CR1 and CR2 correspond directly to rectifiers V1 and V2 in the electron-tube circuit description. For these reasons, an explanation of circuit operation is not given here.

Charging capacitors C1 and C2 are connected in series across the load resistance, and each capacitor receives a charge on alternate half-cycles of the applied voltage; therefore, the output voltage, e_o, contains some voltage variations, or ripple. The frequency of the main component of the ripple voltage is equal to twice the frequency of the a-c source and, therefore, additional filtering is required to obtain a steady d-c voltage. (Filter circuits are discussed in Part D of this section of the handbook.)

The regulation of the voltage-doubler circuit is relatively poor; the value of the output voltage obtained is determined largely by the resistance of the load and the resulting load current. If the load current is large, the voltage across capacitors C1 and C2 is reduced accordingly.

FAILURE ANALYSIS.

No Output. In the full-wave voltage-doubler circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of a defective transformer or an open surge resistors Rs), a shorted load circuit (including filter circuit capacitor), an open filter choke, or defective rectifiers.

The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is present and is the correct value. If the circuit uses a step-up or isolation transformer, measure the voltage at the secondary terminals to determine whether it is present and is the correct value. With the primary voltage removed from the transformer, continuity measurements of the primary and secondary windings should be made to determine whether one of the windings is open, since an open circuit in either winding will cause a lack of secondary voltage.

If the circuit includes a surge resistor (Rs), a resistance measurement can be made to determine whether the resistor is open. If the resistor is found to be open, the voltage-doubler and load circuit should be checked further to determine whether excessive load current, a defective rectifier, or a shorted capacitor has caused the resistor to act as a fuse and to open.

With the a-c supply voltage removed from the input to the circuit and with the load (including filter circuit) disconnected from capacitor C1, resistance measurements can be made across the load to determine whether the load circuit (including filter components) is shorted. Measurements should be made across the terminals of charging capacitors C1 and C2 to determine whether one or both capacitors are shorted. (If the circuit includes equalizing resistors R1 and R2, the resistance measured across a capacitor will normally measure something less than the value of the equalizing resistor.) Because C1 and C2 are electrolytic capacitors, the resistance measurements may vary, depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the capacitor terminals for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value.

A quick method which can be used to determine whether capacitors C1 and C2 are the source of trouble is to substitute known good capacitors in the circuit, and then measure the resulting output voltage.

The rectifiers should be checked to determine whether they are open or otherwise defective. A relative check of the rectifier condition can be made by use of an ohmmeter, as outlined in a previous paragraph of this section. However, failure of the rectifiers may be the result of other causes; therefore, tests of the filter and load circuit are necessary. Once it is determined that the filter components and load circuit are satisfactory, a procedure which can be used to quickly determine whether the rectifiers are defective is to substitute known good rectifiers in the circuit and measure the output voltage.

Low Output. The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is the correct value, since a low applied voltage can result in a low output voltage.

Each rectifier should be checked to determine whether the low output is due to normal rectifier aging. A relative check of rectifier condition can be made by use of an ohmmeter, as outlined in a previous paragraph of this section. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease, and the amplitude of the ripple voltage will increase.

The load current should be checked to make sure that it is not excessive, because the voltage-doubler circuit has poor regulation and an increase in load current (decrease in load resistance) can cause a decrease in output voltage.

One terminal of each charging capacitor, C1 and C2, should be disconnected from the circuit and each capacitor checked, using a capacitance analyzer, to determine the effective capacitance and leakage resistance of each capacitor. A decrease in effective capacitance or losses within either capacitor can cause the output of the voltage-doubler circuit to be below normal, since the defective capacitor will not charge to its normal operating value. If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter; the measurements are made with one terminal of the capacitor disconnected from the circuit and, using the ohmmeter procedure outlined in a previous paragraph for the no-output condition, two measurements are made (with the test leads reversed at the capacitor terminals for one of the measurements). The larger of the two measurements should be greater than 1 megohm for a satisfactory capacitor. A procedure which can be used to quickly determine whether the capacitors are the cause of low output is to substitute known good capacitors in the circuit and measure the resulting output voltage under normal load conditions.

VOLTAGE TRIPLER.

APPLICATION.

The voltage-tripler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional rectifier circuit utilizing the same input voltage. It is normally used in "transformerless" circuits where the load current is small and voltage regulation is not critical.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-c output voltage is approximately three times the voltage obtained from basic half-wave rectifier circuit utilizing the same input voltage; output current is relatively small.

Output requires filtering; d-c output ripple frequency is either twice or equal to a-c source frequency, depending upon tripler circuit arrangement.

Has poor regulation characteristics; output voltage available is a function of load current.

Uses three semiconductor rectifiers (single, multiple, or stacked units).

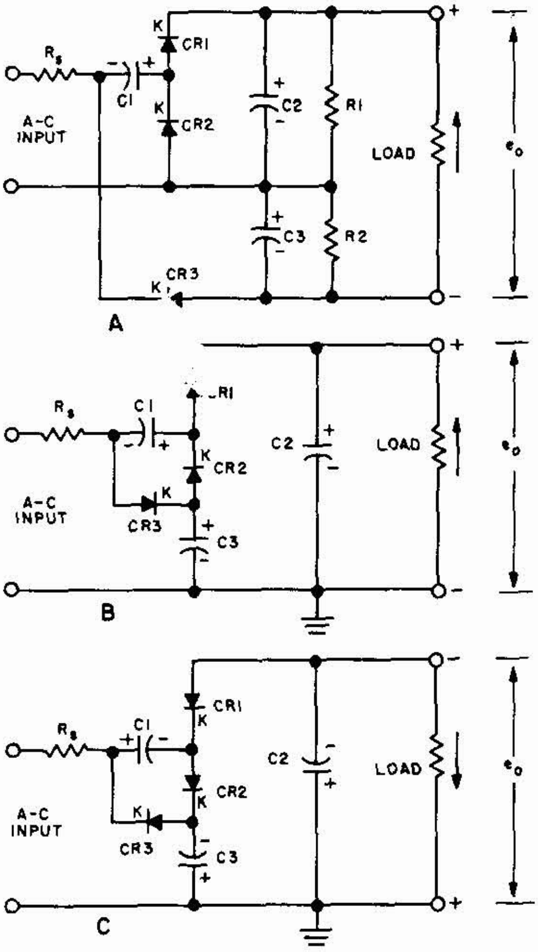
Depending upon circuit application, may be used with or without a power or isolation transformer.

CIRCUIT ANALYSIS.

General. The voltage-tripler circuit is used with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage tripler** implies, the output voltage is approximately three times the input voltage. The voltage regulation of the voltage tripler is relatively poor as compared with the regulation of either the half-wave or the full-wave voltage-doubler circuit. Assuming that a given voltage-multiplier (doubler, tripler, or quadrupler) circuit uses the same value of capacitors in each instance, the greater the voltage-multiplication factor of the circuit, the poorer the regulation characteristics. However, the regulation characteristics can be improved somewhat by increasing the value of the individual capacitors used in the voltage-multipler circuit. Because of the regulation characteristics of the voltage tripler, the use of the circuit is generally restricted to applications in which the load current is small and relatively constant.

Circuit Operation. Three voltage-tripler circuits are shown in the accompanying illustration. The schematic of part A shows a basic voltage-tripler circuit, which is fundamentally a half-wave voltage-doubler and a half-wave rectifier arranged so that the output voltage of one circuit is in series with the output voltage of the other. The schematic of part B shows a modified tripler circuit arranged for positive output, with the negative output terminal common to one side of the a-c source; part C shows this same circuit arranged for negative output, with the positive terminal common to one side of the a-c source. In each of the voltage-tripler circuits shown in the accompanying illustration, the total output voltage developed across the load resistance is approximately three times the applied voltage.

The rectifiers, CR1, CR2, and CR3, are identical-type semiconductor diodes in each of the three circuits illustrated. Charging capacitors C1, C2, and C3 are of equal capacitance value in each of the three circuits; however, because of the higher voltage developed across capacitor C2, the voltage rating of C2 is always greater than the voltage rating of either C1 or C3. Resistors R1 and R2, shown in the circuit of part A, are not necessary for circuit operation; however, when they are included in the circuit, resistors R1 and R2 stabilize the voltage developed across the two series capacitors, C2 and C3, respectively, and also act as a bleeder to discharge the capacitors when the circuit is de-energized. The value of resistor R1 is generally twice the value of resistor R2.



Voltage-Tripler Circuits

A surge resistor, Rs, is placed in series with the a-c source; however, if a transformer is used in the circuit, and if there is sufficient resistance in the secondary winding, the resistor may be omitted.

Each tripler circuit illustrated has one disadvantage in that neither d-c output terminal can be directly connected to ground (chassis). (The circuits shown in parts B and C have one output terminal in common with the a-c source.) If a step-up or isolation transformer is used to supply the input to a tripler circuit, either output terminal may be connected to ground or to the chassis.

The operation of the tripler circuits can be readily understood from a study of the equivalent electron-tube circuit descriptions given previously in this section of the handbook. The action of the semiconductor rectifiers in a tripler circuit is essentially the same as that described for the equivalent electron-tube circuit. Semiconductor rectifiers CR1, CR2, and CR3 correspond directly to rectifiers V1, V2, and V3 in the electron-tube circuit description. For these reasons, an explanation of circuit operation is not given here.

In the circuit shown in part A, charging capacitors C2 and C3 are in series across the load resistance, and each capacitor receives a charge on alternate half-cycles of the applied voltage; as a result, the output voltage contains some ripple. In this tripler circuit, the frequency of the main component of the ripple voltage is equal to twice the frequency of the a-c source. In the circuits shown in parts B and C, charging capacitor C2 receives a charge on alternate half-cycles only; thus, the output voltage of these two circuits contains a ripple voltage which has a frequency equal to that of the a-c source.

As stated previously, the regulation of a voltage- tripler circuit is relatively poor; therefore, the value of the output voltage obtained from the voltage tripler is determined largely by the resistance of the load and the resulting load current. The output of each of the circuits illustrated requires filtering to obtain a steady d-c voltage. (Filter circuits are discussed in Part D of this section of the handbook.)

FAILURE ANALYSIS.

No Output. In the voltage-tripler circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of an open surge resistor, Rs, or a defective step-up or isolation transformer), a shorted load circuit (including filter circuit components), open charging capacitors (dependent upon circuit configuration), or defective rectifiers.

The a-c supply voltage should be measured at the input to the circuit to determine whether the voltage is present and is the correct value. If the circuit uses a step-up or isolation transformer, measure the voltage at the secondary terminals to determine whether it is present and is the correct value. If necessary, the primary voltage should be removed from the transformer and continuity measurements of the primary and secondary windings made to determine whether one of the windings is open, since an open circuit in either winding will cause a lack of secondary voltage.

If the circuit includes a surge resistor, Rs, a resistance measurement can be made to determine whether the resistor is open. If the resistor is found to be open, the voltage tripler and the load (including filter) circuit should be checked further to determine whether excessive load current, a defective rectifier, or a shorted capacitor has caused the resistor to act as a fuse and to open.

With the a-c supply voltage removed from the output to the circuit and with the load (including filter circuit) disconnected from the load terminal of capacitor C2, resistance measurements can be made across the load to determine whether the load circuit (including filter components) is shorted. Measurements should be made across the terminals of charging capacitors C2 and C3 in the tripler circuit shown in part A, or across charging capacitor C2 in the tripler circuit of part B or part C, to determine whether the no-output condition is caused by shorted capacitors. The tripler circuit shown in part A includes resistors R1 and R2; therefore, the resistance value measured across capacitors C2 and C3 will normally be something less than the value of the associated bleeder resistor. Since the charging capacitors are electrolytic capacitors, the resistance measurements will vary, depending upon the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the capacitor terminals for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value. Capacitor C1 may be checked in a similar manner.

A quick method which can be used to determine whether an open capacitor is the source of trouble is to substitute a known good capacitor in the circuit for the suspected capacitor, and then measure the resulting output voltage.

The rectifiers should be checked to determine whether they are open or otherwise defective. A relative check of rectifier condition can be made by use of an ohmmeter, as outlined in a previous paragraph of this section. However, failure of one or more rectifiers may be the result of other causes; therefore, tests of the filter and load circuit are necessary. Once it is determined that the filter components and load circuit are satisfactory, a procedure which can be used to quickly determine whether the rectifiers are defective is to substitute known good rectifiers in the circuit and measure the output voltage.

Low Output. The a-c supply voltage should be measured at the input of the circuit to determine whether the voltage is the correct value, since a low applied voltage can result in a low output voltage.

Each rectifier (CR1, CR2, and CR3) should be checked to determine whether the low output is due to normal rectifier aging. A relative check of rectifier condition can be made by use of an ohmmeter, as outlined in a previous paragraph of this section. If the forward resistance of the rectifier increases, the output voltage will decrease. Also, if the reverse resistance decreases, the output voltage will decrease.

The load current should be checked to make sure that it is not excessive, because the voltage-tripler circuit has poor regulation and an increase in load current (decrease in load resistance) can cause a decrease in output voltage.

One terminal of each charging capacitor (C1, C2, and C3) should be disconnected from the circuit and each capacitor checked, using a capacitance analyzer, to determine its effective capacitance and leakage resistance. A decrease in effective capacitance or losses within the capacitor can cause the output of the voltage-tripler circuit to be below normal, since the defective capacitor will not charge to its normal operating value. If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by use of an ohmmeter. First, disconnect one terminal of the capacitor from the circuit; then, using the ohmmeter procedure outlined for the no-output condition, make two measurements (reverse the test leads at the capacitor terminals for one of the measurements). The larger of the two measurements should be greater than 1 megohm for a satisfactory capacitor. A procedure which can be used to quickly determine whether the capacitors are the cause of low output is to substitute known good capacitors of the same value in the voltage-tripler circuit and measure the resulting output voltage under normal load conditions.

VOLTAGE QUADRUPLER.

APPLICATION.

The voltage-quadrupler circuit is used to produce a higher d-c output voltage than can be obtained from a conventional rectifier circuit utilizing the same input voltage. It is normally used in "transformerless" circuits where the load current is small and voltage regulation is not critical.

CHARACTERISTICS.

Input to circuit is ac; output is pulsating dc.

D-c output voltage is approximately four times the voltage obtained from basic half-wave rectifier circuit utilizing the same input voltage; output current is relatively small.

Output requires filtering; d-c output ripple frequency is either equal to or twice the a-c source frequency, depending upon quadrupler circuit arrangement.

Has poor regulation characteristics; output voltage available is a function of load current.

Uses four semiconductor rectifiers (single, multiple, or stacked units).

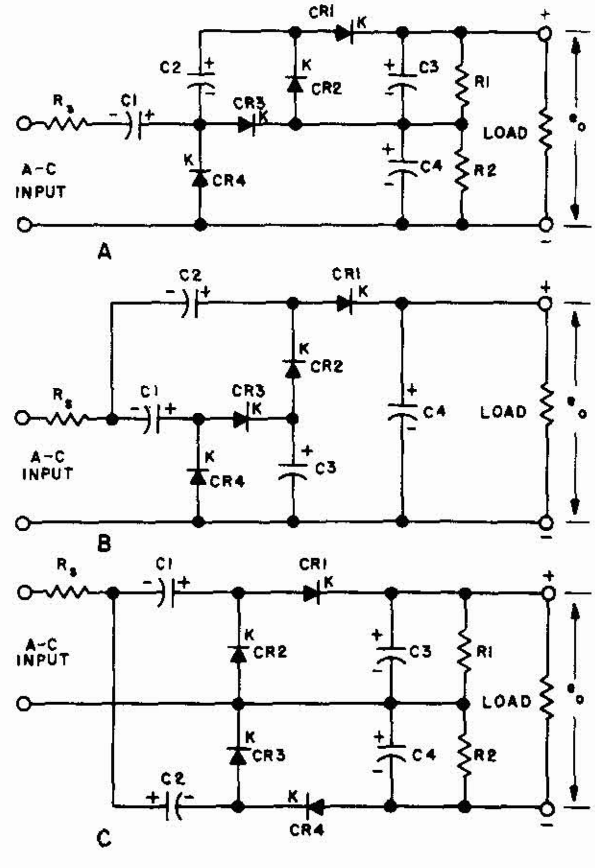
Depending upon circuit application, may be used with or without a power or isolation transformer.

CIRCUIT ANALYSIS.

General. The voltage-quadrupler circuit is used with or without a transformer to obtain a d-c voltage from an a-c source. As the term **voltage quadrupler** implies, the output voltage is approximately four times the input voltage. The voltage regulation of the voltage quadrupler is very poor as compared with the regulation of either the voltage-doubler or voltage-tripler circuit. Assuming that a given voltage-multiplier (doubler, tripler, or quadrupler) circuit uses the same value of capacitors in each instance, the greater the voltage-multiplication factor of the circuit, the poorer will be regulation characteristics. Because of the poor regulation characteristics of the voltage quadrupler, the use of the circuit is generally limited to applications in which the load current is small and relatively constant.

Circuit Operation. Three voltage-quadrupler circuits are shown in the accompanying illustration. The schematic of part A shows a basic cascade voltage-quadrupler circuit; fundamentally, this circuit consists of two voltage doublers whose outputs are in series. The schematic of part B shows a circuit arrangement which is a variation of that given in part A. The schematic of part C is a quadrupler circuit consisting of two complete half-wave voltage-doublers connected back-to-back and sharing a common a-c input. The circuits shown in parts A and B have the negative output terminal common to one side of the a-c source; both of these circuits can be arranged to have the positive output terminal common to one side of the a-c source by simply reversing the connections to each rectifier (CR1 through CR4) and to each charging capacitor (C1 through C4).

The rectifiers, CR1, CR2, CR3, and CR4, are identical-type semiconductor diodes in each of the three circuits illustrated. Charging capacitors C1, C2, C3, and C4 are of equal capacitance value in each of the three circuits; however, because of the differences in the voltages developed across individual capacitors in a particular circuit, the voltage ratings of the capacitors will differ. In the circuit of part A, the voltage rating of capacitors C3 and C4 is the same for each capacitor; the voltage rating of capacitor C2 is less than that of C3 or C4, and the rating of capacitor C1 is less than that of C2. In part B, the voltage rating of capacitors C2 and C4 is the same for each capacitor; the rating of C3 is less than that of C2 or C4, and the rating of C1 is less than that of C3. In part C, the voltage rating of capacitors C3 and C4 is the same for each capacitor, and the rating of capacitors C1 and C2 is the same for each capacitor; however, the rating of capacitors C1 and C2 is less than that of C3 and C4.



Voltage-Quadrupler Circuits

Equalizing resistors R1 and R2, shown in the circuits of parts A and C, are not necessary for circuit operation;

however, when they are included in the circuit, resistors R1 and R2 equalize the voltages developed across capacitors C3 and C4, respectively, and also act as a bleeder to discharge the capacitors when the circuit is de-energized. A surge resistor, Rs, is placed in series with the a-c source to limit the peak current in the rectifier circuit.

One disadvantage common to all three quadrupler circuits illustrated is that neither d-c output terminal can be directly connected to ground or to the chassis; however, when a step-up or isolation transformer is used to supply the input to any one of these quadrupler circuits, either output terminal may be connected to ground or to the chassis. Furthermore, if a transformer is used and if there is sufficient resistance in the secondary winding, the surge resistor, Rs, may be omitted.

The operation of these quadrupler circuits can be readily understood from a study of equivalent electron-tube circuit descriptions given previously in this section of the handbook. The action of the semiconductor rectifiers in the quadrupler circuit is essentially the same as that described for the equivalent electron-tube circuit. For these reasons, an explanation of circuit operation is not given here.

In the circuit shown in part A, charging capacitors C3 and C4 are in series across the load resistance, and each capacitor simultaneously receives a charge, once for each complete cycle of the applied voltage; as a result, the output ripple voltage has a frequency which is equal to the frequency of the a-c source. In part B, charging capacitor C4 in parallel with the load resistance is charged only on alternate half-cycles of the applied a-c voltage; therefore, the frequency of the ripple voltage is the same as the frequency of the a-c source. In part C, charging capacitors C3 and C4 are in series across the load resistance, and the capacitors receive a charge on alternate half-cycles of the applied voltage; as a result, the output ripple voltage for this circuit has a frequency which is equal to twice the frequency of the a-c source.

Since all three circuits described contain a ripple voltage, additional filtering is required to obtain a steady d-c voltage. (Filter circuits are discussed in Part D of this section of the handbook.)

As stated previously, the regulation of the voltage quadrupler is relatively poor; the value of the output voltage obtained is determined largely by the resistance of the load and the resulting load current. If the load current is large, the output voltage is reduced accordingly.

FAILURE ANALYSIS.

No Output. In the voltage-quadrupler circuit, the no-output condition is likely to be limited to one of several possible causes: the lack of applied a-c voltage (including the possibility of an open surge resistor, Rs, or a defective step-up or isolation transformer), a shorted load circuit (including filter circuit components), open charging capacitors (dependent upon circuit configuration) or defective rectifiers.

The failure analysis procedures for the no-output condition, such as voltage and resistance measurements, capacitor and rectifier checks, substitution of known good parts for suspected parts, etc, are essentially the same as those given for the voltage-tripler and half-wave voltage-doubler circuits described previously in this section of the handbook. Therefore, these procedures are not repeated here.

Low Output. The failure analysis procedures for the low-output condition consist of voltage, resistance, and load-current measurements; capacitor and rectifier checks; substitution of known good parts for suspected parts; etc. These procedures are essentially the same as the procedures given for the voltage-tripler circuit described previously, and are somewhat similar to those given for the half-wave voltage-doubler circuit described earlier in this section of the handbook.

HIGH-VOLTAGE (CRT) SUPPLY, SQUARE-WAVE OSCILLATOR TYPE.

APPLICATION.

The square-wave oscillator type high-voltage supply is a dc-to-dc converter used in electronic equipment for applications requiring extremely high-voltage dc at a small load current. The output circuit can be arranged to furnish negative or positive high voltage to the load. The supply is commonly used to provide high voltage for accelerating and final anodes, ultor, and other similar electrodes of cathode-ray tubes used in indicators.

CHARACTERISTICS.

Uses two power transistors in a self-excited oscillator circuit combined with a full-wave voltage-doubler circuit.

Typical operating frequency is between 400 and 2000 cycles.

Output is high-voltage dc at low current.

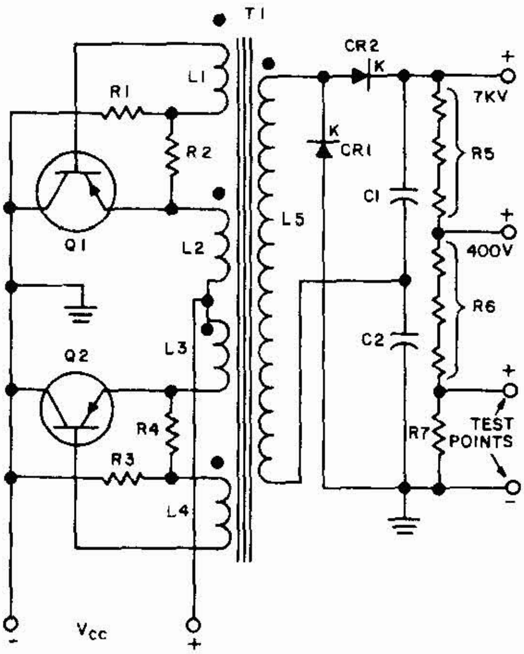
Regulation is fair; may be improved by regulating the input d-c supply voltage.

Rectifier circuit can be arranged to provide either positive- or negative-polarity output voltage.

CIRCUIT ANALYSIS.

General. The square-wave oscillator type high-voltage supply includes a self-excited oscillator which has an operating frequency in the range between 400 and 2000 cycles. The oscillator circuit operates most efficiently as a square-wave generator with the transistors functioning as high-speed switching elements. The transistors provide a form of astable, or free-running, multivibrator circuit; the action can be compared to the switching action which occurs with a mechanical vibrator in a nonsynchronous vibrator supply. The power supply (oscillator and rectifier circuits) is frequently called a **dc-to-dc converter**, and the oscillator circuit itself is referred to as a **saturable-core square wave** oscillator. The square-wave output from the oscillator circuit may be stepped up or down and rectified to provide a d-c voltage higher or lower than the input voltage. The circuit described here is used in conjunction with a full-wave voltage-doubler circuit to obtain high-voltage dc. Because of the square-wave output and the relatively high frequency of oscillation, very little filtering is required to eliminate the ripple voltage from the output; this is especially true when a full-wave rectifier circuit is used.

Circuit Operation. The accompanying circuit schematic illustrates a push-pull, self-excited oscillator circuit used in conjunction with a full-wave voltage-doubler circuit to obtain a high-voltage output. The discussion which follows is limited to the oscillator to the oscillator circuit, since the operation of a typical full-wave voltage-doubler circuit has been described earlier in this section of the handbook.



High-Voltage Supply, Square-Wave Oscillator Type Using PNP Power Transistors

Transistors Q1 and Q2 are identical PNP, alloy-junction type, power transistors. The power transistors used in this common-emitter circuit configuration normally have the collector connected to the case or shell of the transistor; thus, the circuit shown here permits the collectors to be in physical and electrical contact with a metal chassis or a grounded heat sink. Rectifiers CR1 and CR2 are identical semiconductor diodes; although the schematic shows only two rectifiers in the voltage-doubler circuit, each graphic diode symbol represents two or more diodes in series to obtain the necessary peak-inverse characteristics for high-voltage operation in the voltage-doubler circuit.

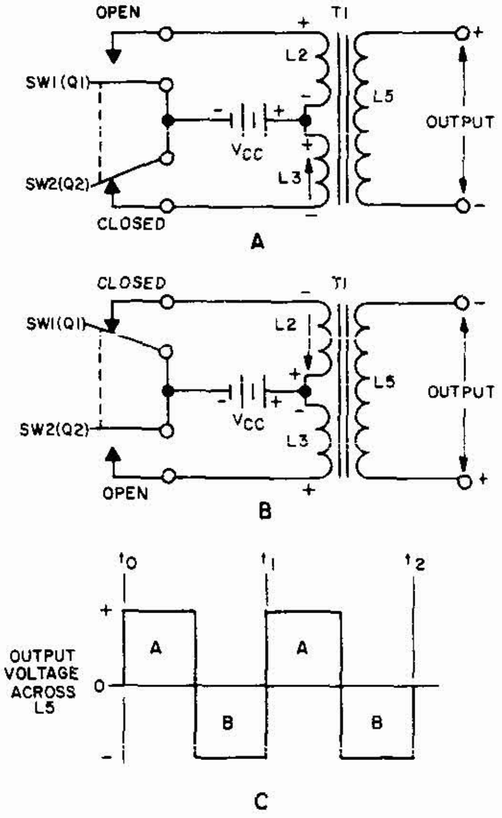
Transformer T1 provides the necessary regenerative feedback coupling from the emitter to the base of the power transistors, Q1 and Q2, and is also the source of high voltage for the rectifier circuit. Transformer windings L2 and L3 are emitter windings; L1 and L4 are the feedback, or base, windings. The load for the transistors is formed by windings L2 and L3 connected between the emitters and the voltage source. Transformer winding L5 is the high-voltage (step-up) winding, and is the a-c source for the voltage-doubler circuit. In the schematic, the dots adjacent to the transformer windings are used to indicate similar winding polarities.

Resistors R1 and R2 form a voltage divider to provide forward-bias voltage for the base of transistor Q1; in like manner, resistors R3 and R4 establish the bias for the base of transistor Q2. Separate voltage dividers are used in this push-pull circuit to provide an independent base-voltage source for each transistor and thereby increase the reliability of the circuit. In the event of failure of one transistor, such as an open circuit in one of the transistor junctions, the independent base-biasing arrangement enables the remaining transistor of the oscillator circuit to continue operation at reduced efficiency, and the d-c output of the power supply is reduced accordingly.

Capacitors C1 and C2 are the charging capacitors of the voltage-doubler circuit. Since the frequency of the applied voltage is generally between 400 and 2000 cycles, the value of these capacitors is relatively small, usually between 5600 pf and 0.02 μf. Resistors R5, R6, and R7 in series form a bleeder and voltage-divider resistance for the output of the doubler circuit. The tap at the junction of resistors R5 and R6 enables a lower voltage to be supplied to a low-current load, such as the lower-voltage electrodes of a cathode-ray tube. In actual practice, resistors R5 and R6 are made up of a number of resistors in series to obtain the desired value of total resistance for each portion of the bleeder (R5 and R6). To prevent failure, the voltage drop across each resistor must be less than the maximum terminal-voltage rating of the resistor.

Resistor R7 is used as a shunt resistor for test metering purposes, to permit measurement of the high-voltage d-c output without the requirement for a special voltmeter or high-voltage probe. The test points located at each end of R7 permit a low-resistance microammeter to be connected across the resistor; in this case the bleeder resistance (R5 and R6) is used as a series multiplier for the test microammeter. When this test circuit is employed, the high-voltage output can be calculated by using Ohm's law, once the bleeder current is determined by measurement and the total resistance of R5 and R6 is known. As an alternative, an electronic voltmeter can be connected to the test points, to measure the voltage drop across R7; the output voltage can then be calculated by taking into account the voltage division provided by the bleeder resistance. In other cases, a predetermined (calculated) voltage drop across R7, when measured by use of a high-resistance voltmeter, will indicate the presence of the correct value of high-voltage output.

The operation of transistors functioning as high-speed switching elements can be understood by reference to the accompanying illustration for a fundamental switching circuit. The reference designations used for the windings of transformer T1 in the illustration correspond to those used in the schematic given earlier in this discussion.



Fundamental Switching Circuit and Resulting Output Waveform

The switching action, such as occurs with a mechanical vibrator, is represented in the simplified schematic by ganged switches SW1 and SW2, mechanically linked together so that when one switch is closed, the other switch is opened. When switch SW1 is open (transistor Q1 cut off), switch SW2 is closed (transistor Q2 conducting heavily), as shown in part A of the illustration, and heavy current flows in transformer winding L3. When the switches are reversed, as shown in part B, switch SW1 is closed (Q1 conducting heavily) and switch SW2 is open (Q2 cut off); thus, heavy current flows in winding L2. The polarities of the voltages produced across the primary and secondary windings are as indicated in parts A and B of the illustration. Assuming a rapid rate of switching, the resulting output voltage developed across secondary winding L5 is essentially a square waveform, as shown in part C.

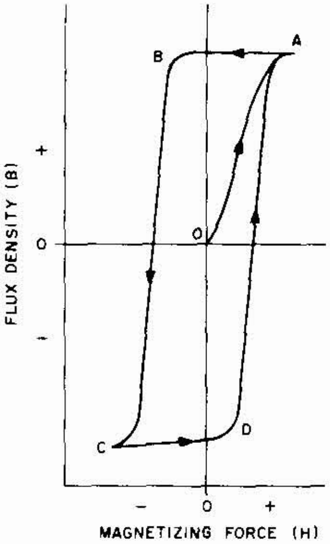
Bias and stabilization techniques employed for a transistor oscillator are essentially the same as those employed for a transistor amplifier. The grounded-collector, common-emitter configuration illustrated earlier in the discussion utilizes a single-battery power source; as mentioned previously, this d-c source produces the required bias voltages through the voltage-divider action of resistors R1 and R2, and resistors R3 and R4. Since the collector is at negative (ground) potential and the emitter is at a positive potential, each pair of resistors form a voltage divider to place the base of the associated transistor at a negative potential with respect to its emitter; the required forward bias for the PNP transistor is thereby established.

The square-wave oscillator can be compared to an amplifier with feedback of the proper phase and amplitude. In the PNP transistor schematic given earlier, feedback is obtained by transformer coupling from the emitter to the base in order to sustain oscillations; the feedback signal must be in phase with the emitter signal. If NPN transistors are used in the oscillator circuit, the polarity of the supply voltage must be opposite to that indicated in the schematic; however, for either type of transistor, the feedback signal must be in phase with the emitter signal.

When d-c power is first applied to the circuit, the current which flows through each primary winding, L2 and L3, is initially determined by the effective resistance offered by transistors Q1 and Q2, and their associated bias resistors R1 and R2 and resistors R3 and R4. The push-pull circuit appears to be balanced, since each half of the circuit is identical to the other; however, there will always be minor differences in circuit resistance and within the transistors themselves. As a result of this inherent unbalance, the initial current in one primary winding of transformer T1 does not exactly equal the initial current in the other. It is this unequal current flow in primary windings L2 and L3 which starts the oscillation in a manner which is typical of free-running multivibrators or relaxation oscillators.

In order to compare the action of the square-wave oscillator with the action of the fundamental switching circuit, assume that more current flows through primary winding L3 than flows through primary winding L2 because of the circuit unbalance mentioned previously. As emitter-current flow increases through winding L3, a voltage is induced in the feedback (or base) winding, L4. This voltage is in phase with the voltage produced across winding L3. The induced voltage across L4 effectively increases the forward bias, and transistor Q2 rapidly approaches saturation. As this regenerative process continues, core saturation is eventually reached; at this time no further increase in the emitter current through L3 can occur, and the effective inductance of the transformer windings decreases. The flux in the core of transformer T1 during this period has changed from point 0 to point A on the hysteresis curve, as shown in the accompanying illustration.

During the interval that transistor Q2 is approaching saturation, voltage is induced in winding L1 by the resultant field of L2 and L3. This induced voltage is in opposition to the initial voltage developed when the d-c supply voltage was first applied to the circuit. As a result of the action occurring in the circuit associated with transistor Q2, the voltage across winding L1 causes the base of transistor Q1 to approach a condition of reverse bias. The emitter current of transistor Q1 decreases rapidly, and Q1 reaches cutoff because the feedback from winding L1 has driven the base of Q1 to a condition of reverse bias. Since no further increase or change in current through L3 occurs, the base of transistor Q2 is no longer driven by a voltage from L4, and it starts to return to the normal (forward) bias



Core Hysteresis Curve

condition. Also, the magnetic flux developed in the core of T1 starts to decrease to point B on the hysteresis curve. Consequently, the voltage induced in L4 starts to drive the base of Q2 to a reverse bias condition. The emitter current of transistor Q2 decreases rapidly and Q2 finally reaches cutoff. As a result of this regenerative process, the magnetic flux developed in the core rapidly changes from point B on the hysteresis curve. At the same time, transistor Q1 receives a signal from L1 and its base is driven toward the forward bias condition. Q1 conducts heavily, causing the flux in the core to reach point C. During the interval when transistor Q1 is at saturation, no further change in the current through winding L2 occurs; thus, the base of transistor Q1 is no longer driven by a voltage from L1, and it starts to return to the normal (forward) bias condition. Also, the magnetic flux developed in the core of T1 starts to decrease to point D on the hysteresis curve. Consequently, the voltage induced in L1 starts to drive the base of Q1 to a reverse bias condition. The emitter current of transistor Q1 decreases rapidly, and Q1 finally reaches cutoff. As a result of this regenerative process, the flux developed in the core rapidly changes from point D on the hysteresis curve. At the same time, transistor Q2 receives a signal from winding L4, and its base is driven into the forward bias condition. Q2 conducts heavily, causing the flux in the core to reach point A once again. At this time, transistor Q2 is at saturation (point A on the hysteresis curve) and transistor Q1 is cut off; the cycle is now complete and ready to be repeated.

The output frequency and secondary voltage are determined by the turns ratio of the transformer windings and by the saturation flux of the core. The core laminations of transformer T1 are usually made of nickel-iron or other material exhibiting similar magnetic characteristics. The nickel-iron material has a high permeability and a square-loop hysteresis curve, which is ideal for use with transistors operating in a switching mode. The transistors, functioning as high-speed switches, operate alternately from cutoff to saturation; when this action is combined with the flux characteristics of the transformer core, the output voltage produced is essentially a square wave. This is because the core flux changes rapidly at a relatively constant rate from point B to point C and from point D to point A on the hysteresis curve.

The output-voltage regulation of this high-voltage supply is sufficient for most cathode-ray-tube circuit applications without additional circuitry, especially if the d-c input supply voltage is regulated. The output-voltage stability could be improved somewhat by the use of a regulator in the collector circuit of the transistors, but the added regulator circuit would become rather complex if stability better than that already provided by the circuit were to be obtained.

The transistorized push-pull oscillator circuit offers several advantages; its efficiency is relatively high, the physical size of the supply is small and much of the circuit can be encapsulated, and the grounded-collector configuration simplifies the method used to dissipate heat developed by the transistors. Furthermore, the circuit has the ability to continue to operate, but with reduced output, even though an open circuit develops in one of the transistors. If a failure of this nature occurs at a time when continued operation is vital to the mission, sufficient output voltage will normally be available to sustain emergency operation until corrective maintenance can be performed. With such a failure, the cathode-ray-tube indicator brilliance is likely to decrease somewhat, and an increase in deflection may be noticed.

FAILURE ANALYSIS.

General. The square-wave oscillator type high-voltage supply consists of two basic circuits—a push-pull oscillator and a voltage doubler. It must be determined initially whether the oscillator or the voltage-doubler portion of the power-supply circuit is at fault. Tests must be made to determine whether the oscillator is performing satisfactorily; if it is, the trouble is then assumed to be located within the associated voltage-doubler circuit. The failure analysis outlined in the following paragraphs is somewhat brief because the subject of oscillators is discussed in another section of this handbook; furthermore, the voltage-doubler circuit is described earlier in this section. Since the square-wave oscillator type high-voltage supply is a combination of two basic circuits, additional information concerning failure analysis for either portion of the high-voltage supply can be obtained by reference to the applicable basic circuit given elsewhere in this handbook.

No Output. The d-c input voltage, V_{CC}, should be measured to determine whether it is present and of the correct value.

The push-pull oscillator can be quickly checked to determine whether it is oscillating by using an oscilloscope to observe the emitter-to-collector waveform at each transistor. When the push-pull oscillator is functioning normally, the emitter-to-collector waveform is essentially a square wave having a peak-to-peak amplitude which is approximately equal to twice the value of the d-c input voltage, V_{CC}.

Each biasing resistor should be disconnected and, using an ohmmeter, the value of each resistor should be measured to determine whether the resistor is within tolerance. If the values of the biasing resistors (R1 through R4) change appreciably, it is likely that the forward bias will change for the associated transistor; if the forward bias increases, such a condition may cause thermal runaway, with eventual damage to the transistor(s) and failure of the circuit to oscillate. Thus, with one transistor conducting heavily or with a shorted junction within the transistor, the resulting current flow in the windings of transformer T1 will cause the effective inductance to be decreased; the core may reach saturation, in which case the circuit will not oscillate because of the loading on the circuit caused by the defective transistor.

Any defect in transformer T1, such as an open base or emitter winding, or shorted turns in any of the windings, will prevent the circuit from operating properly, since oscillations in each half of the circuit depend upon regenerative feedback from the transformer.

A shorted secondary circuit, reflected to the emitter and base windings, may cause excessive losses which will prevent sustained oscillations. Also, if the high-voltage winding, L5, should open, the circuit will continue to oscillate; however, no output will be obtained from winding L5 for the input to the voltage-doubler circuit.

If the oscillator circuit is found to be functioning normally, then it must be assumed that the trouble is in the voltage-doubler circuit or its associated load, and a check of the rectifier circuit must be made in accordance with the procedures outlined earlier in this section for the applicable rectifier circuit.

Low Output. The d-c input voltage, V_{CC}, should be measured to determine whether it is of the correct value.

If one transistor should develop an open circuit in one of its junctions, the high-voltage output will decrease (for a given load current), and the peak-to-peak amplitude of the ripple voltage will increase. Because of the independent base-biasing arrangement, the remaining good transistor will continue to oscillate. Under these conditions the transformer core may not reach saturation. In this case there will be a reduction in the efficiency of the circuit, together with an accompanying decrease in the output voltage; furthermore, the oscillator frequency will increase to two or three times the normal operating frequency when only one transistor is operating. A calibrated oscilloscope can be used to observe the emitter-to-collector waveform at each transistor. If the oscillator is functioning normally, the emitter-to-collector waveform is essentially a square wave having a peak-to-peak amplitude which is approximately equal to twice the value of the d-c input voltage, V_{CC}. However, if only one transistor is functioning and the other transistor has an open circuit in one of its junctions, the emitter-to-collector waveform will not resemble a square wave on both halves of the cycle; instead it will resemble a square wave for one half-cycle and a trapezoid for the other half-cycle. As mentioned previously, the frequency of oscillation will be higher than normal under these conditions.

If the oscillator circuit is found to be operating normally, a defect within the voltage-doubler circuit or associated load must be suspected as the cause of low output. For example, because of the relatively high-impedance rectifier and filter circuits, an excessive load current can cause the output voltage to be low. Failure analysis procedures for typical rectifier circuits used in high-voltage supplies are outlined earlier in this section.

DC-TO-DC CONVERTER.

APPLICATION.

The dc-to-dc converter is typical of transistorized power supplies used in electronic equipment for applications requiring high-voltage dc at a moderate load current. The output circuit can be arranged to furnish negative or positive high voltage to the load. The supply is commonly used to provide high voltage for the operation of small receivers and transmitters from a d-c power source.

CHARACTERISTICS.

Uses two power transistors in a self-excited oscillator circuit combined with a bridge rectifier circuit.

Typical operating frequency is between 400 and 4000 cycles.

Output high-voltage dc is normally between 250 and 550 volts; load current is between 60 and 200 milliamperes.

Regulation is good.

Semiconductor diodes are used in the rectifier circuit.

Rectifier circuit can be arranged to provide either positive- or negative-polarity output voltage.

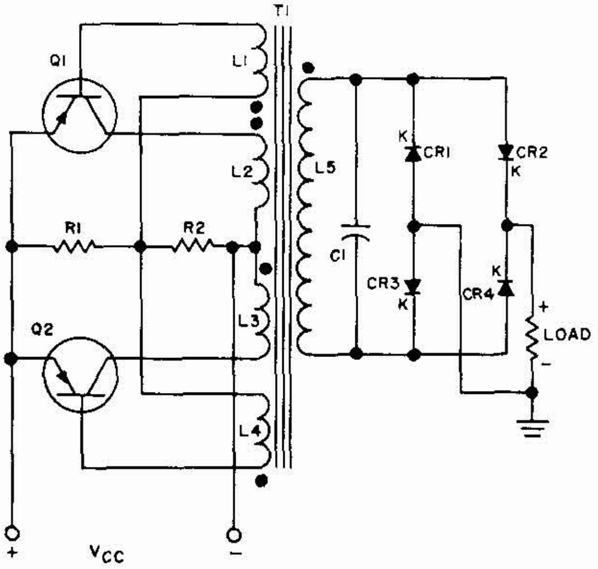
CIRCUIT ANALYSIS.

General. The dc-to-dc converter is a special application of power transistors to convert a low d-c voltage to high-voltage dc. Transistorized power supplies are frequently used in place of mechanical converters, such as vibrators and dynamotors. The circuit discussed here is typical of several types of dc-to-dc converters; the combination of a push-pull oscillator and a bridge rectifier results in a power supply with relatively high efficiency.

The oscillator circuit itself operates most efficiently as a square-wave generator, with the transistors functioning as high-speed switching elements. The oscillator circuit is a form of astable, or free-running, multivibrator circuit; the action can be compared to the switching action of a mechanical vibrator in a non-synchronous vibrator supply. The oscillator circuit is frequently referred to as a **saturable-core square-wave** oscillator.

The high-voltage a-c output from the oscillator is rectified to provide a d-c output voltage, which is filtered. A full-wave rectifier circuit is desirable in this type of power supply to reduce the filter circuit requirements; for this reason and because only a single high-voltage winding is required, the bridge rectifier circuit is commonly employed with this power supply. Semiconductor diodes are used as rectifiers in the bridge circuit. Because of the square-wave output from the oscillator and because the frequency of oscillation is relatively high, very little filtering is required to obtain a d-c output voltage which is relatively free from ripple.

Circuit Operation. The accompanying circuit schematic illustrates a push-pull, self-excited oscillator circuit used in conjunction with a bridge circuit to obtain high-voltage output. The discussion which follows is limited to the oscillator circuit, since the operation of a typical bridge rectifier circuit using semiconductor diodes has been described earlier in this section of the handbook.



DC-to-DC Converter, Square-Wave Oscillator Type, Using PNP Power Transistors

Transistors Q1 and Q2 are identical PNP, alloy-junction type power transistors. The power transistors used in this common-emitter circuit configuration normally have the collector connected to the case or shell of the transistor; therefore, the circuit shown here requires that either the collector or the collector and its associated heat sink be electrically insulated from chassis or ground. Rectifiers CR1, CR2, CR3, and CR4 are identical semiconductor diodes; although the schematic shows only four rectifiers in the bridge circuit, each graphic diode symbol can represent two or more diodes in series, if necessary, to obtain greater peak-inverse characteristics than can be obtained with a single diode.

Transformer T1 provides the necessary regenerative feedback coupling from the collector winding to the base of the power transistors, and is also the source of high voltage for the bridge rectifier circuit. The transformer may be either a toroidal-core type or a conventional laminated-core type with bifilar primary windings. Transformer windings L2 and L3 are the collector windings; L1 and L4 are the feedback, or base, windings and have fewer turns than L2 and L3. The load for the transistors is formed by primary windings L2 and L3 connected between the collectors and the voltage source. Transformer winding L5 is the high-voltage secondary (step-up) winding, and is the a-c source for the bridge circuit. In the schematic, the dots adjacent to the transformer windings are used to indicate similar winding polarities.

Resistors R1 and R2 form a voltage divider to provide forward-bias voltage for the base of both transistors, Q1 and Q2. The ratio of resistance between these two resistors is chosen in the design of the power supply to insure that the circuit will start to oscillate under loaded conditions; furthermore, the value of the resistors is made sufficiently high to prevent shunting an excessive amount of current from the transistor collector circuit, and also to prevent excessive power dissipation within the resistors themselves. In a practical circuit, one of the resistors is usually made variable to permit the forward bias to be adjusted to a specified voltage. If for any reason the value of the resistors should change, the bias for both transistors will change, and the power output of the oscillator circuit will be affected. In extreme cases the oscillator will stop oscillating, either because the transistors are approaching cutoff, or because the transistors are conducting heavily (saturated).

Capacitor C1, called a **buffer** capacitor, is placed across the high-voltage secondary winding, L5. The exact value of this capacitor is critical, and is determined by the turns ratio and effective inductance of T1, the frequency of operation, and other similar circuit design factors. The function of the capacitor is to effectively absorb the induced transient surges that occur when the switching function takes place in the primary circuit of T1.

A simple explanation of the operation of transistors functioning as high-speed switching elements was given previously in connection with the description of circuit operation for the high-voltage (CRT) supply.

The common-emitter configuration illustrated earlier in this discussion utilizes a single-battery power source; as mentioned previously, this d-c source produces the required base-bias voltage through the voltage-divider action of R1 and R2. Since the collectors are at a negative potential and the emitters are at a positive potential, the resistors (R1 and R2) form a voltage divider, placing the transistor base at a negative potential with respect to its emitter; the required forward bias for the PNP transistor is thereby established.

The square-wave oscillator can be compared to an amplifier with feedback of the proper phase and amplitude. In the PNP transistor schematic given earlier, feedback is obtained by transformer coupling from the collector to the base to sustain oscillations; the feedback signal must undergo a phase reversal when the feedback is from the collector to the base. If NPN transistors are used in the oscillator circuit, the polarity of the supply voltage must be opposite that given on the schematic; however, for either type of transistor, the feedback signal must be 180 degrees out of phase with the collector signal. (Although the circuit described here is a common-emitter configuration, a common-collector configuration could also be used, provided that the proper bias and signal polarities are observed.)

When d-c power is first applied to the circuit, the current which flows through each primary winding, L2 and L3, is initially determined by the effective resistance offered by transistors Q1 and Q2 for a given value of base-bias voltage. The push-pull circuit appears to be balanced, since each half of the push-pull circuit is identical to the other; however, there will always be minor differences in circuit resistance and within the transistors themselves. As a result of this inherent unbalance, the initial current in one primary winding does not exactly equal the current in the other winding; it is this unequal current flow in primary windings L2 and L3 which starts the oscillation. The immediate effect is that one transistor conducts while the other is cut off.

For the purpose of this explanation, assume that more current flows through winding L2 than flows through winding L3 because of the slight difference in the transistors: thus, transistor Q1 attempts to conduct more heavily than does transistor Q2. As the collector-current flow increases through winding L2, a voltage is induced in the feedback (or base) winding, L1. The induced voltage in L1 is 180 degrees out of phase with the voltage of L2, as shown by the dots used on the schematic to indicate winding polarities for transformer T1. Thus, an out-of-phase voltage is applied to the base of transistor Q1, which drives the base more negative and causes Q1 to increase conduction. While Q1 rapidly approaches saturation, because of the increase in forward bias caused by the voltage from L1, the voltage induced in feedback winding L4 by the resultant field of L2 and L3 applies a positive signal to the base of transistor Q2; thus, the base of Q2 is driven toward a condition of reverse bias, transistor Q2 approaches cut off, and collector-current flow through winding L3 decreases rapidly.

This regenerative process continues until transistor Q1 is at saturation, transistor Q2 is cut off, the magnetic flux developed in the core reaches saturation, and no further increase in collector current occurs in primary winding L2. Since the current through L2 is at maximum and the effective inductance of the windings has decreased as the core reached flux saturation, no further voltage is induced in windings L1, L3, and L4. The base of transistor Q1 is no longer driven by a feedback signal from L1 and thus starts to return to the normal (forward) bias condition established by resistors R1 and R2. The flux in the core starts to decrease as the magnetic field about the core starts to collapse. This action, in turn, induces voltages in the windings opposite to those which previously existed. The base of transistor Q1 now receives a positive signal from winding L1, which drives the base into a reverse-bias condition to cut off Q1. Also, the voltage induced in winding L4 is negative, and returns the base of Q2 to a forward-bias condition to start conduction. As transistor Q2 starts to conduct, collector-current flow through primary winding L3 increases and induces a voltage in feedback winding L4. As a result, the negative voltage induced in winding L4 is further increased; thus, the base of Q2 is driven still further into the forward-bias condition, which causes Q2 to rapidly approach saturation. While Q2 approaches saturation, the positive voltage induced in feedback winding L1 is applied to the base of transistor Q1; thus, the base of Q1 is driven toward a condition of reverse bias, transistor Q1 approaches cutoff, and collector-current flow through winding L2 decreases rapidly.

This regenerative process continues until transistor Q1 is cut off, transistor Q2 is at saturation, the magnetic flux developed in the core again reaches saturation, and no further increase in collector current occurs in primary winding L3. Since the current through L3 is at maximum and the effective inductance of the windings has decreased as the core reached flux saturation, no further voltage is induced in windings L1, L2, and L4. The base of transistor Q2 is no longer driven by a feedback signal from L4, and thus starts to return to the normal (forward) bias condition established by resistors R1 and R2. The flux in the core once again starts to decrease as the magnetic field about the core starts to collapse. This action, in turn, induces voltages in the windings opposite to those which previously existed. The base of transistor Q2 now receives a positive signal from winding L4, which returns the base into a reverse-bias condition to cut off Q2. Also, the voltage induced in winding L1 is negative, and returns the base of Q1 to a forward-bias condition to start conduction. As transistor Q1 starts to conduct, collector-current flow through primary winding L2 increases and induces a voltage in feedback winding L1. As a result, the negative voltage induced in winding L1 is further increased; thus, the base of Q1 is driven still further into the forward-bias condition, which causes Q1 to rapidly approach saturation. While Q1 approaches saturation, the positive voltage induced in feedback winding L4 is applied to the base of transistor Q2; thus, the base of Q2 is driven toward a condition of reverse bias, transistor Q2 approaches cutoff, and collector-current flow through winding L3 decreases rapidly.

This regenerative process continues to complete the cycle; transistor Q2 is cut off, transistor Q1 is at saturation, the magnetic flux developed in the core again reaches saturation, and no further increase in collector current occurs in primary winding L2. Since the current through L2 is at maximum and the effective inductance of the windings has decreased as the core reached flux saturation, no further voltage is induced in windings L1, L3, and L4. The base of transistor Q1 is no longer driven by a feedback signal from L1, and thus starts to return to the normal (forward) bias condition. This action completes the first cycle of operation and another cycle is initiated as the flux in the core once again starts to decrease and the magnetic field about the core starts to collapse.

From the discussion above it can be concluded that transistors Q1 and Q2 function as high-speed switches, operating alternately from cutoff to saturation. When this multivibrator-type action is combined with the flux characteristics of the transformer core, the output voltage produced across the high-voltage secondary winding, L5, is essentially a square wave. The output voltage amplitude and oscillator frequency are determined by the turns ratio of the primary and secondary windings and by the saturation flux of the transformer core material.

FAILURE ANALYSIS.

General. The dc-to-dc converter consists of a push-pull, square-wave oscillator and a bridge rectifier circuit. It must be determined initially whether the oscillator or the bridge rectifier portion of the power supply is at fault. Tests must be made to determine whether the oscillator is performing satisfactorily; if it is, the trouble is then assumed to be located within the bridge rectifier circuit (including filter circuit components). The failure analysis outlined in the following paragraphs is somewhat brief because the subject of oscillators is discussed in another section of this handbook; furthermore, the bridge rectifier circuit using semiconductor diodes as rectifiers is described earlier in this section. Since the dc-to-dc converter is a combination of two basic circuits, additional information concerning failure analysis for either portion of the transistorized power supply (oscillator or bridge rectifier) can be obtained by reference to the applicable basic circuit given elsewhere in this handbook.

No Output. The d-c input voltage, V_{CC}, should be measured to determine whether it is present and of the correct value.

The push-pull oscillator can be quickly checked to determine whether it is oscillating by using an oscilloscope to observe the collector-to-emitter waveform at each transistor. When the oscillator is functioning normally, the collector-to-emitter waveform is essentially a square wave having a peak-to-peak amplitude which is approximately equal to twice the value of the d-c input voltage, V_{CC}.

If the value of either or both biasing resistors, R1 and R2, should change appreciably, the forward bias on both transistors will change. If resistor R1 decreases or resistor R2 increases, the forward bias on both transistors will decrease and cause less collector current to flow; conversely, if resistor R1 increases or resistor R2 decreases, the forward bias on both transistors will increase and cause additional collector current to flow. A decrease in forward bias causes both transistors to approach cutoff and to eventually stop oscillations; on the other hand, an increase in forward bias causes both transistors to approach saturation and to eventually stop oscillations. This latter condition (increased forward bias) may cause thermal runaway, with subsequent damage to the transistors themselves. Therefore, the forward-bias voltage must be measured to determine whether it is correct and within tolerance for the voltage specified. If not, remove the input voltage, disconnect one end of each resistor, and, using an ohmmeter, measure the value of each resistor (R1 and R2) to determine whether the resistors are the correct value.

Any defect in transformer T1, such as an open base or collector winding, or shorted turns in any of the windings, will prevent the circuit from operating properly, since oscillations in each half of the circuit depend upon regenerative feedback from the transformer.

A shorted secondary circuit, reflected to the collector and base windings, may cause excessive losses which will prevent sustained oscillations. Also, if the high-voltage winding, L5, should open, the circuit will continue to oscillate; however, no output will be obtained from winding L5 for the input to the bridge rectifier circuit.

A shorted junction in one of the transistors will cause excessive current to flow in the associated winding (L2 or L3) of transformer T1. This, in turn, will cause the effective inductance of the transformer to decrease, the core may reach saturation, and, because of the loading on the circuit caused by the defective transistor, the circuit will not oscillate.

If the oscillator circuit is found to be functioning normally, then it must be assumed that the trouble is in the bridge rectifier circuit or its associated load, and a check of the bridge rectifier must be made in accordance with the procedures outlined earlier in this section for the applicable rectifier circuit.

Low Output. The d-c input voltage, V_{CC}, should be measured to determine whether it is of the correct value.

If one transistor should develop an open circuit in one of its junctions, the remaining good transistor will continue to oscillate; however, the high-voltage output will decrease (for a given load current), and the peak-to-peak amplitude of the ripple voltage will increase. Under these conditions of operation the transformer core may not reach saturation. In this case there will be a reduction in the efficiency of the circuit, together with an accompanying decrease in the output voltage. Also the oscillator frequency will increase to two or three time the normal operating frequency when only one transistor is operating. A calibrated oscilloscope can be used to observe the collector-to-emitter waveform at each transistor. If the oscillator is functioning normally, the collector-to-emitter waveform is essentially a square wave having a peak-to-peak amplitude which is approximately equal to twice the value of the d-c input voltage, V_{CC}. However, if only one transistor is functioning and the other transistor has an open circuit in one of its junctions, the collector-to-emitter waveform will not resemble a square wave on both halves of the cycle; instead, it will resemble a square wave for one half-cycle and a trapezoid for the other half-cycle. As mentioned previously, the frequency of oscillation will be higher than normal under these conditions.

In the common-emitter circuit configuration, a relatively small change in base current produces a relatively large change in collector current. Therefore, the forward-bias voltage applied to the base of the transistors is important, since the voltage has a direct effect upon collector current and upon the oscillator power output. (Refer to the failure analysis discussion concerning bias resistors R1 and R2 given in a previous paragraph for the no-output condition.) Therefore, the forward-bias voltage should be measured to determine whether it is correct and within tolerance. If not, the value of the bias resistors should be checked by use of the ohmmeter procedure outlined previously; if the power supply is equipped with a variable bias resistor, a bias adjustment may be required.

If the oscillator circuit is found to be operating normally, a defect within the bridge rectifier circuit (including filter components) or the associated load circuit must be suspected as the cause of low output. For example, an excessive load current can cause the output voltage to be low. Failure analysis procedures for the bridge rectifier circuit using semiconductor diodes were given earlier in this section of the handbook.

DOSIMETER CHARGER (DC-TO-DC CONVERTER).

APPLICATION.

The dosimeter charger is one typical application of the dc-to-dc converter circuit. The dosimeter charger is a self-contained, portable, battery-operated, transistorized power supply which is used to generate a d-c output (charging) voltage at a small load current. The circuit can be arranged to furnish either a negative or a positive high-voltage output. The dosimeter charger is commonly used to provide a high-voltage charge for radiation detectors employed for personnel monitoring. The d-c output voltage developed by the charger is transmitted, through an appropriate connection or receptacle, to the dosimeter being charged.

CHARACTERISTICS.

Uses single transistor self-excited oscillator circuit combined with a half-wave rectifier circuit.

Typical operating frequency is between 400 and 2000 cycles.

Output is high-voltage dc at low current.

Regulation is poor; however, for the application the regulation is not important.

Rectifier circuit can be arranged to provide either positive- or negative-polarity output voltage; rectifier is semiconductor diode.

CIRCUIT ANALYSIS.

General. The dosimeter charger consists of a tickler-coil (Armstrong) audio-frequency oscillator operating in conjunction with a rectifier to convert a low d-c voltage to a high d-c voltage. The oscillator described here operates in the range between 400 and 2000 cycles as a sine-wave generator, although with slight modification the circuit can operate as a blocking oscillator to produce a square-wave. The high-voltage a-c output from the oscillator is rectified to provide a d-c output voltage which is then filtered to remove ripple, and applied to the electroscope assembly of the dosimeter (or radiacmeter).

A brief description of a small, direct-reading pocket dosimeter, used to measure X and gamma radiation, is in order at this time so that the application of the charger may be better understood.

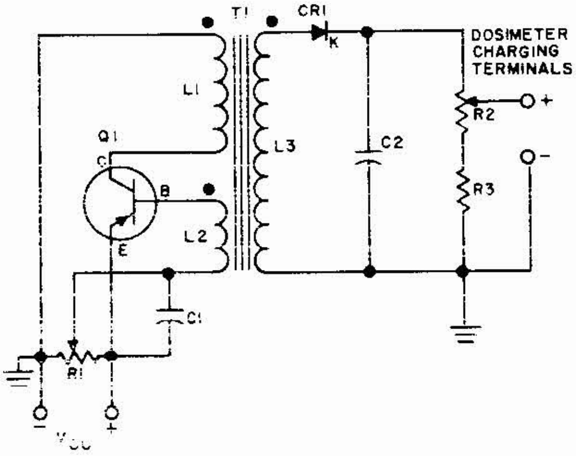
The pocket dosimeter is one of several radiation monitoring instruments utilizing the ability of radiation to produce ionization in gases. The dosimeter is approximately the size of a fountain pen, and consists of a hermetically sealed metal tube, or barrel, with an inner ionization chamber electrically connected to the metal tube. An electroscope assembly, consisting of a stiff support wire mounted in a clear plastic insulator and a freely moving quartz fiber supported by the wire, is mounted within the ionization chamber. The support wire is connected to a charging contact which is insulated from, and mounted in, the sealed end of the metal tube. A sealed optical system, consisting of an eyepiece lens, a calibrated scale, and an objective lens, is mounted axially in the other end of the metal tube.

Before the dosimeter can be used to detect radiation, it must be charged. This is accomplished by applying a d-c voltage between the metal tube and the charging contact located on the end of the tube. The charging voltage causes a mutual repulsion between the support wire and the quartz fiber, and a mutual attraction between the ionization chamber wall (tube) and the quartz fiber. As a result, the quartz fiber is deflected away from the support wire toward the chamber wall. The amount of deflection is a direct function of the charging voltage; the greater the voltage, the greater the deflection. The dosimeter is charged prior to use by looking into the eyepiece and adjusting the voltage output of the charger until the quartz fiber indicates "O" on the internal calibrated scale of the optical system.

As radiation passes through the dosimeter, the gas within the chamber ionizes. The ionized gas is capable of electrical conduction, and thus partially neutralizes the charge existing on the quartz fiber. As a result, the fiber moves toward the support wire a distance equivalent to the amount of radiation received. The amount of total radiation exposure can be read directly from the calibrated scale by viewing it through the eyepiece.

Circuit Operation. The accompanying circuit schematic illustrates a self-excited, tickler-coil (Armstrong) audio-frequency oscillator used in conjunction with a half-wave rectifier circuit. The discussion which follows is limited to a brief discussion of the oscillator circuit, since the operation of the Single Phase Half-Wave Rectifier Circuit using a semiconductor diode has been described earlier in this section (Section 4, Part B) of the handbook.

Transistor Q1 is a PNP transistor, either a point-contact or a diffused-junction type, used in a common-emitter circuit configuration. Since the power output required of the charger is extremely small, the transistor need not be a power transistor as was the case in other Dc-to-Dc Converter Circuits described previously in this section. Rectifier CR1 is a semiconductor diode used in a conventional half-wave rectifier circuit. Because the d-c output voltage is usually limited to approximately 400 volts, dc, a single rectifier having the necessary peak-inverse voltage characteristics is normally employed.



Typical Dosimeter Charger Circuit

Transformer T1 provides the necessary regenerative feedback coupling from the collector to the base of the transistor, and is also the source of high voltage for the half-wave rectifier circuit. Transformer winding L1 is the collector winding, winding L2 is the feedback (tickler coil), or base, winding, and winding L3 is the high-voltage secondary (step-up) winding. In the schematic, the dots adjacent to the transformer windings are used to indicate similar winding polarities.

Potentiometer R1 is used as a voltage divider to provide forward bias for the base of the transistor. Once R1 has been set to establish forward bias for proper operation of the transistor, it normally does not require further readjustment unless the transistor is replaced or a change in transistor characteristics occurs.

Capacitor C1 is an audio bypass capacitor provided to return the end of feedback winding L2 to the emitter of transistor Q1. Capacitor C2 is the filter capacitor of the half-wave rectifier circuit. Since the frequency of the oscillator is relatively high (400 to 2000 cycles), the value of capacitor C2 need not be very large (usually 0.01 to 0.02 μf) in order to effectively remove any trace of ripple voltage; furthermore, since the load is an extremely high impedance and the load current is small, the capacitor charges to the peak value of the applied ac.

Potentiometer R2 and resistor R3 form a voltage divider across the output of the rectifier circuit. The value of R2 is usually several times greater than the value of R3, and the total series resistance is usually 15 to 20 megohms; thus, the voltage available at the output terminals of the supply can be varied between approximately 125 and 425 volts, dc. Potentiometer R2 is controlled by a front panel knob, and permits the d-c output voltage of the charger, which is applied to the dosimeter electroscope assembly, to be adjusted and thus calibrate the instrument prior to use.

The common-emitter configuration illustrated earlier in this discussion utilizes a single-battery power source; as mentioned previously, this d-c source produces the required base-bias voltage through the voltage-divider action of potentiometer R1. Since the collector of Q1 is at a negative potential and the emitter is at a positive potential, the base is effectively placed at a negative potential with respect to its emitter; thus, forward bias is established for the PNP transistor.

The oscillator circuit can be compared to an amplifier with feedback of the proper phase and amplitude. The oscillator may be operated Class A if a linear waveform is required, or Class C if the output waveform is not very important. In the PNP transistor schematic given earlier, feedback is obtained by transformer coupling from the collector to the base in order to sustain oscillations. If an NPN transistor is used in the circuit, the polarity of the supply voltage must be opposite to that shown on the schematic; however, for either type of transistor, the feedback signal must be 180 degrees out of phase with the collector signal. Although the transistor can also be arranged in a common-base or a common-collector circuit, the common-emitter circuit is most commonly used because greatest gain is achieved with this configuration. The oscillator circuit shown in the schematic is essentially a transformer-coupled, feedback oscillator; its operation is similar to that of the common-emitter circuit described for the Tickler Coil (Armstrong) Oscillator Circuit in Section 7, OSCILLATOR CIRCUITS in this Handbook. Although the circuits described in Section 7 are L-C oscillators, the operation of the audio-frequency oscillator discussed here is essentially the same; the frequency of oscillation is determined primarily by the inductance of collector winding L1, stray circuit capacitance, and the collector-to-emitter capacitance of the transistor itself. When voltage is first applied to the oscillator, the initial rush of current through L_1 and L_2 induces a feedback voltage in the windings. The feedback is regenerative and causes emitter and collector current to increase rapidly until the collector is saturated and no further change of current occurs. At this time the magnetic field around the windings of T_1 collapses, and causes a reversed feedback voltage. This feedback is now in a direction which causes a reduction of collector and emitter current. Thus the collector is quickly driven to cutoff, and once again the collapsing magnetic field (at cutoff) causes a reversal of current flow through the induced feedback voltage. As the current through L_1 alternately flows back and forth at the oscillation period, it induces a similar but higher alternating voltage in winding L3, the high-voltage winding.

The voltage produced across the high-voltage secondary winding, L3, may be either a sine wave or essentially a square wave, depending upon the class of transistor operation. This voltage is rectified by semiconductor diode CR1, is filtered by capacitor C2, and is applied across R2 and R3. A d-c output voltage which is determined by the setting of potentiometer R2 is applied to the dosimeter charging contact for calibration of the radiation monitoring instrument.

FAILURE ANALYSIS.

General. The dosimeter charger is a self-contained, battery-operated power supply. The unit is usually very small and operates from a self-contained, 1.5-volt-battery power source. It must be determined initially whether the battery, the oscillator, or the rectifier portion of the power supply is at fault. Since the most common failure for a battery-powered device is the battery itself, a quick check can be made by substituting a known good battery in the power supply and checking the operation once again to determine whether the battery is at fault. If the operation is not satisfactory after battery substitution, tests must then be made to determine whether the oscillator or the rectifier circuit is at fault.

As stated before, the dosimeter charger is a combination of two basic circuits, an oscillator and a half-wave rectifier using a semiconductor diode. Therefore, the failure analysis outlined in the following paragraphs is somewhat brief since oscillators are completely discussed in Section 7 of this handbook, and the Half-Wave Semiconductor Diode Rectifier is discussed earlier in this section of the handbook.

No Output. The battery power source (V_{CC}) should be measured to determine whether it is present and of the correct value.

The oscillator can be quickly checked to determine whether or not it is oscillating by using an oscilloscope to observe the collector-to-emitter waveform.

If potentiometer R1 should change value (or is misadjusted), the forward bias will change accordingly. If the forward bias decreases the collector current also decreases, and, conversely, if the forward bias increases the collector current increases. At either extreme of these two conditions, oscillations will cease.

Any defect in transformer T1, such as an open feedback or collector winding, or shorted turns in any of the windings, will prevent the circuit from oscillating. A shorted secondary circuit, reflected to the collector and feedback windings, will cause excessive losses in the circuit and prevent sustained oscillations. If the high-voltage winding, L3, should open, the circuit will oscillate; however, no output will be obtained from winding L3 for the rectifier circuit.

A shorted junction or an open junction in the transistor, Q1, will cause the circuit to stop oscillating.

If the oscillator circuit is found to be functioning normally, then it must be assumed that the trouble is in the associated rectifier circuit.

Low Output. The battery power source (V_{CC}) should be measured to determine whether it is present and of the correct value.

In the common-emitter configuration, a relatively small change in base current produces a relatively large change in collector current. Therefore, the value of the forward-bias voltage applied to the base of the transistor is rather critical, since the bias voltage has a direct effect upon collector current and thus upon the oscillator power output. While reduced output can result from a loss of gain in the transistor, this condition is not very common; therefore, it is more logical to measure the supply and bias voltages before deciding to replace the transistor.

A change in the resistance ratio of potentiometer R1, an open or short in a portion of potentiometer R1, or leakage in bypass capacitor C1 will affect the output, since any of these conditions will cause a change in bias; however, a change in bias is easily detected by measuring the operating bias with a high-resistance voltmeter, or preferably an electronic voltmeter. For example, if the positive end of R1 should open, the base of Q1 is returned to $-V_{CC}$ through the remaining portion of R1; in this case, since the base remains in a forward-bias condition, the circuit will continue to oscillate. However, the oscillator output will no longer remain a sine wave, and the oscillator may start to pulse in a manner similar to that of a blocking oscillator. On the other hand, if the negative end of R1 should open, the base of Q1 is returned to $+V_{CC}$, and oscillations will cease. Either of these two conditions can be detected by a measurement of the bias voltage.

If resistance measurements are to be made on potentiometer R1, at least two of the terminals should be disconnected from the circuit, or the transistor removed from the circuit, in order to obtain valid resistance measurements (that is, measurements that are unaffected by the junctions of the transistor).

If the oscillator circuit is found to be operating normally, a defect within the rectifier circuit must be suspected as the cause of low output. Since the rectifier circuit is a high-impedance circuit, an excessive load current caused by a decrease in the value of R2 or R3, or by a leaky bypass capacitor (C2), can result in reduced output. Also, a defective semiconductor diode (CR1) can cause decreased output. Failure analysis procedures for the Half-Wave Semiconductor Diode Circuit are given earlier in this section of the handbook.

PART C. ELECTROMECHANICAL CIRCUITS

ROTATING ELECTROMECHANICAL SYSTEMS.

General. The primary electrical power source in many small boats and aircraft is a 12- or 24-volt storage battery; the battery is kept in a charged condition by means of an engine-driven generator. The battery supplies the voltage for the engine ignition system, navigation lights, and other electrical loads. When communications or similar electronic equipment is a part of the electrical load, an electromechanical-type power supply is frequently employed to supply high voltage for operation of the electronic equipment. In such cases, a rotating electromechanical device called a **dynamotor** is used to obtain high-voltage dc for operation of the electronic equipment, although a transistorized dc-to-dc converter or a vibrator-type power supply could also be used for the same purpose.

In some instances where the primary electrical power source is ac, an electromechanical device called a **rotary converter** is used to convert ac to dc. By definition, a rotary converter is a machine that changes electrical energy of one form to electrical energy of another form. A rotary converter can convert alternating current to direct current, or it can convert direct current to alternating current. It can also be used to change frequency and phase. In the normal sense, the rotary converter is a machine used to convert ac to dc; when it is used to convert dc to ac it is called an **inverter,** and is occasionally referred to as an **inverted converter.** When ac is available as the primary electrical power source, it is usually more efficient to use a power transformer and rectifier combination to obtain high-voltage dc than to use a rotary converter; for this reason, the application of rotary converters is limited. However, the rotary converter in another more common form, that of an inverter, is frequently used to convert dc to ac.

In naval aircraft, a source of alternating current is frequently required to power some of the instruments, electronic equipment, fluorescent lighting, etc. If the aircraft does not have an engine-driven a-c primary power source (single-phase or polyphase), it is necessary to provide a means of changing the primary d-c source to ac for use by the electrical load. In this application an inverter (one form of rotary converter) is used to change the dc to ac; the output of the inverter may be either single- or three-phase ac at a frequency which is normally 400 or 800 cycles.

From the brief discussion above, it can be seen that the dynamotor, rotary converter, and inverter are merely specialized combinations of motors and generators (or alternators). The detailed theory of operation and the construction of a-c and d-c motors, generators, and alternators are covered in Navy publications on basic electricity, and, therefore, will not be treated in this handbook. Only the basic principles will be discussed in this section of the handbook, as required, to provide a better understanding of the application and the failure analysis of the electromechanical devices discussed.

DYNAMOTOR.

APPLICATION.

A dynamotor performs the dual functions of motor and generator to change the relatively low voltage of a d-c power source into a much higher value for use in electronic equipments which employ electron tubes. The dynamotor may be contained within the electronic equipment, or it may be a separate unit external to the equipment. The dynamotor is frequently used in aircraft, small-craft, and portable-equipment applications where the primary source of power is dc.

CHARACTERISTICS.

Input to dynamotor is dc; output is dc (or ac).

D-C output requires filtering to remove commutation ripple.

Requires filtering of input and output leads, and shielding of complete assembly to eliminate radiated interference.

A rotating machine; field poles are common to both motor and generator windings.

Has fair regulation characteristics.

Efficiency as high as 45 percent can be obtained.

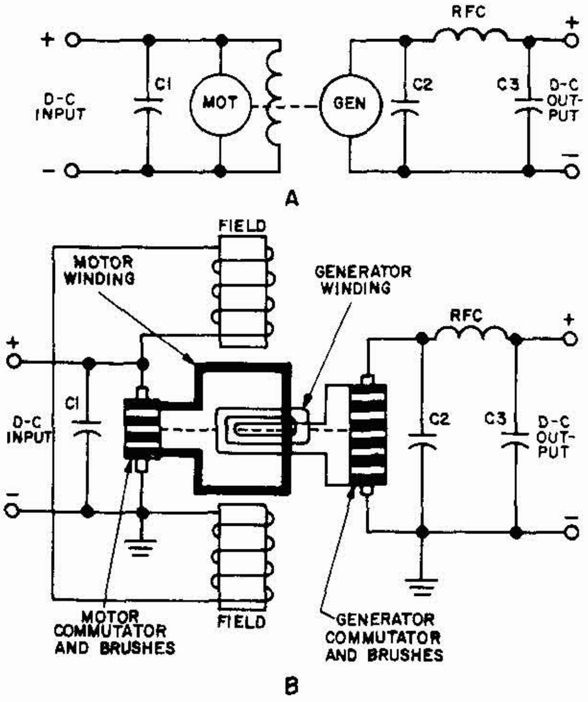
CIRCUIT ANALYSIS.

General. The dynamotor is a rotating electromechanical device used to change one value of d-c voltage to a different value of d-c voltage. By definition, a dynamotor is a combination electric motor and generator having two (or more) separate rotor windings and a common set of field poles; one winding receives direct current from a primary power source and operates as a motor to produce rotation of the armature assembly, while the remaining winding(s) operates as a generator to produce a d-c output voltage.

Circuit Operation. A simplified schematic for a typical dynamotor is shown in part A of the accompanying illustration, and a functional diagram is shown in part B of the illustration.

Capacitor C1 is an input filter capacitor provided to remove variations in the input d-c voltage, caused by sparking of the brushes at the motor commutator; the capacitor also reduces interference which can be radiated to other equipments connected to the same power source. Capacitor C2, r-f choke RFC, and capacitor C3 form a filter network at the output of the dynamotor to remove the effects of sparking at the generator commutator. Depending upon the design of the dynamotor, inductance- capacitance filters may be installed at both the input and the output to prevent undesirable voltage transients (hash), caused by commutation, from being radiated or coupled through the input and output leads to other electronic equipments. Also, in many dynamotor output circuits, because the generator commutation ripple frequency is relatively high, an iron-core choke and a capacitor (4 μf or larger) are used to filter the d-c output and remove the ripple-voltage component.

The single, rotating armature assembly carries both the motor winding and the generator winding. Each winding terminates in a separate commutator; the commutators are usually located at opposite ends of the armature assembly. The two windings occupy the same set of slots in the armature, and terminate in their respective commutators. Since



Simplified Schematic and Functional Diagram of Typical Dynamotor

the motor and generator windings are both on the same rotor assembly, the field is common to both the motor and the generator. Because the field winding is connected in parallel with the motor winding, the motor is called a **shunt-connected**, or **shunt-wound**, motor. One of the desirable characteristics of this type of motor is that the speed of armature rotation remains relatively constant, regardless of the changes in load placed upon the motor; as a result, the output voltage is also held relatively constant.

When a d-c voltage is applied to the low-voltage motor commutator (input terminals) of the dynamotor, current flows in the motor winding of the armature. At the same time, the applied voltage appears across the field coils and a current flows in them to produce a strong magnetic field. The flux produced by the field reacts with the flux produced by the motor winding; this results in torque, which causes the armature assembly to rotate. Because the generator winding is wound on the same assembly, it also rotates in the same magnetic field produced by the field coils. Therefore, since the generator winding cuts the magnetic field as it rotates, this action induces a voltage in the generator winding. The d-c output voltage is taken from the generator commutator of the dynamotor, is filtered if necessary, and is applied to the load.

Since the motor and generator share a common magnetic field, the relationship of input voltage to output voltage depends on the ratio of the number of turns in the motor winding to the number of turns in the generator winding. For example, if the number of turns in the generator winding is increased (with respect to a given motor winding), the output voltage will increase accordingly; whereas, if the number of turns in the generator winding is decreased, the output voltage will decrease. In like manner, changing the number of turns in the motor winding (for a given generator winding) will affect the output voltage and also the speed of armature rotation. Changing the strength of the magnetic field will not appreciably affect the voltage ratio of the dynamotor. If the field strength is increased, the armature is slowed down, but the induced voltage in the generator winding remains unchanged; on the other hand, if the field strength is decreased, the armature speed increases, but the induced voltage remains the same. This is true because the field strength and the speed of rotation are inversely proportional to each other. For example, when the magnetic flux is increased in the field, the armature speed decreases and the generator winding cuts more lines of flux at a lower speed; conversely, when the magnetic flux is decreased, the armature speed increases and the generator winding cuts fewer lines of flux at a higher speed. In either case, the induced voltage in the generator winding remains essentially the same.

The inverse relationship between armature speed and field strength is a basic principle of d-c motors, and exists because of the counter emf which is generated by the armature cutting flux as it rotates through the magnetic field. The current induced by the counter emf flows in a direction opposite to that of the applied current. If the field strength of a motor is reduced, the value of the counter emf, which is dependent upon the strength of the field flux, is also reduced. A drop in counter emf allows a greater current to flow in the armature and this causes the motor speed to increase. The speed increases because the effect of the increase in armature current far exceeds that of the decrease in field flux. When the field strength is increased, the reverse action takes place. The increase in field current, and thus field strength, causes the counter emf to increase. This action decreases the applied current and thus reduces the motor speed.

One disadvantage of the dynamotor is that the output voltage cannot be adjusted to different values without changing the input to the motor and field windings. For this reason, the dynamotor must be designed for a given output voltage and load current.

Dynamotors operating from a d-c source commonly have an input voltage rating of 6, 12, or 24 volts, and, depending upon the design and output requirements, can deliver 1200 volts or more to the load. A dynamotor is not necessarily restricted to only one generator winding—more than one winding is sometimes placed on the armature to provide for additional outputs, as required. For example, a low-voltage winding for the operation of electron-tube filaments may be incorporated in the armature assembly. In this case a separate commutator for d-c output (or separate slip rings for a-c output) and associated brushes are required for connection to the low-voltage winding.

One variation of this motor has, in addition to the shunt-connected field coils, another set of field coils connected in series with the motor winding. See the accompanying

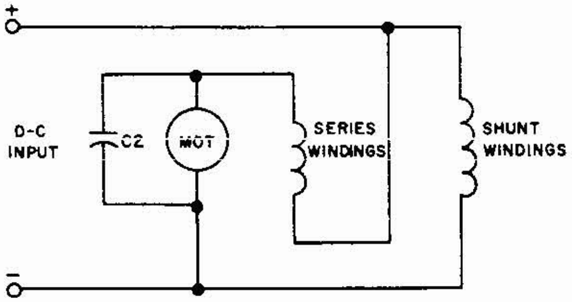


Diagram of Compound Motor

illustration. This type of motor is called a **compensated, compound,** or **stabilized shunt** motor; the flux components developed in the shunt and series field coils are combined within the dynamotor to produce a strong magnetic field. Still another variation in design utilizes a permanent magnet to furnish the magnetic field; this variation is satisfactory for many applications, and is somewhat more efficient than an equivalent dynamotor with field coils, because less input current is required for operation.

FAILURE ANALYSIS.

General. Dynamotors are built to high standards and are characterized by long life and relatively trouble-free operation. If normal preventive maintenance is carried out at regular intervals as recommended by the equipment maintenance handbook, few failures will result. However, many dynamotors are subject to operation under conditions which are less than ideal, and, as a result, failures do occur.

The dynamotor can best be thought of as two separate machines combined in a single frame and sharing a common magnetic field. The relationship between motor and generator is purely mechanical. There is no electrical connection between the motor and generator windings. Since the currents in the two windings flow in opposite directions, their resultant magnetic effect is zero, which effectively isolates one winding from the other. In failure analysis procedures for the dynamotor, the two windings are treated separately; that is, the input circuit is treated as a conventional d-c motor, and the output circuit is treated as a conventional d-c generator.

In testing the dynamotor, the procedures are the same as those given in Navy publications for similar d-c machinery (d-c motors and generators). It must be first established whether the trouble is of an electrical or a mechanical nature, or both; therefore, several of the more common dynamotor troubles are given in the paragraphs which follow, to help the technician recognize typical failures.

No Output. If the dynamotor fails to start, the input circuit and fuse should be checked to make certain that the applied input voltage is present and of the correct value. If necessary, the associated primary power source control or relay circuit should be checked to make certain that it is functioning normally. Also, a low applied input voltage or an open field circuit can prevent the motor from starting. If the dynamotor is operating but there is no output, the load should be disconnected and checks made to determine whether the load is shorted; after the load is disconnected, a voltage measurement can be made at the output terminals of the dynamotor to determine whether voltage is present. As a further check, a voltage measurement can be made at the high-voltage brush terminals to determine whether voltage is present at the output of the generator winding. If filter capacitor C2 or C3 should become shorted, there will be no output from the dynamotor; if capacitor C3 should become shorted, it is likely to result in the opening of the filter choke, RFC. If voltage is found to be present at the high-voltage brush terminals, the filter circuit used to remove the ripple voltage from the d-c output should be checked for a shorted capacitor or an open filter choke in a manner similar to the procedures used for any other type of d-c power supply.

Low Output. The primary power source is normally connected to the input of the dynamotor, using relatively short and heavy leads. Since a low applied voltage can cause a low output condition, the input to the dynamotor should be measured to determine whether the voltage is of the correct value.

A low-output condition can be the result of one or a combination of causes, and may be accompanied by a temperature rise or mechanical noise, or both. Opens or shorts in the armature windings, excessive sparking at either commutator, poor commutation because of the presence of dirt or oil, worn brushes, and brushes improperly seated are all typical troubles which contribute to a low-output condition.

If the load current is excessive, the output voltage may be below normal; therefore, the load current should be checked to determine whether it is within tolerance. As mentioned previously, this condition is likely to be accompanied by a temperature rise in the machine and by sparking at the commutator. A leaky bypass capacitor (C2 or C3) or a leaky filter circuit capacitor, used to remove the ripple voltage from the d-c output, may cause additional load and drop the output voltage accordingly.

Mechanical Noise. Excessive mechanical noise in a dynamotor is another indication of impending trouble. Although the dynamotor itself (or the unit in which the dynamotor is located) is usually mounted on some form of shock-mount support, to reduce mechanical vibration and noise resulting from armature rotation, various abnormal mechanical noises can still be heard, identified, and traced to the source. High mica, an out-of-round or eccentric commutator, high or low commutator segments, and worn bearings are all typical causes of abnormal operating noise.

Broken or chipped brushes, or brushes which are not seating properly, develop a characteristic high-frequency whine, while worn or dirty bearings generally cause a low-frequency (or grinding) sound. Bearing failure is frequently the result of wear caused by lack of proper lubrication; badly worn bearings may allow the rotating armature assembly to strike the field poles and create additional noise.

Commutator Sparking. Excessive sparking at the commutator is generally an indication of brush or commutator trouble. Sparking brushes may also be an indication of excessive load current; therefore, the load current should be measured to determine whether it is excessive. As mentioned previously, this condition will likely be accompanied by a rise in the temperature of the dynamotor.

Worn brushes, lack of brush pressure, and brushes not seating properly are common causes of brush sparking; open coils in the armature assembly will also cause brush sparking. Typical commutator troubles are high or low segments, an out-of-round or eccentric commutator surface, and a high mica condition. The high-mica condition occurs when the commutator segments have worn down below the insulating mica separator strips between the copper segments. If any one of the three commutator conditions mentioned is found to exist in the dynamotor, the machine will require dissasemby and repair (by the electrical shop), since it will be necessary to turn down the commutator in a lathe and then undercut the mica to a level which is below the surface of the commutator segments.

Temperature Rise. An excessive temperature rise is one of the first indications of trouble. Dynamotors are designed for either continuous or intermittent duty, and are rated accordingly. Occasionally, a dynamotor which is rated for intermittent duty is run continuously; in this case the dynamotor is not being operated in accordance with its design rating, and a temperature rise may be expected.

An overload condition is a common cause for overheating; therefore, the load current should be checked to determine whether it is excessive. Poor ventilation resulting from restricted cooling vents or clogged internal air passages can cause a temperature rise because of the lack of adequate cooling-air circulation. Shorts in the commutator segments, shorted turns in the armature or field windings themselves, or winding shorts to metal parts of the armature or frame are all typical causes of dynamotor heating. Also, worn brushes or high mica on the commutator, or both, can contribute to an abnormal temperature rise. In any event, excessive heating of a dynamotor should always be considered an effect rather than a cause of trouble.

INVERTER.

APPLICATION.

An inverter is one form of rotary converter, and is used to change the relatively low voltage of a d-c power source to ac for use by the electrical load. Depending upon the design of the inverter, the output can be either single-phase or polyphase (multiphase) ac; the frequency of the output voltage is generally 60, 400, or 800 cycles. The inverter is frequently used in aircraft, shipboard, and small-craft applications where the primary source of power is dc.

CHARACTERISTICS.

Input to inverter is dc; output is ac.

Requires filtering of input leads to eliminate possible interference resulting from commutation.

A rotating machine; commonly uses two sets of rotors and stators, one set (rotor and stator) functioning as a motor and the other as a generator.

A-C output commonly obtained by either of two methods: a stationary field with output taken from a rotating armature, using slip rings and brushes, or a rotating field (rotor) with output taken from one or more stationary armature (stator) windings.

Frequency of output controlled by speed of rotation.

Has fair regulation characteristics; output varies with d-c input.

Maximum efficiency obtained when power factor of load is near unity.

CIRCUIT ANALYSIS.

General. The inverter is a rotating electromechanical device for converting direct current into alternating current. The inverter is a combination electric motor and alternator; the motor is the prime mover which produces the necessary rotation of an armature, field, or rotor assembly. By definition, the winding in which the output voltage is generated is called an **armature winding**, and the winding through which dc is passed to produce an electromagnetic field is called the **field winding.**

Inverters fall into three general classes, depending upon the a-c generator design. These classes are called the **rotating-**or **revolving-armature**, the **rotating-**or **revolving-field**, and the **inductor-type alternator.**

In the rotating- or revolving-armature a-c generator, the stator provides a stationary electromagnetic field. The rotor, acting as the armature, revolves in the magnetic field, cutting the lines of force, and produces the desired output voltage. The armature a-c output is taken through slip rings and brushes. One limitation of this type of generator is that the output is taken through sliding contacts (slip rings and brushes); therefore, this type of machine is usually limited to low-power, low-voltage applications.

The rotating- or revolving-field a-c generator is most widely used. In this type of machine, current from a d-c source is passed through slip rings and brushes to field coils wound on a rotor. Thus, a magnetic field is produced in the rotor of fixed polarity, and, since the rotor is driven by the motor, a rotating magnetic field is created. The rotating magnetic field extends outward and cuts the stationary armature (stator) windings; as the rotor turns, ac is produced in the stationary windings. The output is taken from the stationary windings, either single-phase or polyphase, through the output terminals to the load without the need for slip rings and brushes.

In the inductor-type alternator, a field (exciter) winding and an armature winding are both contained within the same stator frame. The rotor, including its pole pieces, is made of soft-iron laminations. DC is supplied to the field (exciter) winding, thus establishing a magnetic field in the stator. As the rotor revolves, the poles of the rotor become aligned with the poles of the stator, and maximum flux density is produced. As the poles move out of alignment, the flux decreases. The sinusoidal increase and decrease in magnetic flux in the rotor and stator as the rotor rotates induces an alternating voltage in the stationary armature windings. The a-c output is taken from the stationary armature windings without the need for slip rings and brushes. This type of machine is frequently used to generate single-phase, high-frequency ac.

The frequency of the a-c generator voltage depends upon the speed of rotation of the rotor and the number of pairs of poles in the machine. That is:

$$F = \frac{P \times rpm}{60}$$

where P is the number of pairs of poles, and rpm is the revolutions of the rotor per minute. The following examples are provided to illustrate the use of the formula in solving for rpm, F, and P.

Alternators are generally designed with a multipole rotor and a multipole stator; however, for simplicity, the first example will consider a basic alternator having only a two-pole rotor and a two-pole stator. In this machine one complete cycle of a-c voltage will be induced in the armature winding for each complete revolution of the rotor as it passes under the two (north and south) poles of the stator. When the rotor of this simple machine rotates at a rate of 3600 rpm, the frequency (in cps) of the a-c output voltage is easily found by using the basic formula. Thus:

$$F = \frac{P \times rpm}{60}$$

$$= \frac{1 \times 3600}{60}$$

$$= 60 \text{ cps}$$

If six poles are provided on the rotor and on the stator of an a-c generator, then during each revolution each pair of rotor poles passes under three pairs of stator poles, and thus generates three complete cycles of a-c output. Since there are three pairs of poles provided on the rotor, it follows that three times as many cycles will be generated during one rotor revolution as will be for a single pair, or a total of nine cycles. Assuming again that the output frequency is 60 cps, the required rpm of the rotor may be found by transposing the basic formula to solve for rpm. Thus:

$$rpm = \frac{60\,F}{P}$$

$$= \frac{60 \times 60}{3}$$

$$= \frac{3600}{3}$$

$$= 1200 \text{ rpm}$$

This example clearly illustrates the inverse relationship existing between the speed of rotor rotation and the number of pairs of poles of the alternator. For the same output frequency as in the first example (60 cps), when the number of pairs of poles was increased by a factor of three, the required rpm of the rotor was decreased by one third, that is, from 3600 to 1200 rpm.

When the speed of rotor rotation and the output frequency of the alternator are known, the number of pole pairs is easily found. For example, if F = 400 cps and the rotor rotation is 3000 rpm, then the number of pairs of poles is found as follows:

$$P = \frac{60\,F}{rpm}$$

$$= \frac{60 \times 400}{3000}$$

$$= \frac{24000}{3000}$$

$$= 8 \text{ pairs of poles}$$

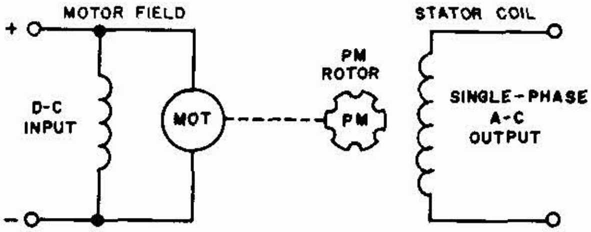
When the load on a generator is changed, the terminal voltage varies with load. The amount of variation depends on the design of the generator and the power factor of the load. Unless the load is fixed and constant, some form of voltage regulation is necessary to maintain the output voltage relatively constant under conditions of varying load. In practice, once a machine is designed and built, the output voltage is controlled by varying the d-c excitation voltage applied to the field winding. When an a-c generator is equipped with a voltage regulator, the regulator uses the a-c output voltage which is to be regulated as a sensing voltage to control the amount of current used to excite the field.

The operation of a typical regulation system can be briefly explained as follows: a drop in output voltage sensed by the regulator causes the regulator to increase the field current, and an increase in field current causes a corresponding increase in output voltage to compensate for the original drop in output voltage. Stated conversely, if the output voltage should rise, the regulator decreases the field current, causing a corresponding decrease in output voltage to compensate for the original rise in voltage. Thus, the regulator senses a change in output voltage and compensates for this change by altering the field (exciting) current accordingly. A detailed description of the construction and operation of various voltage regulators can be found in Navy publications covering basic electricity, or in course materials for EM and AE ratings.

Several typical inverters will be discussed briefly in the paragraphs that follow.

Inverter with Permanent-Magnet Rotor. One of the simplest inverters is the permanent-magnet-type inverter shown in the accompanying schematic. This rotating-field-type inverter is designed to supply single-phase ac at a frequency of either 400 or 800 cycles to a constant and relatively light load.

The inverter consists of a d-c motor and a permanent-magnet-type a-c generator assembly combined within a single housing. The d-c motor is a shunt-connected, or shunt-wound, motor with armature and commutator mounted on a single shaft, and rotating within the stationary field (stator)

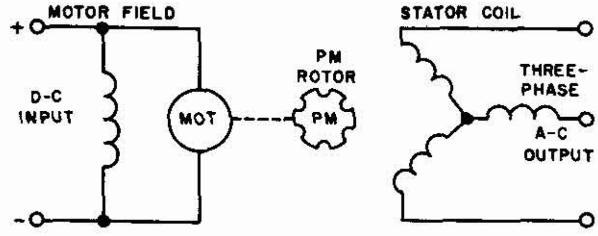


Simple Inverter with Permanent-Magnet Rotor; Single-Phase Output

windings. The motor armature rotates within the stationary field, and the commutator rotates between a pair of spring-loaded brushes. The motor brushes are mounted in holders that are placed on opposite sides of the motor housing; the construction is such that the brushes may be easily removed for inspection and replacement.

The a-c generator portion of the inverter consists of a stationary armature and a rotating permanent-magnet field. The permanent-magnet rotor is mounted on the same shaft as the motor armature and commutator. The rotating magnetic field is produced by a six-pole, permanent-magnet rotor, with alternate poles around the circumference magnetized alike. The stationary armature (stator) is a six-pole, six-slot, laminated stator with the single-phase output winding mounted in the slots of the stator. A magnetic field exists about the poles of the permanent-magnet rotor, and as the rotor revolves the poles of the rotor align with the poles of the stator to produce maximum flux density in the stator. As the poles move out of alignment, the flux decreases in the stator to a minimum, and the flux polarity reverses as the rotor poles move into alignment with the stator once again. The sinusoidal changing of flux polarity as the rotor poles move past the stator poles induces an alternating current in the armature windings located in the slots of the stator. The a-c output is taken from the stationary armature windings, without the need for slip rings and brushes. Since this inverter is designed for use with a constant load, no provision is made for either voltage or speed regulation.

The permanent-magnet-type inverter can also be made to furnish three-phase output. The three-phase inverter, shown in the accompanying schematic, is essentially the same size and weight as the single-phase inverter described above.



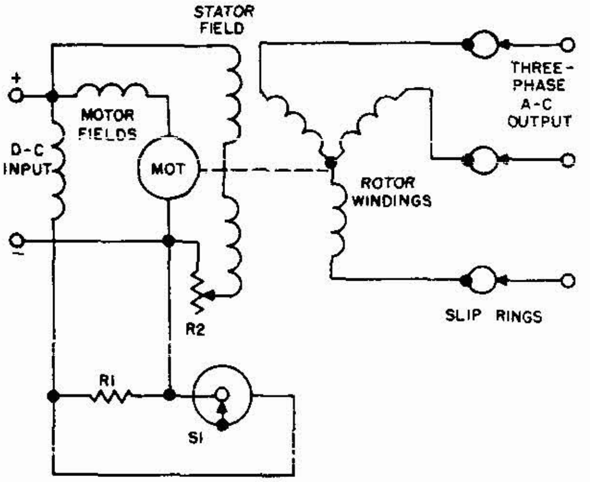
Simple Inverter with Permanent-Magnet Rotor; Three-Phase Output

The d-c motor is essentially the same as that described for the single-phase machine. Also, the six-pole, permanent-magnet rotor of the generator is placed on the same shaft and rotates with the motor armature, as described for the single-phase machine. The three-phase stationary armature consists of a nine-pole laminated stator. In this generator nine separate coils are wound in the stator slots; each set of three coils, located 120 degrees apart on the stator, are connected in series to form an output winding for each phase. The three sets of series coils produce output voltages which differ in phase by 120 electrical degrees; the stator windings are shown on the schematic as a three-phase wye, or star, connection.

As in the single-phase machine, a magnetic field exists about the six poles of the permanent-magnet rotor. When three of the rotor poles spaced 120 degrees apart are in alignment with three of the stator poles of the same winding phase, the remaining three rotor poles are positioned between the remaining six stator poles. Thus, when maximum flux is produced in one set of stator poles, one of the remaining two sets of stator poles is increasing in flux density, while the other set is decreasing in flux density. The flux polarity in any stator pole reverses as alternate rotor poles move past the individual stator poles; as a result, the changing flux induces an alternating current in each of the three armature windings which is 120 degrees out-of-phase with the current produced in either of the other two armature windings. The three-phase a-c output is taken from the three stationary armature windings without the need for slip rings and brushes. Since this inverter is designed for use with a constant load, no provision is made for either voltage or speed regulation.

Inverter with Rotating Armature. The inverter shown in the accompanying schematic is typical of many inverters with separate d-c fields for the motor and generator sections. This type of inverter has a stationary field, and the armature windings rotate within the magnetic field produced by the field. Although the schematic shows an inverter with three-phase output, the same principles discussed here apply to an inverter with single-phase output.

The d-c motor shown in the accompanying schematic has a compounded field consisting of both a series and a shunt winding. This type of motor provides better speed regulation under conditions of varying load; as a result, the output frequency can be held relatively constant. To further improve the frequency stability of the inverter, a speed governor is incorporated in series with the shunt winding to control the shunt-field current and, therefore, the magnetic flux developed by the shunt field. The governor is a centrifugal type, mounted on the armature shaft of the motor. Electrical connection to the governor contacts is accomplished by two slip rings, located at the commutator end of the armature; brushes are used to contact the slip rings and complete the circuit to the speed regulating resistor, R1. The governor controls the speed of the motor by placing resistor R1 into and out of the shunt-field circuit. For example, when the motor attempts to increase speed, the governor contacts close to shunt the resistor, R1. (The governor contacts open and close by centrifugal action.) As a result, the current through the shunt-field winding increases, the magnetic flux developed by the field increases, and the motor speed



Inverter With Rotating Armature

is reduced accordingly. Conversely, when the motor attempts to decrease speed, the governor contacts open and resistor R1 is placed in series with the shunt-field winding. In this case, the current through the shunt-field winding decreases the magnetic flux developed also decreases, and the motor speed is increased accordingly. By controlling the motor speed, the centrifugal governor thus controls the resulting frequency of the a-c output.

The generator portion of the inverter consists of a stationary four-pole field and a three-phase, wye- or star-connected rotating armature. The armature windings are distributed and mounted in the slots of the laminated rotor core, and are brought out to three slip rings which are mounted on the rotor shaft; brushes contact the slip rings to complete the circuit.

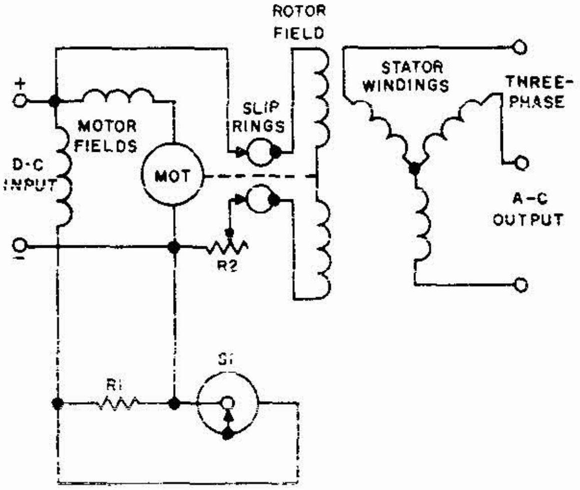
The stationary field, consisting of four series-connected coils (each placed on a pole piece), is supplied direct current from the d-c input to the motor. The strength of the magnetic flux developed by the field is determined by the current which passes through the field windings; consequently, this current also determines the amplitude of the output voltage produced in the armature windings. Resistor R2 is placed in series with the field windings to adjust the value of current through the windings and thus control the amplitude of the a-c output voltage in all three phases.

If the electrical load on the inverter is relatively constant, the output voltage is likely to remain relatively constant; thus, resistor R2 is usually adjusted under conditions of normal load to obtain the desired output voltage. However, when the electrical load is subject to considerable variation, a system of voltage regulation must be employed. As mentioned in a previous paragraph, voltage regulation can be achieved by sensing the a-c output voltage and then controlling the magnetic field to compensate for the original output-voltage variation. A typical system for output-voltage regulation uses d-c voltage rectified from one of the phases to control a carbon-pile voltage regulator. The regulator, in turn, substitutes for resistor R2 in the field circuit and varies the current through the field windings; thus, the magnetic flux of the field is varied. As a result, the a-c output voltage amplitude is controlled by action of the carbon-pile regulator to compensate for changes occurring in the output voltage. (A detailed description of generator and alternator voltage regulation is found in Navy publications covering basic electricity and, therefore, is not given in this handbook.

In the inverter described here, the output can be set to a given value by adjustment of resistor R2, or the output can be automatically regulated by a regulating system which substitutes for resistor R2. The governor assembly, together with resistor R1, on the d-c motor controls the speed of rotation and thus the frequency of the a-c output. One disadvantage of this inverter is that all current delivered to the load must pass through the slip rings and brushes of the armature assembly. Therefore, the use of this type of inverter is usually limited to low-power, constant-load applications, where the use of slip rings and brushes will not seriously affect operating efficiency.

Inverter with Rotating Field. The inverter shown in the accompanying schematic has a rotating field and stationary armature windings; the machine is similar to the inverter using a permanent-magnet rotor, described earlier, except in this instance a d-c rotor field is used. Although the schematic shows an inverter with three-phase output, the same principles discussed here apply to an inverter with single-phase output.

The d-c motor shown in the accompanying schematic has a compounded field consisting of both a series winding and a shunt winding. The motor is identical with the motor just described for the inverter with a rotating armature. The motor is equipped with a centrifugal governor, which controls the motor speed by shunting resistor R1 into and out of the shunt-field circuit. (The speed-regulating action of the



Inverter With Rotating Field

governor assembly and its effect upon output frequency was described in a preceding paragraph.)

The generator portion of the inverter consists of a rotating field assembly and stationary armature windings. D-C exciting coils for the rotating field are wound on the six-pole rotor, and are brought out to two slip rings which are mounted on the rotor shaft; brushes contact the slip rings to complete the d-c circuit to the rotating field. The direct current for the rotating field is obtained from the d-c input to the motor. The strength of the magnetic flux developed by the rotating field is determined by the current which passes through the field windings; consequently, this current also determines the amplitude of the output voltage produced in the stationary armature windings. Resistor R2 is placed in series with the field windings to adjust the value of current through them, and thus controls the amplitude of the a-c output voltage in all three phases.

The three-phase stationary armature consists of a nine-pole, laminated stator, similar to the armature described previously for the three-phase inverter using a permanent-magnet rotor. The nine separate coils of the stator are connected to form three sets of three series coils each; the three sets of series coils produce output voltages which differ in phase by 120 electrical degrees. The armature (stator) windings are shown on the schematic as a three-phase wye or star connection.

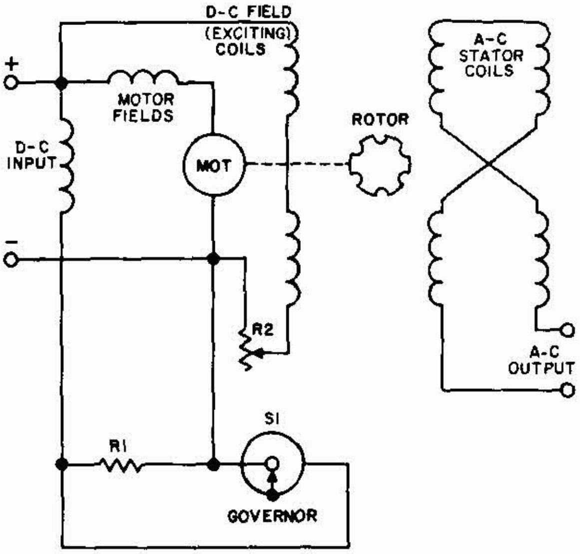
If the electrical load on the inverter is relatively constant, the output voltage is likely to remain relatively constant; thus, resistor R2 is usually adjusted under conditions of normal load to obtain the desired output voltage. However, when the electrical load is subject to considerable variation, a system of voltage regulation must be employed. The voltage and output-frequency regulation principles for this inverter are identical with those given in previous paragraphs for the inverter with rotating armature.

One advantage of this type of inverter is that the three-phase a-c output is taken directly from the stationary armature windings without the need for slip rings and brushes; for this reason the inverter is commonly used for high-power applications, because the load current is not required to pass through the resistance offered by moving contacts (slip rings and brushes).

Inductor-Type Alternator. The inverter shown in the accompanying schematic is typical of inverters which operate on an induction principle and employ stationary field and armature windings located side-by-side in a common frame; the stator windings and their associated poles share a common rotor assembly.

The d-c motor shown in the accompanying schematic has a compounded field consisting of both a series winding and a shunt winding. The motor is identical with the motor previously described for the inverter with a rotating armature. The motor is equipped with a centrifugal governor which controls the motor speed by shunting resistor R1 into and out of the shunt-field circuit. (The speed-regulating action of the governor assembly and its effect upon output frequency were described in a previous paragraph.)

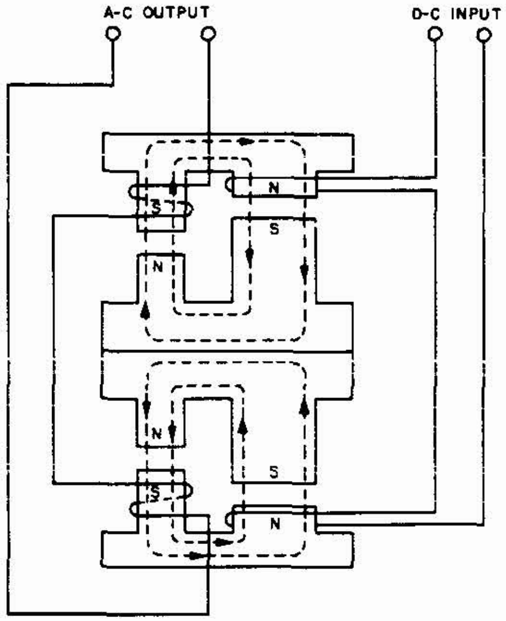
The generator portion of the inverter consists of a six-pole, laminated rotor mounted on the end of the d-c motor shaft, and a stator assembly with two dual-pole pieces on which the stator windings are mounted. The two d-c field (exciting) coils, connected in series, are mounted around both dual-pole pieces, which are opposite each other in the stator assembly; the four a-c armature coils, connected in series, are mounted around the individual poles of the two dual-pole pieces.



Inverter With Inductor-Type Alternator; Single-Phase Output

Direct current is supplied to the d-c field (exciting) coils of the stator from the d-c input to the motor. The field coils establish a magnetic field in each of the two dual-pole pieces that make up the stator assembly, as shown in the accompanying diagram. The current which passes through the field determines the strength of the magnetic flux developed by the d-c field winding, and thus the amplitude of the output voltage. Resistor R2 is placed in series with the field winding to adjust the value of field current, in order to control the amplitude of the a-c output voltage.

For a given value of current in the d-c field winding (as determined by the adjustment of resistor R2), the strength of the field flux linking the a-c armature coils on the stator will vary as the reluctance of the magnetic circuit is varied. Because of the high permeability (as compared with air) of the soft iron laminations of the rotor, the reluctance is varied as the poles of the revolving rotor continuously move in and out of alignment with the poles of the stator. As the rotor revolves and varies the reluctance of the magnetic circuit, the strength of the magnetic field —— and, consequently, the amount of induction coupling to the a-c coils — will also vary. The periodic variation in induction coupling, which is sinusoidal in nature, induces an alternating current in the a-c armature coils. This current achieves a maximum value at a time when the poles of the rotor and stator are in alignment, and reaches a minimum value when the rotor and stator poles are farthest out of alignment. One cycle of generated voltage occurs in the armature winding



Basic Inductor-Type Alternator

as the rotor rotates through an angle equal to the angle of separation for adjacent rotor poles. Since it is relatively easy to build a machine with a large number of rotor poles, the inductor-type design is readily adaptable to the generation of high frequencies. For a given number of rotor and stator poles, the induced voltage in the armature windings alternates at a frequency determined by the speed of the rotor assembly.

If the electrical load on the inverter is relatively constant, the output voltage is likely to remain relatively constant, and, as for the other inverters previously described, resistor R2 is usually adjusted under conditions of normal load to obtain the desired output voltage. However, when the electrical load is subject to considerable variation, a system of voltage regulation must be employed. The voltage and output-frequency regulation principles for the inductor-type alternator are identical with those given in previous paragraphs for the inverter with rotating armature.

The inductor-type alternator is frequently used in applications where high-frequency output at a moderate power level is required. One advantage of this type of inverter is that no slip rings or brushes are used for the alternator portion of the inverter, the output being taken directly from the armature windings.

FAILURE ANALYSIS.

General. Inverters generally provide trouble-free operation as long as normal preventive maintenance is performed in accordance with the procedures recommended by the equipment maintenance handbooks. However, the technician must be aware of possible failures and be able to recognize such failures when they occur.

The inverter can best be thought of as two separate machines combined in a single housing and sharing a common rotating shaft. The relationship between the d-c motor and a-c generator (or alternator) is essentially a mechanical one; therefore, in failure-analysis procedures for an inverter, the d-c motor and a-c generator are usually treated as separate machines mechanically coupled to each other. In testing inverters, the procedures are the same as those given in Navy publications for similar d-c motors and a-c generators. It must be first established whether the trouble is of an electrical or a mechanical nature, or both; therefore, several of the more common d-c motor and a-c generator troubles are given in the paragraphs which follow to help the technician recognize typical failures.

Temperature Rise. As stated previously for the dynamotor, an excessive temperature rise in an inverter is one of the first indications of trouble. Excessive heating of an inverter should always be considered as an effect rather than a cause of trouble.

An overload condition is a common cause for overheating; therefore, the load current should be checked to determine whether it is excessive. The three-phase inverter offers a problem in distributing the electrical load equally between the three phases. For this reason, it is possible that one phase may become overloaded and cause overheating of the machine because of the load unbalance; therefore, the load current in each phase should be checked to determine whether it is excessive and whether the load is balanced for each phase.

Poor ventilation, resulting from restricted cooling vents or clogged internal air passages, can cause a temperature rise because of the lack of adequate cooling-air circulation. Shorts in the d-c motor commutator segments or shorted turns in the motor armature windings, shorted turns in the motor field windings themselves, or windings shorted to metal parts of the armature or frame are all typical causes of motor heating. Worn brushes or high mica on the commutator, or both, can also contribute to an abnormal temperature rise in the motor. Shorted turns in the windings of the a-c generator (alternator) rotor or stator can also contribute to a temperature rise in the machine.

Mechanical Noise. Excessive mechanical noise in an inverter is another indication of impending trouble. Although the inverter itself (or the unit in which the inverter is located) is usually mounted on some form of shock-mount support, to reduce mechanical vibration and noise resulting from the rotating parts of the machine, various abnormal mechanical noises can still be heard, identified, and traced to the source. High mica, an out-of-round or eccentric motor commutator, high or low motor commutator segments, and dry or worn bearings are all typical causes of abnormal operating noise.

Broken or chipped motor brushes, or brushes which are not seating on the commutator properly, develop a characteristic whine; however, this noise may not be readily heard because loose rotor or stator laminations in the a-c generator portion of the machine may develop a high-frequency sound which masks the commutation noise. Worn or dirty bearings generally cause a low-frequency (or grinding) sound, and may also result in the generation of additional heat. Bearing failure is frequently the result of wear caused by lack of proper lubrication; badly worn bearings may allow the rotor assembly to strike the stator and create additional noise. Furthermore, a rotor which is not centered in the stator because of worn bearings, although it may not strike the stator, is likely to cause some localized heating in the stator.

Motor Commutator Sparking. Excessive sparking at the motor commutator is generally an indication of brush or commutator troubles. Sparking brushes may also be an indication of open or shorted coils in the armature winding, or an indication of a grounded, open, or shorted field winding. As mentioned previously, this condition will likely be accompanied by a rise in temperature of the machine. Worn brushes, lack of brush pressure, brushes sticking in their holders, or brushes not seating properly are also causes for sparking.

Typical d-c motor commutator troubles are high or low segments, an out-of-round or eccentric commutator surface, or a high mica condition. (The high mica condition occurs when the commutator segments have worn down below the insulating mica separator strips between the copper segments.) If any one of the three conditions mentioned is found to exist in the motor commutator, the machine will require disassembly and repair (by the electrical shop), since it will be necessary to turn down the commutator in a lathe and then undercut the mica to a level which is below the surface of the commutator segments.

No Output. If the inverter fails to start, the input circuit should be checked to make certain that the applied d-c voltage is present and of the correct value. If necessary, the associated primary power source control or relay circuit should be checked to make certain that it is functioning normally. A low applied input voltage or an open field circuit can also prevent the motor from starting.

If the inverter is running but there is no output, the load should be disconnected and checks made to determine whether the load is shorted; a voltage measurement can be made at the output terminals of the a-c generator after the load is disconnected to determine whether voltage is present. In the case of the three-phase inverter, measurements should be made on each of the three phases. With the inverter disconnected from its input and output circuits, continuity measurements can be made in accordance with the equipment maintenance handbook instructions to determine whether any of the windings are open.

Low Output. A low-output condition can be the result of one or a combination of causes, and may be accompanied by a temperature rise or mechanical noise, or both. Low input dc to the exciter coils, poor slip ring contact because of the presence of dirt or oil, worn brushes, and improper brush tension are typical troubles which contribute to a low-output condition.

Shorted windings can cause low output, and this condition is nearly always accompanied by a temperature rise in the inverter. If the load current is excessive, the output voltage may be below normal; therefore, the load current should be checked to determine whether it is within tolerance. For the three-phase generator or alternator, the load current for each phase should be checked to determine whether it is within tolerance and whether the load is balanced for each phase. As mentioned previously, an unbalance in the load of the three-phase machine is likely to cause a temperature rise in the machine.

A low-output condition can also be caused by a decrease in the current through the exciting field; as a result, the magnetic flux in the field decreases and the output voltage decreases accordingly. If the d-c (exciting) field current is controlled by a voltage regulating system, it is possible that the system is faulty. If the field current is established by means of an adjustable resistor (resistor R2), it is possible that the value of the resistor is too high. In the case of the inverter with rotating field, the slip rings and brushes may cause this condition because of excessive contact resistance.

High Output. A high-output condition is usually caused by an excessive current in the exciting field; as a result, the magnetic flux in the field increases and the output voltage increases accordingly. If the d-c (exciting) field current is controlled by a voltage regulating system, it is possible that the system is faulty. If the field current is established by means of an adjustable resistor (resistor R2), it is possible that the value of the resistor is too low.

Unsteady Output Voltage. The cause of unsteady or fluctuating output voltage, sometimes called **voltage hunting,** varies, depending on the design of the inverter and the method incorporated in the machine to regulate the value of the output voltage. If the output voltage fluctuates (assuming the speed of rotation to be relatively constant), this condition may be caused by fluctuations of the current in the exciting field; as a result, the magnetic flux in the field will also fluctuate. This condition may also be caused by a defective voltage-regulating system (mentioned previously under the high-output and low-output conditions discussed above), or, if the inverter has a rotating field, the slip rings and brushes may not be in good contact with each other.

Unsteady or Incorrect Output Frequency. The cause of unsteady output frequency, sometimes called **frequency hunting,** or simply **hunting,** and the cause of incorrect output frequency varies, depending on the design of the inverter and the method incorporated in the machine to regulate the speed of rotation. If the speed of rotation fluctuates, the output frequency will also fluctuate, since the speed of the rotor determines the frequency of the alternations in the armature windings. Thus, if the rotor speed is below normal, the output frequency will also be below normal, and, conversely, if the rotor speed is above normal, the output frequency will also be above normal. If the d-c motor has a centrifugal-governor assembly, the governor contacts, slip rings, and brushes should be inspected for possible defects. Instability in the motor speed may also be evidenced by mechanical noises, temperature rise, brush sparking, etc, mentioned earlier in this discussion.

VIBRATOR-TYPE POWER SUPPLIES.

General. The primary electrical power source in many portable and mobile (small boats, light aircraft, and ground vehicles) electronic equipments is a storage battery. Vibrator-type power supplies are used to convert direct current from the storage battery to alternating current which can be rectified to furnish high-voltage for the operation of the equipment. Vibrator-type power supplies are designed for operation with specific input voltages; storage batteries having voltage values of 6, 12, or 24 volts are commonly used to operate this type of supply.

The main differences between a conventional power supply operating from an a-c source and a vibrator power supply are the vibrating device used to convert the low d-c voltage to high a-c voltage and the special step-up power transformer used in conjunction with the vibrator. The vibrator itself is essentially a high-speed reversing switch that alternately opens and closes sets of contacts in the primary circuit of the power transformer. The rising and falling magnetic field caused by the current pulses in the transformer primary induces an alternating square wave in the secondary circuit. The vibrator is designed to operate at a given frequency, usually between 60 and 250 cycles per second, although in some applications higher frequencies are employed.

Two basic vibrators are widely used in power supplies of this type; one is called the **nonsynchronous** (or **interrupter**) vibrator, and the other is called the **synchronous** (or **self-rectifying**) vibrator. The primary function of either type of vibrator is to cause the d-c input current to flow in pulses through alternate halves of the transformer primary. The nonsynchronous vibrator requires the use of some form of high-voltage rectifier circuit to produce d-c output from the supply. The synchronous vibrator does not require a separate rectifier circuit since, as the name **synchronous** (or **self-rectifying**) implies, the vibrator itself performs the additional function of rectifying the high-voltage ac it produces by synchronous switching of the transformer secondary winding; the resultant output voltage is essentially dc.

Occasionally, vibrator power supplies are designed to operate on more than one value of input voltage; this is accomplished by providing a number of taps on the transformer primary, and appropriate switching or terminal points to accommodate the different battery voltages.

Several types of vibrator power supplies are capable of operation from both a low-voltage d-c source and a conventional 60-cycle a-c source. A combination power supply of this type is usually equipped with a transformer having an additional primary winding for a-c operation; the primary winding used for vibrator operation is tapped, and is used as the filament winding for the electron tubes when operating on ac. This type of power supply uses a non-synchronous vibrator and a separate rectifier circuit, since the same high-voltage secondary is used for both a-c and d-c operation.

Another combination a-c and vibrator power-supply design uses two separate power transformers, with independent rectifiers in the vibrator circuit and in the a-c input circuit. These two independent power-supply circuits share a common filter circuit to filter their respective d-c outputs; either of the two input circuits is selected by a switching arrangement, depending upon whether d-c input or a-c input operation is desired.

Although there are other circuit arrangements for providing operation from both a-c and d-c input sources, the examples given above are typical. One other combination vibrator supply which is occasionally employed makes use of two vibrator supplies operating from a common d-c input but with two or more output voltages. The outputs of the combined supplies can be either positive or negative, or both, and of different voltage values.

Any of the conventional electron-tube or semiconductor rectifier circuits, such as the half-wave, full-wave, bridge, and voltage doubler, can be used in nonsynchronous vibrator power supplies. The use of semiconductor rectifiers simplifies the design of nonsynchronous vibrator-type power supplies, since no filament voltage is required for the rectifier(s).

NONSYNCHRONOUS VIBRATOR SUPPLY.

APPLICATION.

The nonsynchronous vibrator supply is commonly employed in many portable and mobile equipments where the primary power source is a storage battery. This supply produces a relatively high value of d-c voltage at a moderate load current from a low-voltage d-c source. The supply is commonly used to provide high voltage for the operation of small receivers, transmitters, and public-address systems, although in many recent equipments the transistorized dc-to-dc converter, described earlier in this section of the handbook, is used in lieu of the vibrator supply.

CHARACTERISTICS.

Input is low-voltage dc; output is high-voltage dc.

Input voltage is usually 6, 12, or 24 volts; special vibrators for other input voltages are available.

Typical vibrator operating frequency is between 60 and 250 cycles.

Output high-voltage dc is normally between 180 and 300 volts; load current is normally between 60 and 200 milliamperes.

Output circuit can be arranged to furnish negative or positive high voltage to the load.

Output dc requires filtering; ripple-voltage frequency is relatively high, and is determined by the vibrator frequency and the rectifier circuit used.

Electron-tube or semiconductor diodes are used in the rectifier circuit; rectifier circuit may be half-wave, full-wave, bridge, or voltage-doubler.

Regulation is fair; output voltage regulation may be employed.

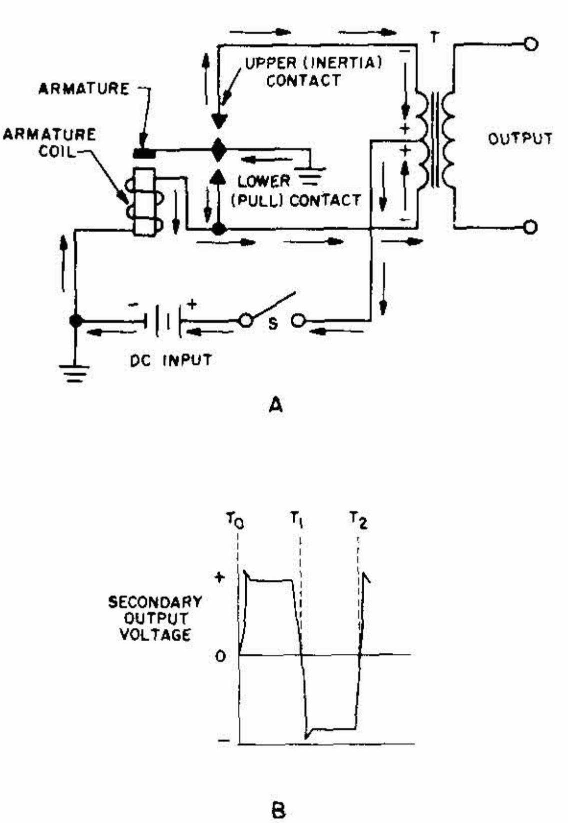
Vibrator must be shielded and leads filtered to prevent r-f radiation and interference to other circuits.

CIRCUIT ANALYSIS.

General. A nonsynchronous vibrator supply converts direct current from a low-voltage power source into alternating current that can be rectified and used to obtain a higher d-c output voltage for use as the plate and screen voltages in the operating equipment. The supply offers the advantages of light weight, small physical size, and good efficiency; its main disadvantages are the limitation in output current and the tendency to produce interference to other circuits. Therefore, the vibrator must be well-filtered and shielded. Another disadvantage is that, although the vibrator itself is relatively inexpensive, its useful life is shorter than that of a dynamotor or of the transistors in a dc-to-dc converter. However, when this type of power supply is used within its rating, it will furnish reliable power for low-power communications and public address equipment.

Nonsynchronous Vibrator Types. A vibrator is an electromechanical mechanism, sometimes called an **interrupter**, which acts as a high-speed reversing switch to control (or interrupt) the current in each half of a tapped primary winding in a special step-up power transformer. The operation of a simple vibrator as a high-speed switching device can be understood by reference to the accompanying illustration of a fundamental vibrator circuit.

In part A of the illustration, when switch S is closed, current flows from the battery, through the vibrator coil, and the lower half of the transformer primary. The magnetic field created by current flow through the vibrator coil attracts the armature and pulls it down against the lower contact. This places a short circuit across the vibrator coil, which causes it to de-energize and release the armature. Spring action draws the armature away from the coil, carries it through the neutral position, and drives it against the upper contact. Since the short circuit is now removed from the vibrator coil, a magnetic field again exists, which draws the armature down until it again touches the lower contact. This action continues at a rate dependent on the natural frequency of the vibrator (typically about 100 cps).



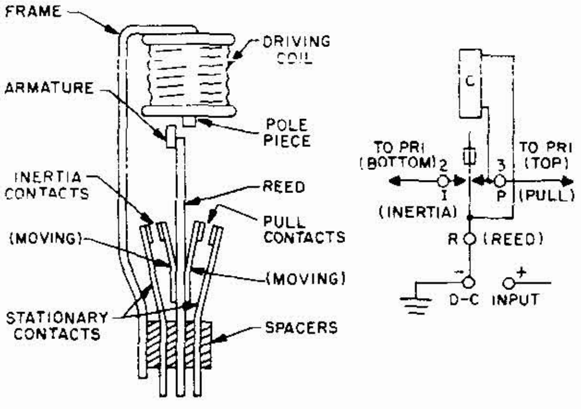
Fundamental Vibrator Circuit and Output Voltage Waveform

During the time when the armature is against the lower contact, the lower portion of the transformer primary is in the circuit. The direction of current flow in this half of the primary is such that the bottom of the primary winding is negative with respect to the center tap. The voltage induced in the secondary, as a result of this current, will be of like polarity, that is, positive-going with respect to the bottom of the secondary winding. This condition is indicated at time t_0 in part B of the illustration. When the armature switches to the upper contact, the upper portion of the transformer primary is placed in the circuit. Since the current through this half of the primary winding flows in a direction opposite to that in the lower half of the winding, a voltage pulse of opposite polarity will be induced in the secondary. This is shown at time t_1. The start of another complete cycle of operation, which is identical in every respect to the cycle just described, is shown at time t_2.

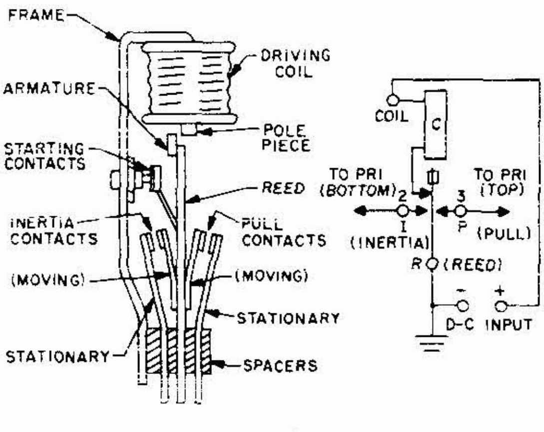
The closing of the lower and upper contacts (in succession) corresponds to one complete cycle of the vibrator frequency, and two pulses of current in alternate directions through the two halves of the transformer primary. The magnetic field created by these current pulses induces a voltage in the transformer secondary which is essentially a square wave, as shown in part B of the illustration. The output voltage does not achieve the shape of an ideal square wave because of the inductance of the transformer. As the current is continuously interrupted in the primary circuit, the alternate build-up and decay of the magnetic field both require a certain finite time. This results from the inductive reactance of the windings, which opposes both the build-up and the decay of the field. Because of this action, and of the high-voltage inductive effect (overshoot), the shape of the output voltage waveform will be as shown in the illustration. Because the vibrator switching action produces a current flow in opposite directions in the two halves of the primary during one complete mechanical cycle of the vibrating reed, the vibrator is sometimes called a **full-wave** nonsynchronous vibrator.

As shown in the accompanying diagram, a nonsynchronous vibrator consists of five basic parts: a heavy frame, an electromagnetic driving coil and core or pole piece, a flexible reed and armature, one or more contacts attached to each side of the reed, and one or more stationary contacts mounted on each side of the reed and armature assembly. There are two basic electrical variations in full-wave nonsynchronous vibrators; the first type is called a **shunt-drive** vibrator and the second is called a **series-drive**, (or **separate-drive**) vibrator. These names are derived from the manner in which the electromagnetic driving coil receives its excitation. Refer to the accompanying illustration of two typical nonsynchronous vibrators; part A shows the construction of a shunt-drive vibrator together with its graphic symbol, and part B shows the construction of a series-drive vibrator and its graphic symbol.

The electromagnetic driving coil is mounted on one end of the frame, as shown in the illustration, and the reed is rigidly clamped in insulating spacers and fixed to the opposite end of the frame. The stationary contacts are similarly clamped at the end of the frame, on each side of the reed. Electrical connections to the vibrator are also made at this point on the frame. The vibrator assembly is usually mounted in a sound-absorbing and cushioning material, such as foam or sponge rubber, which, in turn, is sealed within a metal can. The material placed around the vibrator reduces the amount of mechanical noise created by the vibrating reed, and the metal can acts as an r-f shield to reduce direct radiation of electrical noise. The connecting leads from the vibrator are brought out to metal prongs at the base of the can, and the complete unit is plugged into a special socket in the same manner that an electron tube is installed in a tube socket; the socket also grounds the can to the chassis to completely shield the vibrator. Since the vibrator may require replacement at intervals throughout the useful life of the power supply, the plug-in method of electrical connection insures convenient and easy replacement of a defective vibrator unit.



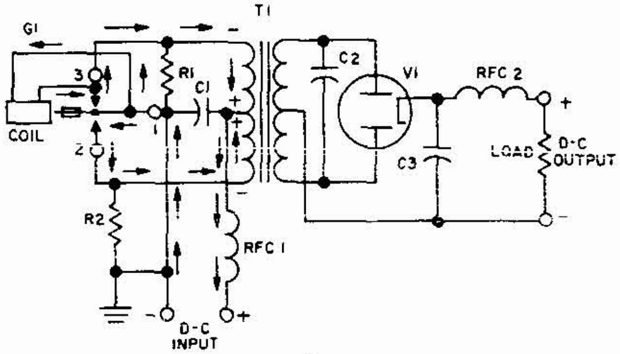
A
SHUNT DRIVE VIBRATOR



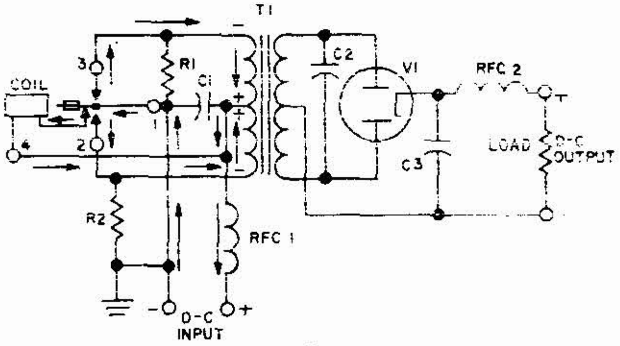
B
SERIES-DRIVE (OR SEPARATE-DRIVE) VIBRATOR

Nonsynchronous Vibrator Types

The shunt-drive vibrator, shown in part A of the illustration, has one end of the driving-coil winding connected to the vibrating reed, which is normally connected to ground. The other end of the winding is connected to an insulated stationary contact on the electromagnetic **pull** (or **power**) side of the reed; this contact is connected to the top of the primary winding. As shown by the graphic symbol in Part A of the illustration, both sets of contacts are open when the vibrator is at rest; however, when voltage is applied to the vibrator circuit, current flows through the driving coil, which magnetizes the core and causes the reed armature to be pulled toward the pole piece. As this occurs, the pull (or power) contacts close to shunt or short out the driving coil as well as to complete one half of the primary circuit. (Refer to the accompanying illustration showing typical nonsynchronous vibrator supplies.) This shunting action of the pull-contacts causes the driving coil to lose its magnetic attraction for the reed armature and, as a result of the spring action stored in the reed, causes the reed to swing back away from the pull contacts to interrupt the primary circuit. The inertia of the reed carries it back across the neutral (at rest) position to the other set of contacts, called the **inertia** contacts, closing these contacts to complete the other half of the primary circuit. While the inertia contacts are closed, current once again flows through



A
SHUNT-DRIVE VIBRATOR



B
SERIES-DRIVE VIBRATOR

Typical Nonsynchronous Vibrator Supplies

the driving coil and causes a high magnetic attraction to be imparted to the reed armature. As the reed moves away from the inertia contacts, these contacts open to interrupt the primary circuit. The cycle is then repeated as the reed is carried across the neutral (at rest) position to close the pull contacts and once again shunt the driving coil. It should be noted at this time that the peak voltage applied to the driving coil, during the time the inertia contacts are closed, is approximately twice the value of the normal d-c input voltage to the supply; this is because the voltage induced by autotransformer action in the half of the primary winding which is connected to the stationary pull contact is in series with the d-c input voltage.

By referring to the diagram of the shunt-drive vibrator, it will be seen that when the armature is in the neutral position (all contacts open), a complete series circuit exists from the negative side of the input source, through the driving coil and pull winding, to the positive side of the d-c source. For a given value of current, as determined by the total resistance in the circuit, the portion of the input voltage that will be dropped across each of the two circuit elements will be in direct proportion to the resistance present in each element. Since the transformer primary winding offers only negligible resistance to the comparatively small and steady d-c current which flows under the conditions stated, no appreciable voltage will be developed across the pull winding.

When the inertia contacts are closed, the series circuit through the driving coil and pull winding remains completed. The voltage existing across the pull winding and the voltage developed in the inertia winding have opposite polarities. Through the autotransformer action which takes place across the tapped primary, the rapidly changing magnetic field around the inertia winding induces a voltage in the pull winding; this voltage has the same polarity as that of the inertia winding. As a result, the voltage now present across the pull winding will be the difference between the induced voltage and the existing voltage. Since the induced voltage has the greater value, the polarity of the difference voltage will be the same as that of the induced voltage. Thus, not only is the counteracting effect of an opposing voltage neutralized, but the voltage in the inertia winding is effectively aided.

The series-drive (or separate-drive) vibrator, shown in part B of both illustrations (the Nonsynchronous Vibrator Types and the Typical Nonsynchronous Vibrator Supplies), differs from the shunt-drive vibrator just described in that it has an extra pair of contacts. These contacts, called **starting** contacts, are normally closed when the vibrator is at rest. The moving contact of this pair is mounted on the armature reed, which is normally connected to ground. The stationary starting contact is wired to one end of the driving coil. The other end of the coil is connected to the high side of the d-c input voltage source, through a terminal in the base of the vibrator provided for this purpose. As shown in part B of both illustrations, both the inertia contacts and pull contacts are open when the vibrator is at rest. However, when voltage is applied to the vibrator circuit, current flows through the driving coil and causes the reed armature to be attracted to the pole piece (magnetized core); thus, the moving pull contact is drawn against the stationary pull contact. The closing of these contacts completes a circuit through one half of the transformer primary. The armature, in moving toward the pole piece, opens the starter contacts, which prevents any further current flow in the driving coil; this results in the collapse of the magnetic field. The reed, now no longer attracted by the pole piece, swings back from the driving coil; this opens the pull contacts and interrupts the primary circuit. The inertia of the reed carries it back across the neutral (at rest) position to the inertia contacts, closing these contacts to complete the other half of the primary circuit. At the same time, the starting contacts close and current once again flows through the driving coil to produce a magnetic attraction for the reed armature. As the reed moves away from the inertia contacts, these contacts open to interrupt the primary circuit; at the same time the starting contacts open to interrupt the circuit to the driving coil. The cycle is then repeated as the reed is carried across the neutral (at rest) position to close the pull contacts and once again complete the primary circuit. It should be noted at this time that if the series-drive vibrator is connected in the circuit so that the driving coil receives voltage directly from the input source (through a separate contact in the vibrator base), the vibrator will continue to vibrate mechanically, even though the transformer center tap and end leads are open. This will not occur with the shunt-drive vibrator since the current to energize the driving coil must pass through one half of the primary winding.

In both the shunt-drive vibrator and the series-drive vibrator the current is alternately switched through each half of the transformer primary, and, as a result of these alternate pulses and the magnetic field they produce in transformer T1, a stepped-up voltage is induced in the transformer secondary. The resulting secondary voltage is essentially square in waveform, and is applied to the full-wave rectifier circuit. In the circuits illustrated by the diagrams of typical nonsynchronous vibrator supplies, transformer T1 has a center-tapped secondary winding; each end terminal of the secondary is connected to a plate of the electron tube, V1. On alternate half-cycles of the secondary voltage, alternate diodes of the full-wave rectifier conduct and produce an output voltage across the load resistance. Since only one diode conducts at any instant of time, electrons flow through the load resistance in pulses to produce a pulsating output voltage. The output of the rectifier circuit is connected to a suitable filter circuit to smooth out the dc for use in the load circuit; because a square-wave voltage is applied to the rectifier circuit, and because the frequency of vibrator switching is fairly high (usually 100 to 120 cycles), very little filtering is required to obtain a d-c output voltage which is free from voltage transients and relatively free from ripple.

In practice, the nonsynchronous vibrator is normally constructed with a four-prong base, and the socket into which the vibrator is plugged is wired to accept either a shunt-drive or a series-drive vibrator; therefore, the two vibrator types may be used interchangeably in a large number of vibrator-type supplies.

Circuit Operation. Both supplies shown in the Nonsynchronous Vibrator Supplies illustration utilize a full-wave rectifier circuit to obtain high-voltage output. The discussion which follows is concerned primarily with the vibrator and its associated transformer, since the operation of a full-wave rectifier circuit has been described under Power Supply Circuits, in Section 4, Part A (Single Phase Full-Wave Rectifier) of the handbook. Furthermore, the nonsynchronous vibrator-type power supply is not necessarily restricted to the use of a full-wave rectifier circuit and, in many instances, the rectifier circuit is likely to be a bridge or voltage-doubler circuit employing either electron-tube or semiconductor diodes as rectifiers.

Vibrator G1 in the circuit of part A is a shunt-drive vibrator; vibrator G1 in the circuit of part B is a series-drive vibrator. Transformer T1, in both circuits, is a special power transformer with a center-tapped primary and center-tapped secondary; however, if a bridge or voltage-doubler rectifier circuit is used instead of a full-wave rectifier shown, the transformer secondary need not be center-tapped. Electron tube V1 is a twin-diode rectifier, and may be either an indirectly heated cathode rectifier or a gas-filled, cold-cathode rectifier. Bypass capacitor C1 and r-f choke RFC1 serve as a filter to eliminate or reduce impulse electrical noise (or "hash"), originated by arcing vibrator contacts, from being radiated by the d-c input leads and coupled into other circuits of the equipment. Resistors R1 and R2 are connected across the interrupter contacts of the vibrator to reduce interference and sparking and also to increase the life of the vibrator contacts; the value of R1 and R2 is usually between 47 and 220 ohms, depending upon the d-c input voltage and circuit design. Resistors R1 and R2 also help to reduce the peak amplitude of any transient voltages which might occur in the primary circuit because of vibrator switching action. Capacitor C2, commonly called the **buffer** capacitor, and occasionally referred to as the surge or timing capacitor, is connected across the transformer secondary to effectively absorb the high transient voltages produced by the inductive reactance when the primary current is interrupted by the opening of the vibrator contacts. Because of the magnitude of these voltages, it is necessary that the buffer capacitor have a rating in working volts of from 6 to 8 times the voltage delivered by the power supply. For example, for a supply which delivers 250 volts, the capacitor should be rated between 1500 and 2000 working volts. A resistor of approximately 5000 ohms is sometimes connected in series with the buffer capacitor to limit the secondary current in case the buffer capacitor becomes shorted. The value of a buffer capacitor depends upon the circuit design (transformer turns ratio and effective inductance, vibrator frequency,etc), but is usually between .001 and .047 μf. Capacitors used in this application generally have a breakdown voltage of 1000 to 2000 volts. In some circuits a buffer capacitor is connected across the transformer primary. Another circuit variation uses two buffer capacitors of equal value; a capacitor is connected at each end of the secondary to ground or to the secondary center tap. Bypass capacitor C3 and r-f choke RFC2 form an additional filter to prevent noise (or "hash") from being coupled to other circuits through the high-voltage, d-c output lead.

When d-c input power is applied to the circuit, the driving coil of vibrator G1 is energized to start the reed vibrating at its own natural frequency. (The operation of shunt-drive and series-drive vibrators was described in considerable detail in previous paragraphs; therefore, a description of vibrator switching action will not be repeated here.)

FAILURE ANALYSIS.

General. A quick check to determine whether the vibrator is operating is to listen for the characteristic mechanical buzzing noise which is made by the vibrating action of the reed assembly; although the reed assembly is enclosed in a sealed can and is cushioned to deaden the sound, an audible indication can usually be detected. However, this simple check is not a positive indication of correct vibrator operation; for example, the series-drive vibrator will often continue to operate even when there are discontinuities in the transformer primary circuit.

The most frequent trouble which develops in a vibrator-type supply is caused by a defective vibrator or a defective buffer capacitor. The power transformer and the rectifier-circuit components generally have a useful life which is comparable to the life of the components in a conventional power supply designed for a-c input.

Although certain waveform measurements can be made with an oscilloscope to check for correct operation of the vibrator supply, this technique will not always immediately reveal troubles within the supply, since mechanical defects which may be of short duration sometimes occur only after the vibrator reaches a certain operating temperature.

An indication of vibrator operation can be quickly obtained by using an oscilloscope to observe the voltage waveform at the primary of the power transformer. If measurements are made at each end of the primary to chassis (ground), the peak-to-peak amplitude of the square wave will be approximately equal to twice the value of the d-c input voltage; however, if the oscilloscope vertical input is connected across the entire primary winding, the peak-to-peak amplitude of the square wave will be approximately equal to four times the value of the d-c input voltage. When the vibrator circuit is operating normally, a square wave will be observed with relatively smooth transition occurring after the contacts break and during the voltage reversal when another set of contacts make to produce the next half-cycle of the waveform. The flat portion of the square wave should be relatively smooth; if radical transients appear on the flat portion of the square wave, this is an indication of poor electrical contact, caused by chattering or bouncing of the contacts, and is a good reason to suspect that the vibrator is defective. Minor roughness, or "ripple", on the flat portion of the square wave is not usually sufficient cause to reject the vibrator, since this indication merely represents some small variation in contact resistance during the time the vibrator contacts are closed. The smoothness of the transition from one flat-topped portion of the square wave, through the voltage reversal (contacts open), to the other voltage extreme of the square wave is controlled by the value of the buffer (timing) capacitor, the inductive reactance of the transformer, the natural frequency of the vibrator reed assembly, and the elapsed time between contact closures.

When the symptoms and checks indicate that the vibrator is definitely at fault, it is important that the replacement vibrator be the same, or an equivalent, type. There are many variations in vibrator terminal connections and operating characteristics; therefore, the replacement vibrator should be the same type as the original, or at least a vibrator which is recommended by the manufacturer as the correct replacement for the original.

No Output. The nonsynchronous vibrator supply consists of a vibrator and associated transformer, and a rectifier and filter circuit. Therefore, when checking the vibrator supply for a possible defect, tests must be made to determine whether the trouble is due to a defective vibrator and associated transformer, or to a defect within the rectifier circuit.

The d-c input voltage should be checked to determine whether it is present and of the correct value.

The operation of the vibrator can be checked by an a-c voltage measurement made at the secondary terminals of the transformer, or by use of an oscilloscope connected to the primary circuit to observe the switching-action waveform. If the vibrator and associated transformer are found to be functioning normally, as indicated by a secondary-voltage measurement or an oscilloscope check, it must be assumed that the trouble is in the rectifier circuit or the associated load. A check of the rectifier circuit can be made in accordance with the procedures outlined in Section 4, Part A for the applicable rectifier circuit; in the case of this particular vibrator-supply circuit, reference should be made to the **Single-Phase Full-Wave** rectifier circuit. If the vibrator-type power supply blows its d-c input fuse each time the supply is energized, the vibrator may be defective. To eliminate this possibility, remove the vibrator and substitute another vibrator of the same type in its place. Then install a new fuse and apply power; if the fuse does not blow and operation appears to be normal, the original vibrator must be considered defective. However, if the fuse blows again, the original vibrator may be considered good, and further checks of the supply will be necessary in order to locate the source of the trouble. When burned or pitted vibrator contacts stick together, a heavy current flows in the associated primary winding, and this current is likely to blow the fuse. A check of the input current should be made with an ammeter to determine whether this current is within tolerance, or whether it is excessive. With the vibrator removed from its socket, continuity measurements of the transformer primary circuit may be made to determine whether the primary winding is open, shorted, or grounded. Again a known good vibrator may be substituted for the suspected vibrator to determine whether the vibrator is one possible cause of improper operation. Also, removal of the rectifier tube, as applicable will indicate whether the trouble is in the vibrator, or in the rectifier or load section of the supply.

A shorted buffer capacitor C2 can be detected by a higher than normal input current to the supply and a very low a-c voltage at the secondary terminals of the transformer. The replacement buffer capacitor should be the same value as the original capacitor and of equal or greater voltage rating. A leaky or shorted filter capacitor C1 will also cause the input current to the supply to be above normal. As a general rule, any time the vibrator is replaced the buffer capacitor should also be replaced.

The indirectly heated cathode rectifier, V1, is frequently subject to heater-to-cathode leakage, and, since the heater is normally at ground potential, this leakage will cause an abnormal load on the rectifier output; a complete short will result in no d-c output from the supply. Also, a short in filter capacitor C3 or an open r-f choke RFC2 will result in no output from the power supply.

Low Output. A low-output condition in a nonsynchronous vibrator-type power supply usually results from a defective vibrator, a leaky buffer capacitor, low input voltage, or a defective component in the rectifier or filter circuit.

A voltage drop in the primary leads to the supply can result in low output; therefore, the input voltage should be checked at the transformer or vibrator terminals to determine whether the input voltage is present and of the correct value.

The a-c secondary voltage may be measured at the transformer to determine whether it is approximately the value specified for normal operation of the supply. The test procedures described for the no-output condition and in previous paragraphs can be used to determine whether the vibrator is at fault. A defective vibrator with only one set of properly making contacts results in reduced output from the supply. A vibrator in which "frequency hunting" occurs may be detected by an uneven or irregular buzzing noise, which indicates that the armature is vibrating erratically and at frequencies other than its normal frequency of vibration. This unstable condition of the vibrator causes the stepped-up voltage induced in the secondary of the transformer to also be erratic, and the output voltage to be below its normal value. This trouble is usually caused by excessive load current, and is an indication of impending vibrator failure. Frequency hunting can also be caused by burned or pitted vibrator contacts which are sticking; this usually results in a higher than normal input current and reduced output from the supply. A check of the input current should be made with an ammeter to determine whether the current is within tolerance; also, an oscilloscope check of the waveform at the primary of the transformer should be made to determine whether the vibrator is faulty. If desired, a known good vibrator may be substituted for the suspected vibrator as a quick check to determine whether the vibrator is actually at fault. A check with the rectifier tube removed is also recommended. Shorts, leakage, or excessive current drain in the filter circuit or in the high-voltage load circuit external to the supply will cause a heavy load on the vibrator contacts, and may cause early failure of the vibrator. The output load current should be measured after installation of a replacement vibrator to determine whether the load current is within tolerance; if the load current is excessive, the replacement vibrator may be damaged unless the cause for the excessive load current is found and corrected.

Continuity measurements of the primary and secondary windings of transformer T1 should be made, since an open circuit in either of the windings will cause a reduction in output.

The rectifier, V1, may be weak and cause low output. The tube is usually an indirectly heated cathode type, such as a type 6X5, 6X4, or 12X4, or a gaseous rectifier, such as a type 0Z4. In either case, a quick check of rectifier condition can be made by substituting a rectifier known to be in good condition, and the output voltage measured to determine whether the voltage has returned to normal. In an emergency, when the vibrator is urgently needed and no replacement is available, the vibrator may be opened and the contacts burnished as an interim corrective measure. The indirectly heated cathode rectifier is frequently subject to heater-to-cathode leakage, and, since the heater is normally at ground potential, this leakage will cause a load on the rectifier output; a complete short will result in no d-c output from the supply. Gaseous, or cold-cathode, rectifiers can also be checked by substitution of a known good rectifier.

The power supply output current should be checked to make sure that it is within tolerance. A low-output condition due to a decrease in load resistance will cause an increase in load current; for example, excessive leakage in the capacitors of the output filter circuit will result in increased load current.

SYNCHRONOUS VIBRATOR SUPPLY.

APPLICATION.

The synchronous vibrator supply is commonly employed in many portable and mobile equipments where the primary power source is a storage battery. This supply produces a relatively high value of d-c voltage at a moderate load current from a low-voltage d-c source. The supply is commonly used to provide high voltage for the operation of small receivers, transmitters, and public-address systems, although in many equipments the transistorized dc-to-dc converter, described in Section 4, Part B (Semiconductor Circuits) of the handbook, is used in lieu of the vibrator supply.

CHARACTERISTICS.

Input is low-voltage dc; output is high-voltage dc.

Input voltage is usually 6, 12, or 24 volts; special vibrators for other input voltages are available.

Typical vibrator operating frequency is between 60 and 250 cycles.

Output high-voltage dc is normally between 180 and 300 volts; load current is normally between 60 and 200 milliamperes.

Output circuit can be arranged to furnish negative or positive high voltage to the load.

Output dc requires filtering; ripple-voltage frequency is relatively high, and is determined by the vibrator frequency.

Synchronous vibrator is self-rectifying; electron-tube or semiconductor rectifier circuit is not required.

Regulation is fair; output voltage regulation may be employed.

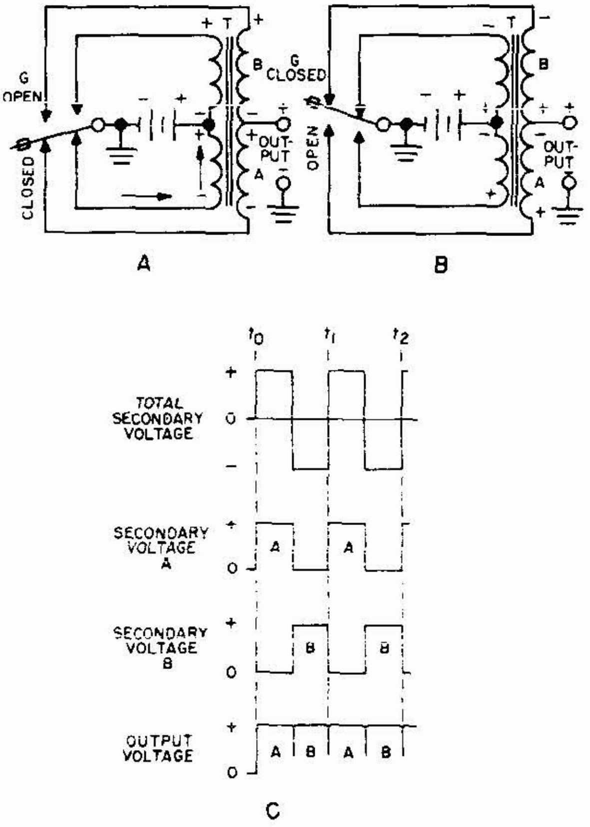
Vibrator must be shielded and leads filtered to prevent r-f radiation and interference to other circuits.

CIRCUIT ANALYSIS.

General. A synchronous vibrator supply converts direct current from a low voltage power source into high-voltage dc that can be filtered for use as the plate and screen voltages in the operating equipment. A separate rectifier is not required with this circuit because rectification is accomplished by means of an extra set of contacts on the vibrator. The supply offers the advantages of light weight, small physical size, and good efficiency; its main disadvantages are the limitation in output current and the tendency to produce interference to other circuits. Therefore, the vibrator must be well-filtered and shielded. Another disadvantage is that, although the vibrator itself is relatively inexpensive, its useful life is shorter than that of a dynamotor or of the transistors in a dc-to-dc converter. However, when this type of power supply is used within its rating, it will furnish reliable power for low-power communications and public address equipment.

Synchronous Vibrator Types. A vibrator is an electromechanical mechanism, sometimes called an **interrupter,** which acts as a high-speed reversing switch to control (or interrupt) the current in each half of a tapped primary winding in a special step-up power transformer; in addition, the synchronous vibrator is equipped with two additional sets of contacts, operating in synchronism with the primary circuit interrupter contacts, to provide rectification of the transformer secondary voltage. The operation of a simple vibrator as a high-speed switching device and its rectifying action can be understood by reference to the accompanying illustration.

In this illustration, a vibrating reed is equipped with two sets of interrupter contacts arranged so that when one set of contacts is closed to complete one primary circuit,



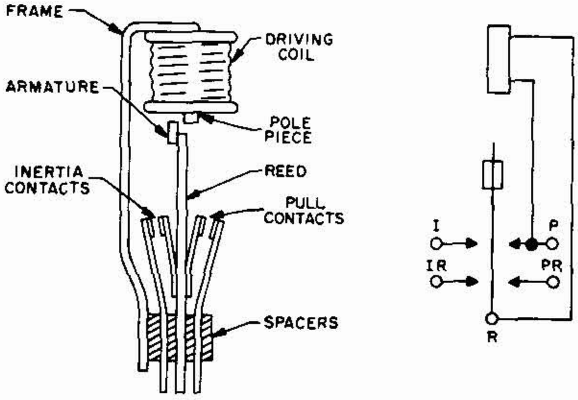
Fundamental Switching Circuit, Using Synchronous Vibrator, and Resulting Output Waveform

the other set of contacts is open to interrupt the other primary circuit. Two additional sets of contacts, called the **rectifier** contacts, operate in synchronism with the primary interrupter contacts. The action of the rectifier contacts is identical with the action of the primary contacts; that is, when one set of rectifier contacts is closed to complete one half of the secondary circuit, the other set of rectifier contacts is open to interrupt the other half of the secondary circuit. Thus, as shown in part A of the illustration, when the upper sets of contacts are open, the lower sets of contacts are closed, and heavy current flows in the lower primary winding of the transformer. Also at this time, the lower half of the secondary, marked "A", is grounded through the lower set of vibrator contacts to complete the secondary circuit and produce a voltage at the output terminals. The polarities of the voltages produced across the primary and secondary windings of the transformer, which are so wound that no phase reversal occurs, are as indicated in part A of the illustration.

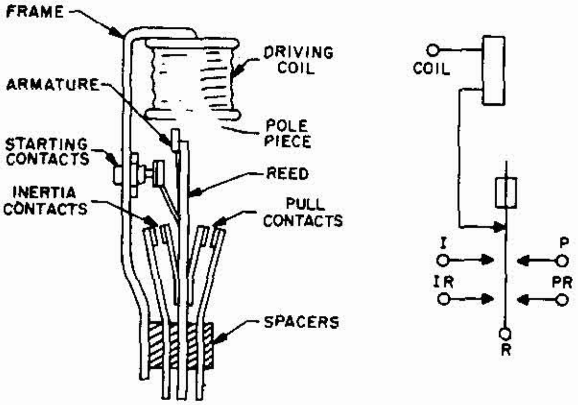
When the vibrating reed reverses its position, as shown in part B, the upper sets of contacts are closed, and heavy current flows in the upper primary winding of the transformer. Also at this time, the upper half of the secondary, marked "B", is grounded through the upper set of rectifier contacts to complete the secondary circuit and produce a voltage at the output terminals. The polarities of the voltages produced across the primary and secondary windings of the transformer are as indicated in part B of the illustration.

Assuming a rapid rate of primary switching, the voltage developed across the entire secondary is essentially a square waveform, as shown in part C. The voltage produced in each half of the secondary on alternate half-cycles, when combined, results in an output voltage which is essentially pulsating d-c voltage. Small transients occur in the output voltage during the time the vibrator reed is transferring from one set of contacts to the other; however, these transients are easily removed by a filter circuit connected to the output of the vibrator supply.

A synchronous vibrator consists of five basic parts: a heavy frame, an electromagnetic driving coil and core or pole piece, a flexible reed and armature, two contacts attached to each side of the reed, and two (or more) stationary contacts mounted on each side of the reed and armature assembly. There are two basic electrical variations in synchronous vibrators; the first type is called a **shunt-drive** vibrator, and the second is called a **series-drive** (or **separate-drive**) vibrator. These names are derived from the manner in which the electromagnetic driving coil receives its excitation. The two types of sychronous vibrators are shown in the accompanying illustration; part A shows the construction of a shunt-drive vibrator and its graphic symbol, and part B shows the construction of a series-drive vibrator and its graphic symbol.



A
SHUNT DRIVE VIBRATOR



B
SERIES-DRIVE VIBRATOR

Synchronous Vibrator Types

The electromagnetic driving coil is mounted on one end of the frame, as shown in the illustration, and the reed is rigidly clamped in insulating spacers and fixed to the opposite end of the frame. The movable contacts are mounted on the sides of the reed. The stationary contacts are similarly clamped at the end of the frame, on each side of the reed. Electrical connections to the vibrator are also made at this point on the frame. The vibrator assembly is usually mounted within a sound-absorbing and cushioning material, such as foam or sponge rubber, which, in turn, is sealed within a metal can. The material placed around the vibrator reduces the amount of mechanical noise created by the vibrating reed, and the metal can acts as an r-f shield to reduce direct radiation of electrical noise. The connecting leads from the vibrator are brought out to metal prongs at the base of the can, and the complete unit is plugged into a special socket in the same manner that an electron tube is installed in a tube socket; the socket also grounds the can to the chassis to completely shield the vibrator. Since the vibrator may require replacement at intervals throughout the useful life of the power supply, the plug-in method of electrical connection insures convenient and easy replacement of a defective vibrator unit.

The shunt-drive vibrator, shown in part A, has one end of the driving-coil winding connected to the vibrating reed (normally connected to ground); the other end of the winding is connected to one of the insulated stationary primary contacts on the electromagnetic **pull** (or **power**) side of the reed. As shown in part A of the illustration, all contacts are open when the vibrator is at rest; however, when voltage is applied to the vibrator circuit through the power transformer primary, current flows through the driving coil and causes the reed armature to be pulled toward the pole piece. As this occurs, one set of primary contacts, called the **pull** or **power** contacts, close to shunt or short out the driving coil and also complete one half of the primary circuit. (An additional set of pull contacts, called the **rectifier** contacts, close to complete one half of the secondary circuit at this time.) The shunting action of the primary pull contacts causes the driving coil to lose its magnetic attraction for the reed armature and, as a result of the mechanical energy stored in the reed, causes the reed to swing back away from the pull contacts to interrupt the primary circuit and also break the secondary circuit. The inertia of the reed carries it back across the neutral (at rest) position to the other set of primary contacts, called the **inertia** contacts, closing these contacts to complete the other half of the primary circuit. (An additional set of inertia contacts, called the **rectifier** contacts, close to complete the other half of the secondary circuit at this time.) While the inertia contacts are closed, current once again flows through the driving coil and causes a high magnetic attraction to be imparted to the reed armature. As the reed moves away from the inertia contacts, these contacts open to interrupt the primary circuit and also break the secondary circuit. The cycle is then repeated as the reed is carried across the neutral (at rest) position to close the primary pull contacts, thus shunting the driving coil, and also closing the rectifier pull contacts to complete the secondary circuit. It should be noted at this time that the peak voltage applied to the driving coil, during the time the inertia contacts are closed, is approximately twice the value of the normal d-c input voltage to the supply; this is because the voltage induced by autotransformer action in the half of the primary winding which is connected to the stationary pull contact is in series with the d-c input voltage.

By referring to the diagram of the shunt-drive vibrator, it will be seen that when the armature is in the neutral position (all contacts open), a complete series circuit exists from the negative side of the input source, through the driving coil and pull winding, to the positive side of the d-c source. For a given value of current, as determined by the total resistance in the circuit, the portion of the input voltage that will be dropped across each of the two circuit elements will be in direct proportion to the resistance present in each element. Since the transformer primary winding offers only negligible resistance to the comparatively small and steady d-c current which flows under the conditions stated, no appreciable voltage will be developed across the pull winding.

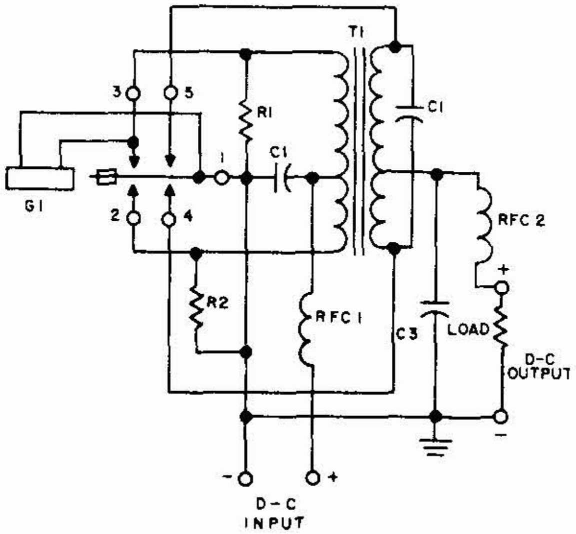
When the inertia contacts are closed, the series circuit through the driving coil and pull winding remains completed. The voltage existing across the pull winding and the voltage developed in the inertia winding have opposite polarities. Through the autotransformer action which takes place across the tapped primary, the rapidly changing magnetic field around the inertia winding induces a voltage in the pull winding; this voltage has the same polarity as that of the inertia winding. As a result, the voltage now present across the pull winding will be the difference between the induced voltage and the existing voltage. Since the induced voltage has the greater value, the polarity of the difference voltage will be the same as that of the induced voltage. Thus, not only is the counteracting effect of an opposing voltage netralized, but the voltage in the inertia winding is effectively aided.

The series-drive (or separate-drive) vibrator, shown in part B, differs from the shunt-drive vibrator just described in that it has an extra pair of contacts which are normally closed when the vibrator is at rest. These contacts, called **starting** contacts, are in series with the ground connection to one end of the driving coil, while the other end of the driving coil is connected to the d-c input voltage, either through a separate terminal in the vibrator base or to one of the stationary primary contacts. As shown in the illustration (part B), all pull and inertia contacts are open when the vibrator is at rest; however, when voltage is applied to the vibrator coil circuit, either through a stationary primary-pull contact or through a separate terminal in the base, current flows through the driving coil and causes the reed armature to be pulled toward the pole piece. The reed continues to move toward the pull contacts and, as the pull contacts close to complete one half of the primary and secondary circuits, the starting contacts are opened, causing the driving coil to lose its magnetic attraction for the reed armature. The reed now swings back away from the pull contacts, because the driving coil has lost its magnetic attraction for the reed armature, and the pull contacts open to interrupt the primary and secondary circuits. The inertia of the reed carries it back across the neutral (at rest) position to the inertia contacts, closing both the primary and rectifier contacts to complete the other half of the primary and secondary circuits. At the same time, the starting contacts close and current once again flows through the driving coil to produce a magnetic attraction for the reed armature. As the reed moves away from the inertia contacts, the primary and rectifier inertia contacts open to interrupt both circuits; at the same time the starting contacts open to interrupt the circuit to the driving coil. The cycle is then repeated as the reed is carried across the neutral (at rest) position to close the pull contacts and once again complete the primary and secondary circuits. It should be noted at this time that if the series-drive vibrator is connected in the circuit so that the driving coil receives voltage directly from the input source (through a separate contact in the vibrator base), the vibrator will continue to vibrate mechanically, even though the transformer primary center-tap and end leads are open. This will not occur with the shunt-drive vibrator, since the current to energize the driving coil must pass through one half of the primary winding.

The output polarity of a synchronous vibrator power supply depends upon the polarity of the d-c input voltage. For this reason, means are often provided for reversing the d-c output polarity. In practice, the synchronous vibrator is normally constructed with a special five-prong base, and the special seven-prong socket into which the vibrator is plugged accepts the vibrator in either of two positions. When installed in one position a positive output is obtained, and when installed in the other position a negative output is obtained. In other vibrator installations, a reversing switch (or flexible jumpers on a terminal board) is used to reverse the secondary-winding (or the primary-winding) connections to the power transformer.

Circuit Operation. The accompanying illustration shows a typical synchronous vibrator supply using a shunt-drive vibrator. (Except for the manner in which connections are made to the driving coil, the operation of a series-drive vibrator is essentially the same.)

Vibrator G1 is a shunt-drive vibrator; transformer T1 is a special power transformer with a center-tapped primary and center-tapped secondary. Bypass capacitor C1 and r-f choke RFC1 serve as a filter to reduce or eliminate impulse electrical noise (or "hash"), originated by arcing vibrator contacts, from being radiated by the d-c input leads and coupled into other circuits of the equipment. Resistors R1 and R2 are connected across the primary interrupter contacts of the vibrator to reduce interference and sparking and also to increase the life of the vibrator contacts; the value of R1 and R2 is usually between 47 and 220 ohms, depending upon the d-c input voltage and circuit design. Resistors R1 and R2 also help to reduce the peak amplitude of any transient voltages which might occur in the primary circuit because of vibrator switching action. Capacitor C2, commonly called the **buffer** capacitor, and occasionally referred to as the **surge** or **timing** capacitor, is connected across the transformer secondary to effectively absorb the high transient voltages produced by the inductive reactance when the primary current is interrupted by the opening of the vibrator contacts. A resistor of approximately 5000 ohms is sometimes connected in series with the buffer capacitor to limit the secondary current in case the buffer capacitor becomes shorted. The value of a buffer capacitor depends upon the circuit design (transformer turns ratio and effective inductance, vibrator frequency, etc), but is usually between .001 and .047 μf. Capacitors used in this application generally have a breakdown voltage of from 1000 to 2000 volts. In some circuits a buffer capacitor is connected across the transformer primary. Another circuit variation, commonly used with the synchronous vibrator, uses two buffer capacitors of equal value; a capacitor is connected at each end of the secondary winding to ground (chassis). Bypass capacitor C3 and r-f choke RFC2 form an additional filter to prevent noise (or "hash") from being coupled to other circuits through the high-voltage, d-c output lead.



Typical Synchronous Vibrator Supply Using a Shunt-Drive Vibrator

When d-c input power is applied to the circuit, the driving coil of vibrator G1 is energized to start the reed vibrating at its own natural frequency. (The operation of shunt-drive and series-drive vibrators was described in considerable detail in previous paragraphs; therefore, a description of vibrator switching action will not be repeated here.) The current is alternately switched through each half of the transformer primary, and, as a result of these alternate pulses and the magnetic field they produce in transformer T1, a stepped-up voltage is induced in the transformer secondary. The resulting voltage in each half of the secondary is essentially square in waveform. During the time that a square wave is being produced in the secondary winding, one set of rectifier contacts close in the vibrator to connect the proper secondary winding to ground, and current flows through the load resistance. The rectifier contacts operate in synchronism with the primary interrupter contacts and alternately connect opposite ends of the secondary to ground; this action causes each half of the secondary to supply current to the load resistance on alternate half-cycles. Since only one half of the secondary is connected to the load circuit at any instant, electrons flow through the load resistance in pulses to produce a pulsating output voltage. (The action is similar to that of a full-wave rectifier circuit.) The output of the synchronous vibrator supply is connected to a suitable filter circuit to smooth out the dc for use in the load circuit. Because a square-wave voltage is switched in synchronism with the switching of the primary circuit, and because the frequency of the switching is fairly high (usually 100 to 120 cycles), very little filtering is required to obtain a d-c output voltage which is free from voltage transients and relatively free from ripple.

FAILURE ANALYSIS.

General. A quick check to determine whether the vibrator is operating is to listen for the characteristic mechanical buzzing noise which is made by the vibrating action of the reed assembly; although the reed assembly is enclosed in a sealed can and is cushioned to deaden the sound, an audible indication can usually be detected. However, this simple check is not a positive indication of correct vibrator action, but merely indicates that mechanical action is taking place.

The most frequent trouble which develops in a vibrator-type supply is caused by a defective vibrator or a defective buffer capacitor(s). The power transformer and the associated circuit components generally have a useful life which is comparable to the life of the components in a conventional power supply designed for a-c input.

Although certain waveform measurements can be made with an oscilloscope to check for correct operation of the vibrator supply, this technique will not always immediately reveal troubles within the supply, since mechanical defects which may be of short duration sometimes occur only after the vibrator reaches a certain operating temperature.

An indication of vibrator operation can be quickly obtained by using an oscilloscope to observe the voltage waveform at the primary of the power transformer. If measurements are made at each end of the primary to chassis (ground), the peak-to-peak amplitude of the square wave will be approximately equal to twice the value of the d-c input voltage; however, if the oscilloscope vertical input is connected across the entire primary winding, the peak-to-peak amplitude of the square wave will be approximately equal to four times the value of the d-c input voltage. When the vibrator circuit is operating normally, a square wave will be observed with relatively smooth transition occurring after the contacts break and during the voltage reversal when another set of contacts make to produce the next half-cycle of the waveform. The flat portion of the square wave should be relatively smooth; if radical transients appear on the flat portion of the square wave, this is an indication of poor electrical contact caused by chattering or bouncing of the contacts, and is a good reason to suspect that the vibrator is defective. Minor roughness, or "ripple", on the flat portion of the square wave is not usually sufficient cause to reject the vibrator, since this indication merely represents some small variation in contact resistance during the time the vibrator contacts are closed. The smoothness of the transition from one flat-topped portion of the square wave, through the voltage reversal (contacts open), to the other voltage extreme of the square wave is controlled by the value of the buffer (timing) capacitor, the inductive reactance of the transformer, the natural frequency of the vibrator reed assembly, and the elapsed time between contact closures.

When the symptoms and checks indicate that the vibrator is definitely at fault, it is important that the replacement vibrator be the same, or an equivalent, type. There are many variations in vibrator terminal connections and operating characteristics; therefore, the replacement vibrator should be the same type as the original, or at least a vibrator which is recommended by the manufacturer as the correct replacement for the original.

No Output. The synchronous vibrator supply consists of a vibrator, transformer, and associated filter circuit. It must be determined initially whether the vibrator is operating; if it is, tests must be made to determine whether the trouble is due to a defective vibrator or transformer, or to a defect located within the filter circuit.

The d-c input voltage should be checked to determine whether it is present and of the correct value.

The operation of the vibrator can be checked by an a-c voltage measurement made at the secondary terminals of the transformer, or by use of an oscilloscope connected to the primary circuit to observe the switching-action waveform. If the vibrator and associated transformer are found to be functioning normally, as indicated by a secondary-voltage measurement or an oscilloscope check, it must be assumed that the trouble is in the filter circuit or the associated load.

If the vibrator-type power supply blows its d-c input fuse each time the supply is energized, the vibrator should be removed from its socket, and, with a new fuse installed, the input power applied once again to determine whether a defective vibrator is the cause of excessive input current. When burned or pitted vibrator contacts stick together, a heavy current flows in the associated primary winding; this current is likely to blow the fuse because of the low d-c resistance of the winding. A check of the input current should be made with an ammeter to determine whether this current is within tolerance, or whether it is excessive. A known good vibrator may be substituted for the suspected vibrator to determine whether the vibrator is one possible cause of improper operation. With the vibrator removed from its socket, continuity measurements of the transformer primary circuit may be made to determine whether the primary winding is open, shorted, or grounded.

A shorted buffer capacitor C2 can be detected by a higher than normal input current to the supply and a very low a-c voltage at the secondary terminals of the transformer. The replacement buffer capacitor should be the same value as the original capacitor and of equal or greater voltage rating. A leaky or shorted filter capacitor C1 will also cause the input current to the supply to be above normal. Also, a short in filter capacitor C3 or an open r-f choke RFC2 will result in no output from the power supply.

Low Output. A low-output condition in a synchronous vibrator-type power supply usually results from a defective vibrator, a leaky buffer capacitor, low input voltage, or a defective component in the filter circuit.

A voltage drop in the primary leads to the supply, due to the high resistance of a defective terminal or connector, can result in low output; therefore, the input voltage should be checked at the transformer or vibrator terminals to determine whether the input voltage is present and of the correct value.

The a-c voltage may be measured between the center tap and each end of the secondary to determine whether the two measurements are equal and approximately the values specified for normal operation of the supply. The test procedures described for the no-output condition and in previous paragraphs can be used to determine whether the vibrator is at fault. A defective vibrator with only one set of properly making contacts results in reduced output from the supply and poor filtering. A vibrator in which "frequency hunting" occurs may be detected by an uneven or irregular buzzing noise; this trouble is usually caused by an excessive load current, and is an indication of impending vibrator failure. Frequency hunting can also be caused by burned or pitted vibrator contacts which are sticking; this usually results in a higher than normal input current and reduced output from the supply. A check of the input current should be made with an ammeter to determine whether the current is within tolerance; also, an oscilloscope check of the waveform at the primary of the transformer should be made to determine whether the vibrator is faulty; an additional check should also be made at the secondary center tap to determine whether the rectifier contacts are operating correctly. If desired, a known good vibrator may be substituted for the suspected vibrator as a quick check to determine whether the vibrator is actually at fault. Shorts, leakage, or excessive current drain in the filter circuit or in the high-voltage load circuit external to the supply will cause a heavy load on the vibrator contacts, and may cause early failure of the vibrator. The output load current should be measured after installation of a replacement vibrator to determine whether the load current is within tolerance; if the load current is excessive, the replacement vibrator may be damaged unless the cause for the excessive load current is found and corrected.

In one circuit variation of a synchronous vibrator supply, buffer capacitor C2 is actually two capacitors; one capacitor is connected at each end of the transformer secondary to ground (chassis). If one of these buffer capacitors becomes shorted, the output voltage will be reduced accordingly.

Continuity measurements of the primary and secondary windings of transformer T1 should be made, since an open circuit in either of the windings will cause a reduction in output.

The power supply output current should be checked to make sure that it is within tolerance. A low-output condition due to a decrease in load resistance will cause an increase in load current; for example, excessive leakage in the capacitors of the output filter circuit will result in increased load current.

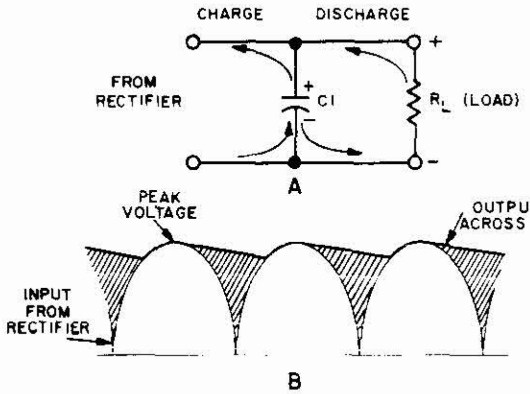
PART D. FILTER CIRCUITS

POWER-SUPPLY FILTERS.

General. While the output of most types of rectifiers is a pulsating direct current, most electronic circuits require a substantially pure direct current for operation. To provide this type of output, single- or multiple-section filter circuits (which effectively eliminate any alternating or ripple-voltage components by smoothing out the d-c pulsations) are placed between the output of the rectifier and the load.

Filtering is accomplished by means of resistors or inductors, and capacitors, which are usually arranged as a low pass filter. Inductors, as series impedances, oppose the flow of alternating (pulsating d-c) current, while capacitors, as shunt elements, by-pass the alternating components that succeed in passing through the series impedances. (Resistors are used in the place of inductors for very low-current outputs.) The four basic types of filter circuits are the shunt-capacitor filter, the R-C capacitor-input filter, the L-C capacitor-input filter, and the L-C choke-input filter. A fifth type of filter, the resonant filter, employs one of the basic filter configurations in conjunction with a series-resonant, or parallel-resonant circuit.

Shunt-Capacitor Filters. The shunt-capacitor filter (which is discussed more thoroughly later in this section) is the simplest type of filter. As shown in part A of the accompanying diagram, it consists of only a single filter element, capacitor C, connected across the rectifier in parallel with the load. In order to obtain good smoothing action when using this filter, the R-C time constant of the circuit should be large. Hence, both the capacitance and the load resistance should be large. Better filtering also results when the ripple frequency is high.

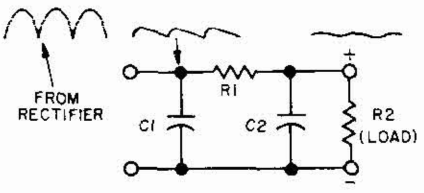


Shunt-Capacitor Filter and Associated Waveforms

Part B of the diagram illustrates the input and output waveforms of the shunt-capacitor filter, using a medium to large value of capacitance in a full-wave rectifier circuit. Capacitor C initially charges up to the peak value of the applied voltage and discharges through the load (R_L) between the rectified pulses. The charge and discharge of C is indicated in part A of the diagram as is the polarity of the voltage developed across the capacitor and the load.

The chief disadvantage of the shunt-capacitor filter is poor regulation, which precludes its use in most power-supply applications. However, the advantages of simplicity and effectiveness recommend its use in some high-voltage applications in preference to more elaborate filters. It finds wide use in power supplies that furnish high-voltage anode potentials to cathode-ray and similar tubes where the current drain is insignificant.

R-C Capacitor-Input Filters. The addition of a series resistor and a second shunt capacitor to the shunt-capacitor filter results in the basic R-C capacitor-input filter, as shown in the accompanying diagram. Because of its resemblance to the Greek letter pi (π), it is known as a **pi-section filter.** The input to the filter is the output voltage from the rectifier developed across input capacitor C1. Typical waveforms of these voltages are included in the diagram.

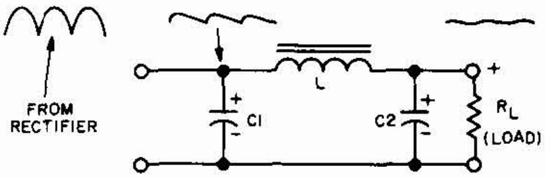


R-C Capacitor-Input Filter and Associated Waveforms

Both the a-c and d-c components of the rectified current flow through series resistor R1. Because the reactance of C2 is small at the frequency of pulsation, most of the a-c component flows through this capacitor and is bypassed to ground around the load resistor. The d-c component flows through load resistor R2. The charging and discharging of C2, due to the passage of the pulsating component, results in a smoothing out of the ripple fluctuations, and a relatively pure direct current is delivered to the load, as is indicated by the output waveform.

The reduction in output voltage due to the excessive voltage drop across the series filter resistor when load current is high makes the R-C filter impracticable for most applications requiring even a moderate amount of current. This type of filter is used effectively in high-voltage, low-current applications. It is also commonly used as a decoupling network in multistage amplifier circuits.

L-C Capacitor-Input Filters. The basic L-C capacitor-input filter has an identical configuration, and is similar in every respect to the R-C capacitor-input filter with one exception—a choke coil (iron-core inductor) replaces the series resistor in the pi-section network, as shown in the accompanying illustration. The L-C capacitor-input filter is probably used to a greater extent than any other type of filter in power-supply applications. The input to the filter section comprising L and C2 is the output voltage of the rectifier, developed across capacitor C1. Typical rectifier output and capacitor C1 input voltage waveforms are included in the diagram. Inductor L and capacitor C2,

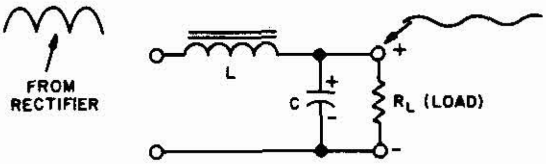


L-C Capacitor-Input Filter and Associated Waveforms

working together, materially reduce the a-c component remaining in the voltage across C1, and thus supply a substantially pure d-c output voltage to the load.

As in the case of the shunt-capacitor filter, and also the R-C capacitor-input filter, the poor regulation of the L-C capacitor-input filter is a major disadvantage. In fact, assuming equal values of C, the regulation of a power supply using an L-C capacitor-input filter is actually worse than that of a power supply using a shunt-capacitor filter. An advantage of the capacitor-input filter is the provision of a much higher output voltage than can be obtained from a comparable filter of the choke-input type.

L-C Choke-Input Filters. With the elimination of capacitor C1, the L-C capacitor-input filter becomes an L-C choke-input filter. This type of filter, together with the associated waveforms, is illustrated in the accompanying diagram.



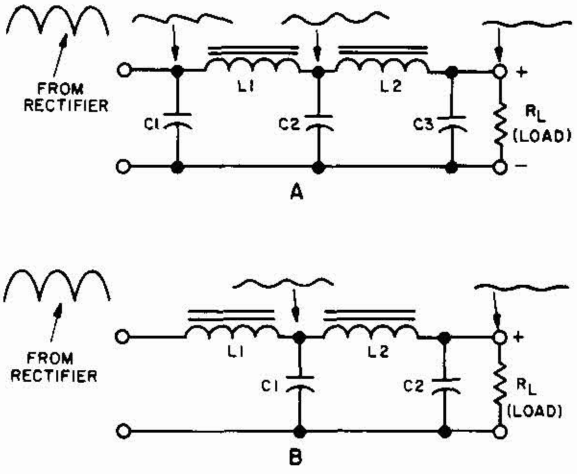
L-C Choke-Input Filter and Associated Waveforms

When rectified pulses are applied to the choke coil (series inductor L), the inductance opposes any change in current through the coil. Thus, the inductance of the coil acts to oppose any increase in current during the rapid positive excursion of the pulses, as well as any decrease in current during the equally rapid negative excursion of the pulses. This action tends to keep a constant current flowing to the load throughout the cycle. Because of this, the pulsating voltage (resulting from the inductance effect) which is developed across capacitor C is maintained relatively constant at a value which approaches the average value of the input voltage. The low reactance presented by capacitor C to the pulsating component functions to decrease the ripple amplitude in the output and thereby to increase the average d-c output voltage.

One disadvantage of the choke-input filter is the significantly lower output voltage of this type of filter as compared with the higher voltage provided by a comparable filter of the capacitor-input type. Another disadvantage, concerned with economics, is that for equivalent filtering, the choke-input filter must employ higher-value components than are required in the capacitor-input filter.

However, the advantage of lower peak currents in the choke-input system, which effects important savings in tube and transformer costs, somewhat offsets the second disadvantage mentioned in the preceding paragraph. Two additional advantages of the choke-input arrangement, in comparison with the capacitor input arrangement, are a greater power capability and much better d-c voltage regulation.

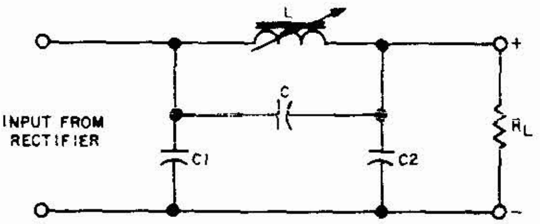
Multiple-Section Filters. To further enhance the filtering action and provide a smoother rectified output voltage (beyond that possible with the simple filter circuits discussed in the preceding paragraphs), one or more additional sections may be added to the basic filter circuit. The accompanying diagram illustrates two multiple-section filters. The capacitor-input type is shown in part A, and the choke-input type is shown in part B. Representative waveforms indicating the approximate shape of the voltage at several different points in each type of multi-section filter are included in the illustration.



Multiple-Section Capacitor-Input and Choke-Input Filters

Multiple-section filters are effective in those applications where only a minimum ripple content can be tolerated in the rectified output voltage to the load. If the ripple attenuation ratio of one L-C section is 100 to 1, then an over-all 10,000-to-1 attenuation ratio will be obtained with two such sections, and a 1,000,000-to-1 attenuation ratio with three L-C sections. While additional filter sections do reduce the ripple component in the output to a minimum, they also result unfortunately, in reduced regulation. With additional sections, more resistance is placed in series with the power supply, which causes greater variations in the output voltage with variations in the load current. Most multiple-section filters consist of a combination of identical L-C sections. However, multiple-section filters are not restricted to this type of design; combinations of L-C and R-C sections may be used effectively to satisfy specific filtering requirements in certain applications.

Resonant Filters. Resonant filters are incorporated in the design of some power-supply circuits. This type of filter is usually made up of two basic types of circuits. One common type of resonant filter uses a series-resonant (or a parallel-resonant) circuit in conjunction with one or more L-C filter sections. Another type employs a parallel-resonant circuit with shunt capacitors in a pi-section filter arrangement. This type of resonant filter is shown in the accompanying illustration.



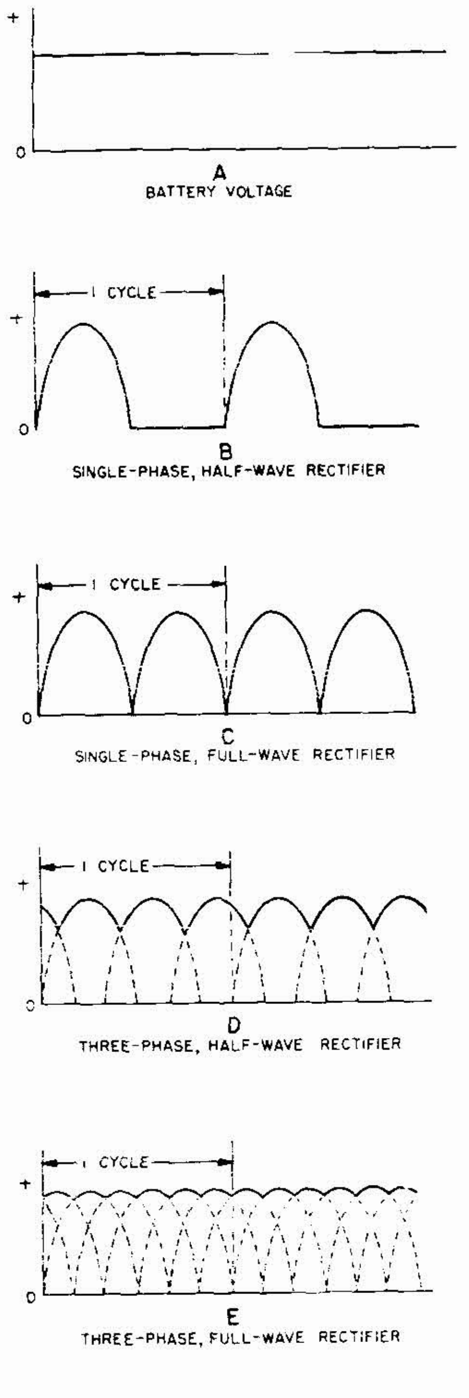
Resonant Filter

The parallel-resonant circuit, consisting of L and C, is tuned to the fundamental ripple frequency, and is connected in series with the output of the rectifier. Since this type of circuit presents an extremely high impedance at resonance, the fundamental-ripple-frequency component will therefore be greatly attenuated in the output voltage to the load.

Two serious disadvantages which limit the use of the resonant filter are as follows: (1) A change in the inductance of L with a change in load current results in detuning of the circuit, and thus a loss in its effectiveness. (2) Harmonics see a much lower impedance than the fundamental ripple frequency (since the circuit is tuned to the fundamental), and are therefore less effectively attenuated. A conventional L-C filter section is sometimes added to the resonant filter shown in the illustration to offset the latter disadvantage.

Filter Output-Voltage Considerations. The unfiltered output from a rectifier can be considered as a pulsating (a-c) voltage superimposed on a d-c voltage. The pulsating component of the rectified voltage is commonly referred to as **ripple**. The frequency components of the ripple and their amplitudes are the major factors which determine the amount of filtering required.

The accompanying illustration shows four typical rectifier output waveforms (parts B, C, D, and E). For contrast, part A shows the smooth d-c output of a battery. The frequency of voltage pulsation, or ripple frequency, is different for each of the rectifier output waveforms. The output of a single-phase, half-wave rectifier, shown in part B, produces pulsations at the frequency of the applied a-c voltage. If the applied a-c voltage has a frequency of 60 cycles per second, the frequency of the ripple component will also be 60 cycles per second. The output of a single-phase, full-wave rectifier, shown in part C, produces pulsa-



A
BATTERY VOLTAGE

B
SINGLE-PHASE, HALF-WAVE RECTIFIER

C
SINGLE-PHASE, FULL-WAVE RECTIFIER

D
THREE-PHASE, HALF-WAVE RECTIFIER

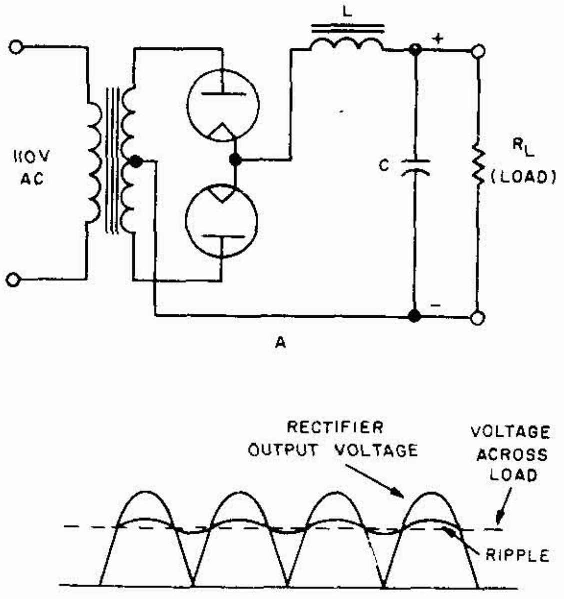
E
THREE-PHASE, FULL-WAVE RECTIFIER

Typical Rectifier Output Waveforms Compared with Voltage Output of a Battery

tions at twice the frequency of the applied a-c voltage because both alternations of the input voltage are rectified. The output of a three-phase, half-wave rectifier, shown in part D, produces pulsations at three times the frequency of the applied voltage; the output of a three-phase, full-wave rectifier, shown in part E, produces pulsations at six times the frequency of the applied voltage. From a comparison of the four typical output waveforms, it can be seen that for an applied a-c voltage of a given frequency, each of the rectifier circuits produces a different ripple frequency. Also, it will be noted that when the output pulses overlap (as shown in parts D and E), an increase in ripple frequency results in a decrease in ripple amplitude. As the ripple frequency is increased and the ripple amplitude is decreased, the rectifier output becomes easier to filter.

It is desirable to furnish a voltage to the load which is free from any ripple component; however, there are several practical limitations (over-all regulation characteristics of the power supply; size, weight, and design of filter components; cost of components; etc) which influence the extent of filtering which is possible. Furthermore, the equipment design may tolerate a small percentage of ripple without any adverse effects upon equipment performance. As a result, the filtered output from the rectifier circuit may contain a small amount of residual ripple voltage which is applied to the load circuit.

Part A of the accompanying illustration shows a typical single-phase, full-wave rectifier system using a choke-input filter to provide d-c voltage to a resistance load. The idealized curves of part B of the illustration show the shape of the output voltage from the rectifier, together with that of the voltage across the load. Since the output voltage of the rectifier can be considered as consisting of a d-c component upon which is superimposed an a-c ripple voltage, it can be shown that (by means of a Fourier analysis) the d-c component of the output wave is $2/\pi$ times the peak value of the a-c input wave. The lowest frequency component of ripple in the output is twice the input frequency and two-thirds the magnitude of the d-c component of the output voltage. The remaining ripple components are harmonics of this lowest-frequency component, and rapidly diminish in amplitude as the order of harmonics is increased. This is graphically illustrated in the accompanying tabulation, which provides pertinent characteristics of three of the four rectifiers considered in this discussion.



Single-phase Full-wave Rectifier System and Associated Output Voltage Waveform

	Rectifier Circuit		
Note: Relative voltage amplitudes are with reference to the d-c component of output voltage, taken as 1.0.	Single-Phase, Full-Wave (Center-tapped)	Three-Phase, Half-Wave	Three-Phase, Full-Wave
a. RMS value of transformer secondary voltage (one-half)	1.11	0.855	0.428
b. Maximum inverse voltage	3.14	2.09	1.05
c. Lowest frequency in rectifier output (F = frequency of applied a-c voltage)	2F	3F	6F
d. Peak value of first three a-c components of rectifier output (ripple frequency):			
Fundamental	0.667	0.250	0.057
Second harmonic	0.133	0.057	0.014
Third harmonic	0.057	0.025	0.006
e. Ripple peaks with reference to d-c axis:			
Positive peak	0.363	0.209	0.0472
Negative peak	0.637	0.395	0.0930

Characteristics of Three Typical Rectifier Circuits Having Choke-Input Filter Systems

In addition to the ripple frequencies present and their respective magnitudes, another very important factor which must also be considered is the amount (percentage) of residual ripple that can be tolerated by the equipment which uses the filtered voltage from the rectifier system. The effectiveness of the filter circuit in this respect is determined from the ratio of the rms value of the ripple voltage to the average value of the *output voltage*. This ratio is expressed as percentage of ripple, as follows:

$$\text{Percentage of ripple} = \frac{E_r}{E_{av}} \times 100$$

Where: E_r = effective (rms) value of ripple voltage
E_{av} = average value of output voltage

As a sine wave, the effective (rms) value of ripple voltage can be expressed by the following equation:

$$E_r = 0.354\,(e_{max} - e_{min})$$

(Refer to preceding tabulation of rectifier voltage relations for percentage values of e_{max} and e_{min}.) An alternate way of stating the percentage of ripple, which may be found preferable in some instances, is (for a single-section filter) as follows:

$$\text{Percentage of ripple} = \frac{mX_C}{(X_L - X_C)}$$

where: X_C = filter capacitance reactance
X_L = filter inductive reactance
C = filter capacitance in microfarads
L = filter inductance in henries

The factor m equals 70 for a single-phase, full-wave rectifier, 24 for a three-phase, half-wave rectifier, and 5 for a three-phase, full-wave rectifier.

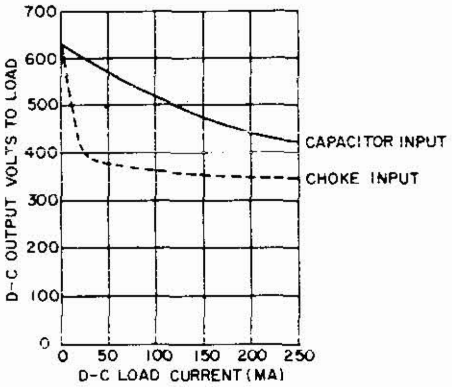
For a double-section filter, the expression becomes:

$$\text{Percentage of ripple} = \frac{m\,X_C{}^2}{(X_L - X_C)^2}$$

In a filter system, as the frequency of the applied voltage is increased (in this case a ripple voltage), the reactance of a shunt capacitor decreases and the reactance of a series inductance increases. This means that the filtering effectiveness of any filter made up of shunt capacitance and series inductance is increased as the frequency of the applied voltage is increased; thus, at the higher ripple frequencies, filter components of smaller size and lighter weight can be used to provide the same degree of filtering as can be obtained at lower ripple frequencies with filter components of larger size and heavier weight.

Voltage Regulation. The output voltage of a power supply decreases as the load current increases because of losses occurring in the various resistances in the rectifier and filter circuit. The accompanying illustration compares the voltage output for varying load currents from a rectifier for a simple capacitor-input filter and for a choke-input filter. In each case, the same type of tube and transformer are used in a center-tapped full-wave circuit to supply power to an identical resistance load. It is immediately apparent, when comparing the two curves on the graph, that while the output voltage for each value of load current is higher for the capacitor-input arrangement, the regulation of the power supply is far greater for the choke-input filter.

Further study of the curves reveals that in the case of the capacitor input, a change in load current from around 25 milliamperes to 250 milliamperes results in a drop in output voltage from 600 to 425 volts, or a total drop of 175 volts. For the same change in load current in the case of the choke input, the d-c output voltage drops from 400 volts to 350 volts, or a total of only 50 volts (as compared with the 175 volts for the capacitor input).



Comparison of Voltage-Regulation Characteristics for Capacitor-Input and Choke-Input Filters

Voltage regulation is a measure of the degree to which a power supply maintains its output-voltage stability under varying load conditions. The amount of change in the output voltage between the no-load and full-load conditions is usually expressed in terms of the percentage of voltage regulation. The percentage of voltage regulation is defined as the ratio of the difference between the no-load and full-load output voltages to the full-load output voltage, times 100. This can be expressed as follows:

$$\text{Percentage of voltage regulation} = \frac{(E_1 - E_2)}{E_2} \times 100$$

where: E_1 = no-load output voltage
E_2 = full-load output voltage

An ideal power supply would have zero internal resistance (impedance), and the percentage of regulation would be zero because there would be no difference between the output voltage for the no-load and full-load conditions. However, since this is not practicable, then the lower the percentage of regulation the better the power supply and the nearer the supply approaches an ideal supply. Well-designed power supplies generally have a regulation of 10 percent or less.

The regulation of the choke-input filter is always better than that of the capacitor-input filter, provided that some minimum value of load current flows through the choke at all times. Under this condition, the output voltage changes only slightly with small changes in load current. However, if the load current is reduced to approach a no-load condition, the choke cannot prevent the associated filter capacitor from charging to the peak value of the applied voltage; thus, the output voltage rises to its maximum value. If the load current is normally a low value, or if the load current varies between zero and a low value, the regulation will be poor as compared with the same circuit operating with a slightly greater load current.

When this is the case, an additional load in the form of a resistor, called a **bleeder resistor**, is placed across the output of the filter to improve the regulation and establish a minimum value of load current for the supply. This minimum value of current, which flows through the filter choke, improves the regulation of the power supply. The value of the current drawn by the bleeder resistor is usually 10 to 15 percent of the total current available from the supply.

The bleeder resistor across the output terminals of the power supply not only assists in maintaining good voltage regulation, but also prevents the capacitors in the filter system from charging up to the peak value of the applied voltage. In addition, the bleeder reduces the possibility of electrical shock to personnel, because the capacitors will discharge through the bleeder resistor after the power supply has been turned off. In many power supplies the bleeder resistor takes the form of a voltage divider, either a tapped resistor or a number of series resistors selected so that several values of output voltage can be supplied to various loads having different voltage and current requirements.

Filter Capacitors. A common type of capacitor used as a filter element in many receiver-type power-supply circuits is the d-c electrolytic capacitor. Within the container of the electrolytic capacitor, rolled aluminum-foil plates are immersed in an electrolyte which is commonly an aqueous solution of boric acid and sodium borate. The actual dielectric in this type of capacitor is the thin oxide film which forms on one set of plates in the presence of a d-c polarizing voltage. The aluminum foil acts as the anode (positive terminal), and the electrolyte acts as the cathode (negative terminal) of the electrolytic capacitor.

There are two general types of electrolytic capacitors—the wet type and the dry type. The physical characteristics of the electrolyte used determines the particular type of capacitor. The wet type uses an aqueous electrolyte in a metal container; the dry type uses a viscous or paste electrolyte, and is available in either a paper (cardboard) or metal container.

The most common working voltages for electrolytic capacitors (both types) run between 6 and 600 volts. Practical values of capacitance run anywhere from 1 or 2 microfarads to as high as 2000 microfarads, the particular value depending on the requirements of a given application.

In keeping with the necessity for a wide range of working voltages and capacitance values, electrolytic capacitors are available in a variety of physical sizes. Generally speaking, the higher the voltage and the greater the capacitance, the larger the physical size. For low-voltage applications, much greater capacitance is provided in units of smaller size than paper-type capacitors (which provide only about one ten-thousandth as much capacitance).

Multiple-section electrolytic capacitors, which have two or more capacitor units housed in a single container, are extensively used in receiver power-supply circuits. For example, a pi-section filter circuit may use a dual-section electrolytic capacitor having two 8-microfarad sections, one connected on each side of the series filter element. However, the capacitance of the different sections need not be the same. In a typical three-section capacitor, for instance, each section may have a different capacitance, or two sections may have the same value and the third section a different value. Any number of combinations are possible, and standardization is the exception rather than the rule.

In addition to the electrolytic capacitor many other nonpolarized types of capacitors are in use; for example: paper-foil, wax-impregnated or oil-impregnated, oxide film, mica, and ceramic. For high-voltage applications such as transmitter power supplies, the individual units are larger and have insulated bushing-type terminals. The higher the voltage, the larger the unit for a given capacitance. Paper-foil types are generally used at voltages from 750 to 2500 volts. Oil-impregnated types are used for voltages of 1500 to 3500 volts (up to 30 kv for large commercial installations). Mica and ceramic capacitors are generally used as blocking capacitors or in tuned filters, since their size is usually limited to values less than 0.25 microfarad. Small, hand-portable equipments sometimes use series-connected receiving or low-voltage-type electrolytic capacitors for economy (the price of two low-voltage units is considerably lower than one high-voltage unit). Since the introduction of transistors, extremely low-voltage (2, 4, 6, and 12-volt) capacitors of very small physical size, with capacitance values on the order of 50, 100, and 150 microfarads or more, are in common use to supply high currents at the low voltages employed. These capacitors are used in power supplies which eliminate the necessity for, and expense of, battery replacement.

SHUNT-CAPACITOR FILTER.

APPLICATION.

The shunt-capacitor filter, as previously stated, is the simplest type of filter. The application of this filter is very limited; it is sometimes used in extremely high-voltage, low-current power supplies for cathode-ray and similar electron tubes which require very little load current from the supply. This filter is also used in applications where the power-supply ripple frequency is relatively high, e.g., to filter the output of a dynamotor.

CHARACTERISTICS.

Capacitance and load-resistance values must be high (large R-C time constant required).

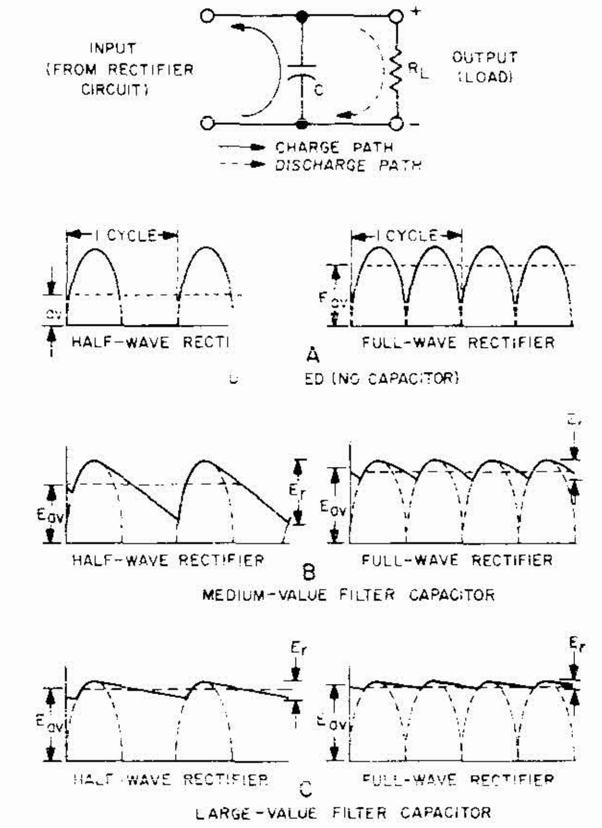
Load current must be relatively small if filter is to have good regulation.

Filtering efficiency increases as ripple frequency is increased.

Regulation of rectifier-type power supply is poor with this type of filter; voltage regulation depends mainly on value of capacitor.

CIRCUIT ANALYSIS.

General. The rectifier circuits previously described in this section of the handbook provide a rectified output voltage, across the load resistance, which has a pulsating waveform. The accompanying illustration shows a simple shunt-capacitor filter and the waveforms obtained when the input to the filter is obtained from either a half-wave or a full-wave (single-phase) rectifier circuit.



HALF-WAVE RECTI[illegible] FULL-WAVE RECTIFIER
A
[illegible]ED (NO CAPACITOR)

HALF-WAVE RECTIFIER FULL-WAVE RECTIFIER
B
MEDIUM-VALUE FILTER CAPACITOR

HALF-WAVE RECTIFIER FULL-WAVE RECTIFIER
C
LARGE-VALUE FILTER CAPACITOR

Shunt-Capacitor Filter and Waveforms

The waveforms given in part A of the illustration represent the unfiltered output (without capacitor C) from the rectifier circuit when current pulses flow through the load resistance, R_L, each time the rectifier conducts. Note that the dashed line indicating the average value of output voltage, E_{av}, for the half-wave rectifier is less than half (approx 0.318) the amplitude of the voltage peaks; the average value of output voltage, E_{av}, for the full-wave rectifier is greater than half (approx 0.637), but is still much less than the maximum peak amplitude of the applied waveform. With no capacitor connected across the output of the rectifier circuit, the waveform has a large value of pulsating component as compared with the average (or d-c) component.

When a capacitor is connected across the output of the rectifier (across load resistor R_L), the average value of output voltage, E_{av}, will be increased because of the filtering action of the capacitor. In part B of the illustration a capacitor of medium value is placed in shunt (parallel) with the load resistance, R_L. The value of the capacitor is fairly large; it thus presents a relatively low reactance to the pulsating current and stores a substantial charge. The rate of charge for the capacitor is limited [illegible] the impedance of the [illegible] source (transformer) and the internal resistance of the rectifier, both of which are relatively low; therefore, the R-C charge time for the circuit is relatively short. As a result, when the pulsating voltage is first applied to the shunt-capacitor filter, the capacitor charges rapidly and almost reaches the peak voltage within the first few cycles. The charge on the capacitor approximates the peak value of the rectifier voltage when the rectifier is conducting, and tends to retain its charge when the rectifier output falls to zero (since the capacitor cannot discharge immediately). The capacitor slowly discharges through the load resistance, R_L, during the time the rectifier is nonconducting.

The rate of discharge for the capacitor is determined by the load resistance; if the capacitor and load-resistance values are large, the R-C discharge time for the circuit is relatively long. From the waveforms shown in part B of the illustration, it can be seen that the addition of capacitor C to the circuit results in an increase in the average value of output voltage, E_{av}, and a reduction in the ripple component, E_r, present across the load resistance.

As previously stated, the capacitor partially discharges through the load, dropping the output voltage until the next positive pulse occurs; when the amplitude of this pulse exceeds the value of voltage on the capacitor, the capacitor once again starts charging to the peak value.

If the value of the capacitor used in the filter circuit is increased, the average value of the output voltage, E_{av}, is also increased. In part C of the illustration, the effect of increasing the value of capacitor C (over that used in part B) is shown. The time constant of the charging circuit is still relatively short, but the time constant of the discharging circuit is considerably greater. Because of the increased discharge time constant, the large-value capacitor does not discharge as rapidly as the medium-value capacitor; therefore, the average voltage is higher and the amplitude of the ripple component, E_r, is decreased.

Compare the increased filtering action shown in the waveform of part C with that of part B. Theoretically, the shunt-capacitor filter can provide any desired degree of filtering; the larger the value of capacitor C, the better the filtering action, because of the lowered impedance (X_C) offered to the pulsating component and the ability of the capacitor to retain a charge longer because of the increased R-C discharge time constant. However, there is a practical limitation to the maximum value of the capacitor used in the filter. If the peak-current rating of the rectifier is exceeded during the charging time for the capacitor, the rectifier will be damaged; thus, a compromise in the value of the capacitor is necessary in order to [illegible] the peak-current rating of the rectifier.

The load resistance is also an important consideration. If the load resistance is made small, the load current increases and the average value of output voltage (E_{av}) decreases. The R-C discharge time constant is a direct function of the value of the load resistance; therefore, the rate of capacitor voltage discharge is a direct function of the current through the load. The greater the load current, the more rapid the discharge [illegible] the average value of output voltage. For this reason, the shunt-capacitor filter is seldom used with rectifier circuits that must supply a relatively large load current.

The pulsations across capacitor C and load resistance R_L, no matter how small in amplitude, are in effect a form of distortion. Although these pulsations represent a fundamental frequency, many other frequency components are also present in the output. In the majority of equipment applications, the presence of a ripple-voltage component is not desirable; therefore, for most equipment application it is impracticable to use a simple shunt-capacitor filter; additional filtering (or another type of filter) is necessary to reduce the ripple amplitude to an acceptable minimum.

Detailed Circuit Operation. Consider now a complete cycle of operation, using a single-phase, half-wave rectifier operating with shunt capacitor C and load resistance R_L, shown in the preceding illustration. Capacitor C is assumed to be large enough to insure small reactance to the pulsating rectified current. The resistance of R_L is assumed to be much greater than the reactance of C at the input frequency.

When the circuit is energized, the rectifier conducts on the positive half of the cycle, and current flows into and charges capacitor C to approximately the peak value of the input voltage. The charge is less than the peak value of voltage by the amount of the voltage drop across the rectifier tube. The charge on C is indicated by the heavy lines on the waveforms in parts B and C of the illustration.

On the negative half-cycle the rectifier cannot conduct, since the plate is negative with respect to the cathode. During this interval, capacitor C discharges through load resistance R_L. The discharge of C produces the downward slope of the heavy lines in parts B and C of the illustration. In contrast to the abrupt fall of the applied a-c voltage from peak value to zero (shown in dotted lines), the voltage across C (and thus across R_L) during the discharge period decreases at a gradual rate until the time of the next half-cycle of rectifier operation. For a given value of load current, the value of C determines the rate at which the discharge voltage decreases. This rate of voltage decline and the value of C are inversely related. Thus the rate is greater for smaller values of C and less for greater values of C. This indicates that for the same load current, if C (or R_L) is increased, the ripple component in the output to the load is decreased. (A longer time constant requires a longer time to charge and discharge.)

Since practical values of C and R_L insure a more or less gradual decrease of the discharge voltage, a substantial charge remains on the capacitor at the time of the next half-cycle of operation. As a result, no current can flow from the rectifier until the rising a-c input voltage on the rectifier plate exceeds the voltage of the charge remaining on C, because this charge voltage is the cathode-to-ground potential of the rectifier tube. When the plate voltage exceeds the charge voltage across C, the rectifier again conducts, and again charges C to approximately the peak value of the applied voltage. Shortly after the charge on the capacitor reaches its peak value, the tube stops conducting. Because the fall of the a-c input voltage on the plate is considerably more rapid than the decrease in the capacitor voltage, the cathode quickly becomes more positive than the plate, and the rectifier ceases to conduct. During the charging period, capacitor C is connected across the output of the rectifier, and the charge time is determined by the effective series resistance, which is only that of the tube plate-to-cathode (forward) resistance and the transformer impedance, plus that of the leads to the tube and capacitor. Hence, the resistance is low and C charges very quickly. During the nonconducting period, the discharge path is through R_L, which is relatively large, so that the time constant is long. Thus capacitor C does not discharge appreciably before the conduction cycle again begins.

The repeated charge and discharge of capacitor C (as described above) with the respective rise and fall of the input voltage constitutes the basic filtering action of this circuit. To reduce the ripple amplitude and increase the d-c component in the output voltage, capacitor C charges up and stores energy when the tube is conductin and discharges to furnish current to the load when the tube is nonconducting.

Using Ohms law, $R = \dfrac{E}{I}$, it is evident that a heavy current drain, for the same output voltage, represents a lower load resistance. Therefore, with a heavy load and lower R_L, capacitor C discharges more quickly. Since the output voltage represents the average charge retained in the capacitor, it can be seen that with heavy loads the capacitor will discharge further between the periods of tube conduction. Hence, the output voltage will also be lower. This is why the single-capacitor filter is used only for very light current drains. Since the output voltage for heavy loads is lower and the output ripple voltage component is also higher, the effective filtering is good only for light loads.

FAILURE ANALYSIS.

General. With the supply voltage removed from the input to the filter circuit, one terminal of the filter capacitor can be disconnected from the circuit. The capacitor should be checked, using a capacitance analyzer, to determine its effective capacitance and leakage resistance. During these checks it is very important that correct polarity be observed. A decrease in effective capacitance or losses within the capacitor can cause the output to be below normal and also cause excessive ripple amplitude.

If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter. Resistance measurements can be made across the terminals of the capacitor to determine whether it is shorted, leaky, or open. When testing electrolytic capacitors, set the ohmmeter to the high range and connect the test prods across the capacitor, being careful to observe polarity. This is important because current flows with less opposition through an electrolytic capacitor in one direction than in the other.

If the correct polarity is not observed, an incorrect reading will result. When the test prods are first connected, a large deflection of the meter takes place, and then the pointer returns slowly toward the infinite-ohms position as the capacitor charges. For a good capacitor with a rated working voltage of 450 volts, dc, the final reading on the ohmmeter should be over 500,000 ohms. (A rough rule of thumb for high-voltage capacitors is at least 1000 ohms per volt.) Low-voltage electrolytic capacitors (below 100 volts rating) should indicate on the order of 100,000 ohms.

If no deflection is obtained in the ohmmeter when making the resistance check explained above, an open-circuited capacitor is indicated.

A steady full scale deflection of the pointer at zero ohms indicates that the capacitor being tested is short-circuited.

An indication of a leaky capacitor is a steady reading on the scale somewhere between zero and the minimum acceptable value. (Be certain this reading is not caused by an in-circuit shunting part.) To be valid, these capacitor checks should be made with the capacitor completely disconnected from the circuit in which it operates.

In high-voltage filter capacitor applications, paper and oil-filled capacitors are used, as also are mica and ceramic capacitors (for low-capacitance values). In this case, polarity is of no importance unless the capacitor terminals are marked + or -. It is, however, good maintenance practice to use the output polarity of the circuit as a guide, connecting positive to positive and negative to negative. Thus any effects of polarity on circuit tests are minimized and the possibility of damage to components or test equipment is avoided. **Remember**-an undischarged capacitor retains its polarity and holds its charge for long periods of time. To be safe, discharge the capacitor to be tested with the **power OFF** before connecting test equipment or disconnecting the capacitor.

A simple check which can be used to quickly determine whether the capacitor is at fault is to substitute a known good capacitor of the same value and voltage rating and note whether the circuit operation returns to normal.

R-C CAPACITOR-INPUT FILTER.

APPLICATION.

The R-C capacitor-input filter is limited to applications in which the load current is small. This type of filter is used in power supplies where the load current is constant and voltage regulation is not necessary, such as in the high-voltage power supply for a cathode-ray tube or as part of a de-coupling network for multistage amplifiers.

CHARACTERISTICS.

Filter is composed of shunt input capacitor, series resistor, and shunt output capacitor.

Filtering efficiency increases as ripple frequency is increased.

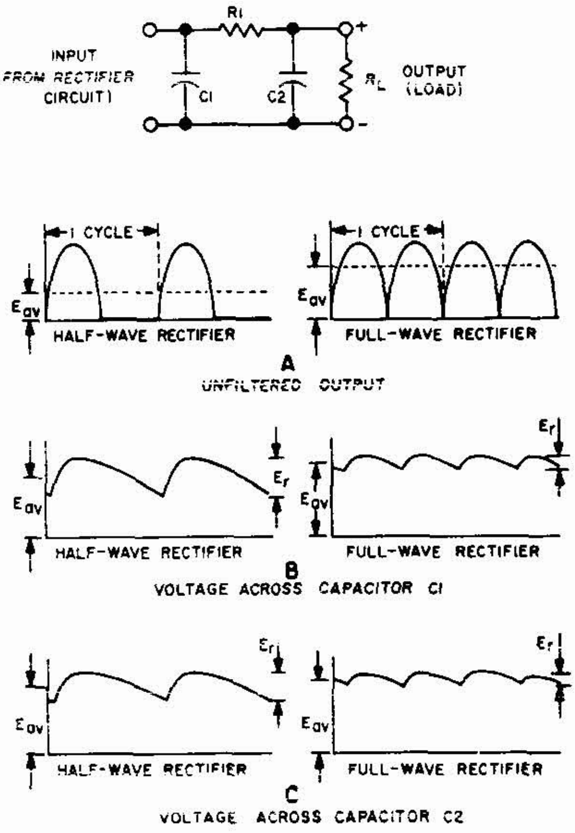
Output current is much less than that obtained from corresponding filter which uses a choke instead of a resistor.

Regulation of rectifier-type power supply is poor with this type of filter; requires relatively constant load current.

Rectifier peak current is high with this circuit because of input capacitance.

CIRCUIT ANALYSIS.

The rectifier circuits previously described in this section of the handbook provide a rectified output voltage (across the load resistance) which has a pulsating waveform. The accompanying illustration shows an R-C capacitor-input filter and the waveforms obtained from either a half-wave or a full-wave (single-phase) rectifier circuit.



R-C Capacitor-Input Filter and Waveforms

The waveforms shown in part A represent the unfiltered output from a typical rectifier circuit when current pulses flow through the load resistance each time the rectifier conducts. Note that the dashed line indicating the average value of output voltage, E_{av}, for the half-wave rectifier is less than half the amplitude of the voltage peaks (approx 0.31). The average value of output voltage, E_{av}, for the full-wave rectifier is greater than half (approx 0.637), but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component as compared with the average (or d-c) component.

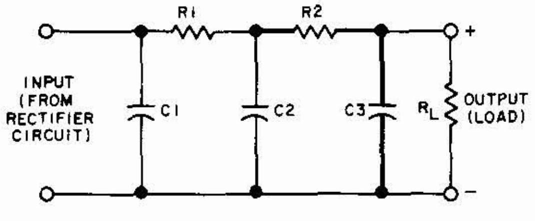
The R-C filter shown in the schematic of the illustration consists of an input filter capacitor, C1, a series resistor, R1, and an output filter capacitor, C2. This filter is called an **R-C capacitor-input filter,** and is sometimes referred to as an **R-C pi-section filter** because the configuration of the schematic resembles the Greek letter π.

Capacitor C1 is placed at the input to the filter, and is in shunt with the output of the rectifier circuit; capacitor C1 has the same filtering action in this circuit that the capacitor does in the SHUNT-CAPACITOR FILTER, described earlier in this section of the handbook. In the capacitor-input filter, the major portion of the filtering action is accomplished by the input capacitor, C1. The average value of voltage across capacitor C1 is shown in part B of the illustration for half-wave and full-wave rectifier circuits. Note that the average value of voltage across capacitor C1 is greater than the average value of voltage for the unfiltered output of the rectifier, shown in part A. The value of the input capacitor is relatively large in order to present a low reactance (X_C) to the pulsating current, and to store a substantial charge. The rate of charge for the input capacitor is limited only by the impedance of the a-c source (transformer) and the internal (or forward) resistance of the rectifier, both of which are relatively low; therefore, the R-C charge time constant for the input circuit is relatively short. As a result, when the pulsating voltage is first applied to the capacitor-input filter, capacitor C1 charges rapidly and reaches the peak voltage within the first few cycles. The charge on capacitor C1 approximates the peak value of the pulsating voltage when the rectifier is conducting, but when the rectifier output falls to zero, the capacitor partially discharges through the series resistor, R1, and the load resistor, R_L, during the time the rectifier is nonconducting. The larger the value of the input capacitor, C1, the better the filtering action; however, there is a practical limitation to the maximum value of the capacitor. If the peak-current rating of the rectifier is exceeded during the charging time for the capacitor, the rectifier will be damaged; for this reason, a compromise in the value of the input capacitor is necessary in order to keep the maximum charging current within the peak-current rating of the rectifier.

The R-C capacitor-input filter is similar to the L-C CAPACITOR-INPUT FILTER, described later in this section, except that a resistor is used in place of the series inductor. Although the series resistor affords filtering action, a resistor can never be as effective as an inductor unless a considerable d-c voltage drop can be tolerated. However, the R-C capacitor-input filter circuit is an improvement over the shunt-capacitor filter, described earlier in this section, because additional filtering results from the added reactances of resistor R1 and capacitor C2.

The pulsating output from the rectifier circuit, which is applied to the input of the filter, can be considered as being composed of two components: an a-c component, represented by pulsations, and a d-c component, represented by the average value of voltage (E_{av}). Because these pulsations occur at a relatively low frequency (which is the input frequency for a half-wave rectifier, or a multiple of the input frequency for full-wave and other types of rectifiers), the value of the shunt capacitors, C1 and C2, is purposely made large so that their reactances are very low at the pulsating (ripple) frequency. Both the a-c and d-c components of the rectifier output (present at the input to the filter) flow through the filter resistor, R1; therefore, a voltage drop occurs across R1, which results from the voltage-divider action of resistor R1 in series with the parallel combination of capacitor C2 and load resistance R_L. Since the reactance of C2 is very low at the ripple frequency, most of the a-c component bypasses the load resistance, R_L, and the d-c component flows through the load resistance. The efficiency of the filter depends, to a great extent, upon keeping the reactance of capacitor C2 very small as compared with the load resistance, R_L. The charging and discharging of capacitor C2 tends to smooth out the voltage fluctuations and reduce the ripple amplitude (E_r) applied to the load. The final result is the waveform shown in part C of the illustration. The average value of voltage developed across capacitor C2 and load resistance R_L is always less than the average value of voltage across capacitor C1, because of the voltage drop occurring across the filter resistor, R1. When the load current is even moderate, an R-C filter is not normally used, because the voltage drop across the series resistor, R1, becomes excessive for most applications.

The output from a pi-section R-C filter may contain an amount of ripple which is considered excessive for the equipment application. By adding another series filter resistor, R2, and a shunt capacitor, C3, to the basic capacitor-input filter, the ripple component across the load resistance can be further attenuated. However, the addition of series resistors increases the voltage drop within the filter, resulting in poorer regulation and a decrease in output voltage. For these reasons, the number of sections that may be added, as well as the size of the resistors, is limited. As shown in the accompanying illustrations, the added R-C filter components, R2 and C3, resemble an inverted letter L.



Capacitor-Input Filter with R-C Filter Section Added

FAILURE ANALYSIS.

General. The shunt capacitors are subject to open circuits, short circuits, and excessive leakage; the series filter resistors are subject to changes in value and, occasionally, to open circuits. Any of these troubles can be easily detected.

The input capacitor has the greatest pulsating voltage applied to it, is the most susceptible to voltage surges, and has a higher average voltage applied; as a result, the input capacitor is frequently subject to voltage breakdown and shorting. The remaining shunt capacitor(s) in the filter circuit is not subject to voltage surges because of the protection offered by the series filter resistor(s); however, a shunt capacitor can become open, leaky, or shorted.

Shorted capacitors or an open filter resistor will result in a no-output indication. An open filter resistor will result in an abnormally high d-c voltage at the input to the filter and no voltage at the output of the filter. Leaky capacitors or filter resistors that have increased in value will result in a low d-c output voltage. Open capacitors, capacitors which have lost their effectiveness, or filter resistors that have decreased in value will result in an excessive ripple amplitude in the output of the supply.

With the supply voltage removed from the input to the filter circuit, one terminal of each capacitor can be disconnected from the circuit. Each capacitor should be checked, using a capacitance analyzer, to determine its effective capacitance and leakage resistance. *It is important that correct polarity be observed at all* times. A decrease in effective capacitance or losses within the capacitor can cause the output to be below normal and also cause excessive ripple amplitude. The value of resistors can be checked by using an ohmmeter.

If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter. Resistance measurements can be made across the terminals of the capacitor to determine whether it is shorted, open, or leaky. When testing electrolytic capacitors, set the ohmmeter to the high range and connect the test prods across the capacitor, being careful to observe polarity. This is important because current flows with less opposition through an electrolytic capacitor in one direction than in the other. If the correct polarity is not observed, an incorrect reading will result. When the test prods are first connected, a large deflection of the meter takes place, and then the pointer returns slowly toward the infinite ohms position as the capacitor charges. For a good capacitor with a rated working voltage of 450 volts, dc, the final reading on the ohmmeter should be over 500,000 ohms. (A rough rule of thumb for high-voltage capacitors is at least 1000 ohms per volt.) Low-voltage electrolytic capacitors (below 100 volts rating) should indicate on the order of 100,000 ohms.

If no deflection is obtained on the ohmmeter when making the resistance check explained above, an open-circuited capacitor is indicated.

A steady full-scale deflection of the pointer at zero ohms indicates that the capacitor being tested is short-circuited.

An indication of a leaky capacitor is a steady reading on the scale somewhere between zero and the minimum acceptable value. (Be certain this reading is not caused by an in-circuit shunting part.) To be valid, these capacitor checks should be made with the capacitor completely disconnected from the circuit in which it operates.

In high-voltage filter capacitor applications, paper and oil-filled capacitors are used, as also are mica and ceramic capacitors (for low-capacitance values). In this case, polarity is of no importance unless the capacitor terminals are marked + or –. It is, however, good maintenance practice to use the output polarity of the circuit as a guide, connecting positive to positive and negative to negative. Thus any effects of polarity on circuit tests are minimized and the possibility of damage to components or test equipment is avoided. **Remember:** an undischarged capacitor retains its polarity and holds its charge for long periods of time. To be safe, discharge *the capacitor to be tested with the* **power OFF** before connecting test equipment or disconnecting the capacitor.

A simple check which can be used to quickly determine whether a capacitor is at fault is to substitute *a known good capacitor of the same value and voltage* rating and note whether the circuit operation returns to normal.

L-C CAPACITOR-INPUT FILTER.

APPLICATION.

The L-C capacitor-input filter is one of the most commonly used filters. This type of filter is used primarily in radio receiver and small audio amplifier power supplies, and in any type of power supply where the output current is low and the load current is relatively constant.

CHARACTERISTICS.

Filter is composed of shunt input capacitor, series inductor, and shunt output capacitor.

Filtering efficiency increases as ripple frequency is increased.

Output voltage is greater than that of choke-input filter; output current is less than that of choke-input filter.

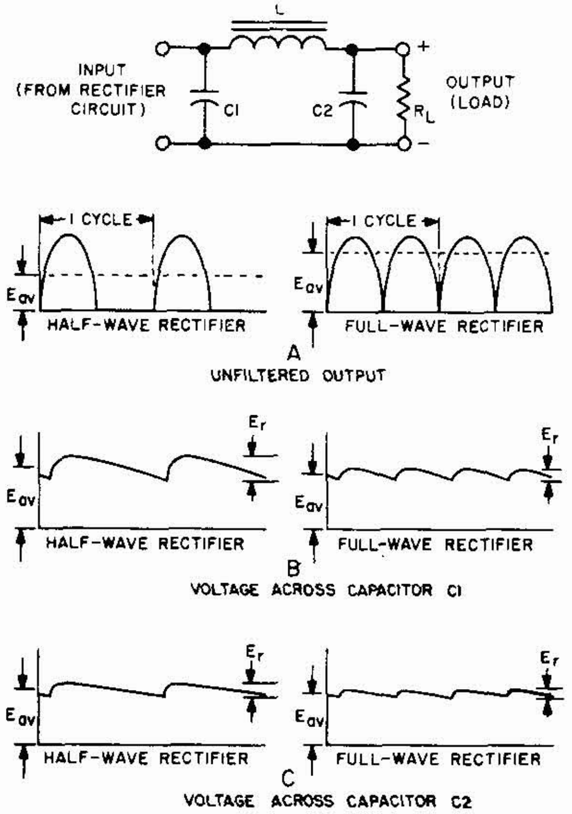
Regulation of rectifier-type power supply is only fair with this type of filter; requires relatively constant load current.

Rectifier peak current is high with this circuit because of input capacitance.

CIRCUIT ANALYSIS.

General. The accompanying illustration shows an L-C capacitor-input filter and the waveforms obtained from either a half-wave or a full-wave (single-phase) rectifier circuit.

The waveforms shown in part A represent the unfiltered output from a typical rectifier circuit when current pulses flow through the load resistance each time the rectifier conducts. *Note that the average value of* output voltage, E_{av} (indicated by the dashed line), for the half-wave rectifier is less than half the amplitude of the voltage peaks; the average value of output voltage, E_{av}, for the full wave rectifier is greater than



L-C Capacitor-Input Filter and Waveforms

half, but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component as compared with the average (or d-c) component.

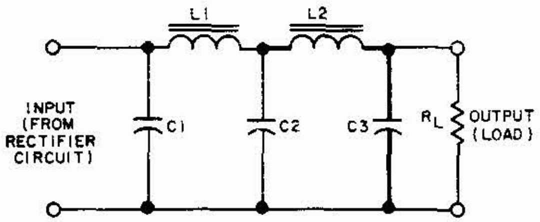
The filter shown in the schematic of the illustration consists of an input filter capacitor, C1, a series inductor, L, and an output filter capacitor, C2. It is called a **capacitor-input filter**, and is often referred to as a **pi-section filter** because the configuration of the schematic resembles the Greek letter π.

Capacitor C1 is placed at the input to the filter, and is in shunt with the output of the rectifier circuit; capacitor C1 exhibits the same filtering action in this circuit that C1 does in the R-C CAPACITOR-INPUT FILTER, described earlier in this section of the handbook. In the capacitor-input filter, the major portion of the filtering action is accomplished by the input capacitor, C1. The average value of voltage across the input capacitor, C1, is shown in part B of the illustration for the half-wave and full-wave rectifier circuits. Note that the average value of voltage across capacitor C1 is greater than the average value of voltage for the unfiltered output of the rectifier, shown in part A. The value of the input capacitor is relatively large in order to present a low reactance (X_c) to the pulsating current and to store a substantial charge. The rate of charge for the capacitor is limited only by the impedance of the a-c source (transformer) and the internal resistance of the rectifier, both of which are relatively low; therefore, the R-C charge time constant for the input circuit is relatively short. As a result, when the pulsating voltage is first applied to the capacitor-input filter, capacitor C1 charges rapidly and reaches the peak voltage within the first few cycles. The charge on capacitor C1 approximates the peak value of the pulsating voltage when the rectifier is conducting, but when the rectifier output falls to zero, the capacitor partially discharges through the series inductor, L, and the load resistance, R_L, during the time the rectifier is nonconducting. The larger the value of the input capacitor, C1, the better the filtering action; however, there is a practical limitation to the maximum value of the capacitor. If the peak-current rating of the rectifier is exceeded during the charging time for the capacitor, the rectifier will be damaged; for this reason, a compromise in the value of the capacitor is necessary in order to keep the maximum charging current within the peak-current rating of the rectifier.

The inductor (or filter choke), L, serves to maintain the current flow to the filter output (capacitor C2 and load resistance R_L) at a nearly constant level during the charge and discharge periods of input capacitor C1. The rate of discharge for capacitor C1 is determined by the d-c resistance of the filter choke, L, and the load resistance, R_L, in series. The average value of voltage developed across capacitor C2 and load resistance R_L is somewhat less than the average voltage developed across capacitor C1. As the load current is increased, the voltage drop across inductor L increases because of the internal d-c resistance of the inductor. Also, there is a decrease in the discharge time constant for capacitor C1 which, in turn, results in a decrease in the average value of voltage across C1 because of the greater discharge between rectifier pulses; thus, the average voltage across output capacitor C2 is also reduced.

Series inductor L and capacitor C2 form a voltage divider across capacitor C1. As far as the ripple component is concerned, the inductor offers a high impedance and capacitor C2 offers a low impedance to the ripple component; as a result, the ripple component, E_r, appearing across the load resistance is greatly attenuated. Since the inductance of the filter choke opposes changes in the value of the current flowing through it, the average value of the voltage produced across the output capacitor, C2, contains a much smaller value of ripple component, E_r, as compared with the value of ripple produced across the input capacitor, C1. Since inductor L operates in conjunction with capacitor C2, if either filter element is decreased in value, the other must be increased accordingly to maintain the same degree of filtering. The pulsations across capacitor C2, which are present in spite of the action of capacitor C1 and inductor L, cause C2 to charge and discharge in the same manner as C1. The final result is the waveform shown in part C of the illustration.

Some electronic equipments require a high degree of filtering, while other equipments are not critical in this respect. The output from a single shunt-capacitor filter, or from an R-C or L-C capacitor-input (single pi-section) filter, may contain an amount of ripple which is considered excessive for the equipment application. When this is the case, it is necessary to use additional filtering to further attenuate the ripple component and reduce the ripple content to a minimum. By adding another series inductor (L2) and shunt capacitor (C3) to the basic capacitor-input filter, the ripple component across the load resistance can be further attenuated. As shown in the accompanying illustration, the added filter components, L2 and C3, are called an **L-section filter** because the schematic configuration resembles an inverted letter L.



Capacitor-Input Filter with L-Section Added

In a practical filter circuit, the reactance of the additional shunt capacitor (C3) is much less than the reactance of the additional series inductor, L2, and of the load resistance, R_L. Therefore, each L-section filter which is added to the basic filter further reduces the output ripple amplitude. When using a multiple-section filter, the operating voltage may be taken from each separate filter section. However, when the L-section (L2 and C3) is added to the basic filter circuit, the regulation of the supply suffers, because adding resistance in series with the load causes greater variation of the output voltage when changes in load current occur. The voltage regulation of a power supply using a capacitor-input filter circuit is relatively poor (as compared with a choke-input filter); for this reason, the use of a capacitor-input filter is usually restricted to low-current applications such as receivers, amplifiers, and the like, where the load current is relatively constant.

Detailed Circuit Operation. Consider now a complete cycle of operation, using a single-phase, full-wave rectifier circuit to supply the input voltage to the filter. The rectifier voltage is developed across capacitor C1. The ripple voltage in the output of the filter is the alternating component of the input voltage reduced in amplitude by filter action, as shown in the preceding illustration.

Each time the plate of the rectifier goes positive with respect to the cathode, the tube conducts and C1 charges to the peak value of the voltage less the internal voltage drop in the tube. Conduction occurs twice during each cycle for a full-wave rectifier; for a 60-cycle supply this produces a 120-cycle ripple voltage. Although each tube alternates (first one conducts while the other is nonconducting, and then the other conducts while the first one is nonconducting), the filter input voltage is not steady. As the positive conducting plate voltage increases (on the positive half of the cycle), capacitor C1 charges rapidly, the charge being limited only by the transformer secondary impedance and the tube forward (plate-to-cathode) resistance. During the nonconducting interval (when the plate voltage drops below the capacitor charge voltage), C1 discharges through choke L and load resistance R_L. The discharge path is an R-L long-time-constant path; thus C1 discharges much more slowly than it charges, as indicated by the waveforms in the illustration above. In this respect, the action of C1 is similar to that of the shunt-capacitor filter described previously in this section, with one exception. This exception is the effect of choke L.

Choke L is usually chosen to be a large value, on the order of 10 to 20 henries, and offers a large inductive reactance to the 120-cycle ripple component produced by the rectifier. Thus each time C1 starts to discharge, the inertia of the choke inductance effectively opposes a change in the ripple current through L. As far as the d-c component of this voltage is concerned, it is affected only by the time constant consisting of the d-c resistance of L and Rl in series with C1.

The effect of L on the charging of capacitor C2 must now be considered. Since C2 is connected in parallel with C1 through choke L, any charge on C1 will also tend to charge C2. However, both the impedance and resistance of L are in series with C2, and a voltage division of both the ripple (a-c) voltage and d-c output voltage occurs. The greater the impedance of the choke to the ripple frequency, the less the ripple voltage appearing across C2 and the output. The d-c output voltage is fixed mainly by the d-c resistance of the choke. For each specific value of current there is a voltage drop across the choke. Thus the d-c voltage across C2 is always less than that across C1 (the higher the output current, the lower the voltage across C2). Since C2 is supplied from C1, which has maximum and minimum voltages produced by the charge and discharge action (the ripple voltage), C2 also follows this charge and discharge pattern. The difference is that the C2 action is smoothed out by the longer time constant. While the peaks and valleys exist, the values are lower. As can be seen from the waveform in part C of the illustration above, the over-all effect is to provide a purer direct current (less ripple).

FAILURE ANALYSIS.

General. Shunt capacitors are subject to open circuits, short circuits, and excessive leakage; series inductors are subject to open windings and occasionally shorted turns or a short circuit to the core.

The input capacitor has the greatest pulsating voltage applied to it, is the most susceptible to voltage surges, and has a generally higher average voltage applied; as a result, the input capacitor is frequently subject to voltage breakdown and shorting. The output capacitor is not as susceptible to voltage surges because of the protection offered by the series inductor, but the capacitor can become open, leaky, or shorted.

A shorted capacitor, an open filter choke, or a choke winding which is shorted to the core results in a no-output indication. A shorted capacitor, depending on the magnitude of the short, may cause a shorted rectifier, transformer, or filter choke. When proper precautions are taken, it may only blow a protective fuse. An open filter choke results in an abnormally high d-c voltage at the input to the filter and no voltage at the output of the filter. A leaky or open capacitor in the filter circuit results in a low d-c output voltage; this condition is generally accompanied by an excessive ripple amplitude. Shorted turns in the winding of a filter choke reduce the effective inductance of the choke and decrease its filtering efficiency; as a result, the ripple amplitude increases.

With the supply voltage removed from the input to the filter circuit, one terminal of each capacitor can be disconnected from the circuit. Each capacitor should be checked, using a capacitance analyzer, to determine its effective capacitance and leakage resistance, being careful always to observe correct polarity. A decrease in effective capacitance or losses within the capacitor can cause the output to be below normal and also cause excessive ripple amplitude.

If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter. Resistance measurements can be made across the terminals of the capacitor to determine whether it is shorted or leaky. If the capacitor is of the electrolytic type, the resistance measurement may vary, depending on the test-lead polarity of the ohmmeter. Therefore, two measurements must be made, with the test leads reversed at the capacitor terminals for one of the measurements, to determine the larger of the two resistance measurements. The larger resistance value is then accepted as the measured value.

A simple check which can be used to quickly determine whether a capacitor is at fault is to substitute a known good capacitor of the same value and voltage rating and note whether the circuit operation returns to normal.

L-C CHOKE-INPUT FILTER.

APPLICATION.

The L-C choke-input filter is used primarily in power supplies where voltage regulation is important and where the output current is relatively high and subject to varying load conditions. The filter is used in high-power applications such as those found in the power-supply circuits of radar and communication transmitters.

CHARACTERISTICS.

Filter is composed of series input inductor and shunt output capacitor.

Filtering efficiency increases as ripple frequency is increased.

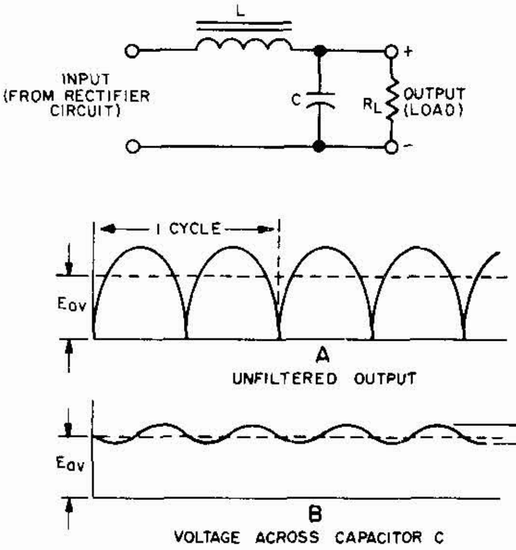
Output voltage is less than that of capacitor-input filter; output voltage from filter approaches average value of voltage from rectifier at filter input.

Regulation of rectifier-type power supply is good with this type of filter; further improvement in regulation characteristics can be realized with swinging-choke input inductor.

Rectifier output current approaches maximum rated current; output current is generally greater than that of capacitor-input filter.

CIRCUIT ANALYSIS.

The accompanying illustration shows an L-C choke-input filter and the waveforms obtained from a single-phase, full-wave rectifier circuit.



L-C Choke-Input Filter and Waveforms

The output from a single-phase, half-wave rectifier circuit is not illustrated because the choke-input filter is seldom used with this circuit. The unfiltered output obtained from three-phase, half-wave and full-wave rectifier circuits produces a higher average voltage and ripple frequency; however, the principle of filter action is essentially the same as that illustrated for the single-phase, full-wave rectifier; therefore, these waveforms are not illustrated.

The waveform given in part A represents the unfiltered output from a typical single-phase, full-wave rectifier circuit when current pulses flow through the load resistance each time the rectifier conducts. Note that the dashed line indicating the average value of output voltage, E_{av}, is slightly greater (0.637) than half the amplitude of the voltage peaks. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component as compared with the average (d-c) component.

The filter shown in the schematic of the illustration consists of an input inductor or filter choke, L, and an output filter capacitor, C. The filter illustrated is called a **choke-input filter**, and is often referred to as an **L-section filter** because the schematic configuration resembles an inverted letter L.

Inductor L is placed at the input to the filter and is in series with the output of the rectifier circuit. Since the action of an inductor is to oppose any change in current flow, the inductor tends to keep a constant current flowing to the load throughout the complete cycle of the applied voltage. As a result, the output voltage never reaches the peak value of the applied voltage; instead, the output voltage approximates the average value of the input to the filter. Also, the reactance of the inductor (X_L) reduces the amplitude of ripple voltage without reducing the d-c output voltage an appreciable amount.

The shunt capacitor, C, charges and discharges at the ripple frequency, but the amplitude of the ripple voltage, E_r, is relatively small because the inductor, L, tends to keep a constant current flowing from the rectifier circuit to the load. The reactance of the shunt capacitor (X_C) presents a low impedance to the ripple component existing at the output of the filter, and the capacitor attempts to hold the output voltage relatively constant at the average value of the voltage. Since the reactance of the series inductor (X_L) is greater than the reactance of the shunt capacitor (X_C), and the reactance of the shunt capacitor (X_C) is less than the load resistance, R_L, the amplitude of the ripple frequency at the output of the filter is considerably reduced from that present at the input to the filter circuit. The output waveform is shown in part B of the accompanying illustration; assuming a single-phase, full-wave rectifier circuit, note that the frequency of the ripple voltage, E_r, is twice the frequency of the applied voltage.

Both the output voltage from the filter and the peak current of the rectifier depend upon the inductance of the choke and the resistance of the load. The minimum value of inductance necessary to keep the output voltage from increasing above the average value of rectified ac is called the **critical value** of inductance. If the inductance of the input filter choke is less than the critical value for the circuit, the filter acts more like a capacitor-input filter and the output voltage will rise above the average value.

The critical value of inductance is given by the expression:

$$L_h = \frac{E_{out}}{I_{out}}$$

where:

L_h = critical inductance in henries
E_{out} = output of power supply in volts
I_{out} = current drawn from power supply in milliamperes

An increase in the value of choke inductance above the critical value will decrease the ratio of peak-to-average rectifier current and maintain a more uniform current flow through the inductor. Increasing the of inductance
above a certain value, called the **opt** **lue** of induct-
ance, does not provide any apprecia vement in per-
formance or filtering efficiency. In the optimum
value of inductance for a given set ons is con-
sidered to be twice the critical value ctance.

The value of inductance require filter varies
directly with the effective load resistance R_L. Since the
inductance of a filter choke varies inversely with dc
flowing through it, an increase in the load resisto causes
the ratio of peak-to-average current to decrease; ersely,
a decrease in the load resistance causes the rati peak-
to-average current to increase.

The regulation characteristics of a power su sing
a choke-input filter can be improved by the us wing-
ing choke as the input inductor. A swinging g
choke whose inductance varies inversely with to
the current flowing through it over the specifi ating
range. It is designed to have slightly more than critical
value of inductance at full load and an optimum value of inductance at no load. This characteristic maintains the peak-to-average current ratio within certain limits over a considerable range of changing load currents, and results in improved regulation for the supply.

The choke-input filter is widely used in electronic equipments where the power supply is required to deliver
relatively high values of current to the load with d
regulation characteristics. In some cases the eq ent
requires a high degree of filtering, while in othe es the
equipment is not critical in this respect. The o from
a single choke-input filter (single L-section) m tain
an amount of ripple which is considered excess r the
equipment application. When this is the case eces-
sary to use additional filtering to further atte e
ripple component. By adding another series L2,
and a shunt capacitor, C2, to the basic cho lter,
the ripple component across the load resist e
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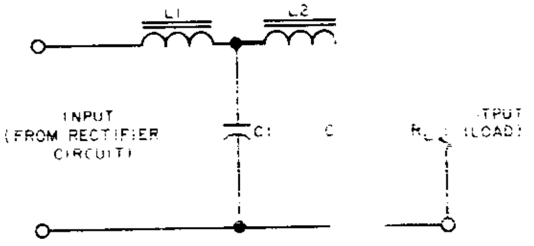
sembles an inverted letter L.

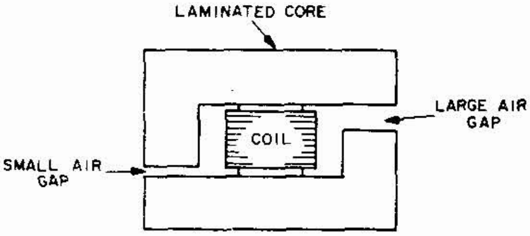


Choke-Input Filter with ided

In a practical filter circuit, the shunt
capacitor (C2) is much less than of the series
inductor (L2) and of the load resi Therefore,
each L-section filter which is add asic filter

further reduces the output ripple amplitude. However, when the L-section, L2 and C2, is added to the basic filter circuit, the regulation of the supply suffers somewhat because the added resistance of inductor L2 is in series with the load and thus causes a variation of the output voltage when changes in load current occur. Although the voltage regulation of a power supply using a choke-input filter circuit is good (as compared with the capacitor-input filter), the regulation can be further improved if inductor L1 is a swinging choke. In fact, the circuit may be designed to over-regulate, in which case the rise in average voltage across capacitor C1 compensates for the additional voltage drop occurring across inductor L2; as a result, the output voltage tends to remain constant.

The inductance of any iron core inductor shows a marked decrease as magnetic saturation is reached. The core of ordinary inductors is designed so that saturation occurs at a value just above the maximum current rating. Swinging chokes are generally designed to have one or more air gaps in the laminated core. The accompanying diagram illustrates a swinging choke which has two air gaps—one large and one small. (The sizes of the gaps are exaggerated in the illustration.)



Swinging Choke with Two Air Gaps

The purpose of the large gap is to provide effective inductance at the largest currents, while that of the small gap is to assure high inductance at the smallest currents. Saturation of the core starts at some specified current; at full rated current, saturation is almost complete. Swinging chokes are rated to indicate the variations of inductance with variations of current through the coil. A rating of 15 to 3 henries at 25 to 250 ma, for example, means that the value of inductance is 15 henries at 25 ma, and reduces to only 3 henries at 250 ma. When handling small currents, the swinging choke functions as a conventional choke-input filter. For larger currents, where the output voltage tends to drop, the inductance decreases and the filter starts to approach the characteristics of a capacitor-input filter. Because the decrease in inductance permits the capacitor to charge more nearly to the peak value instead of the average valve, the loss of voltage in the d-c resistance of choke L2 is thereby compensated for, and the output voltage tends to remain constant. As a result, regulation is greatly improved.

The output voltage available from a power supply using a choke-input filter circuit is much less than that obtained with a capacitor-input filter. However, since the input choke opposes a rapid build-up of current, there are no abrupt peak-rectifier currents with the choke-input filter, as there are with the capacitor-input filter. Therefore, the rectifier can deliver a higher continuous current to the load without exceeding its maximum safe ratings.

Detailed Circuit Operation. Consider now one cycle of operation of the basic choke-input filter, as illustrated previously with waveforms.

The input to the filter circuit is the output of the single-phase, full-wave rectifier. The rectified pulses applied to the filter are as shown in part A of the illustration. During the rising portion of the input voltage, choke L produces a back emf which opposes the constantly increasing input voltage. The net result is to effectively prevent the rapid charging of filter capacitor C. Thus, instead of reaching the peak value of the input voltage, capacitor C is charged only to the average value of input voltage. After the input voltage reaches its peak and decreases, the back emf tends to keep the current flowing in the same direction, in effect broadening the peak.

During the rising portion of the pulse, the current flow through L is reduced, and during the falling portion of the pulse, the current continues to rise until the diminshing energy of the pulse as it approaches zero becomes insufficient to maintain the current, which then commences to decrease.

When the next pulse starts, the back emf is still opposing an increase in current, and the current continues to decrease. (The choke, in effect, shifts the ripple peaks almost 90 degrees with respect to the rectifier output.) When the rectified pulse nears the peak value, the rate of change and the inductive effect decreases, and once again the current through L starts to rise. This cycle of operation is continuously repeated during the time the circuit is energized and rectified pulses are applied to choke L. The fluctuating voltage which results from the action of choke L appears across capacitor C and load resistor R_L in parallel. The low reactance of the capacitor to this ripple voltage effectively bypasses the ripple voltage to ground, so that the amplitude of the ripple voltage in the filter output is significantly reduced.

The voltage across C is the d-c component or output voltage, and is produced by the charging of C through L. Essentially, the charging of C is controlled by the value of the time constant, consisting of the d-c choke resistance in series with C. Such a typical time constant is on the order of tenths of a second or seconds rather than microseconds or milliseconds. Thus it takes many cycles of operation to charge C. The discharging of C through the load is usually slower than the charge time, since the load resistance is normally greater than that of the choke. Therefore, the output voltage tends to remain fairly constant. The choke-input filter is effective in reducing the ripple voltage because choke L and capacitor C act as an a-c voltage divider for ripple voltage. With the impedance of L high and the impedance of C low, any ripple voltage appearing across C is small, because of the large voltage drop across L, and is effectively bypassed around the load by the low value of X_c.

FAILURE ANALYSIS.

General. The shunt capacitors are subject to open circuits, short circuits, and excessive leakage; the series inductors are subject to open windings and, occasionally, shorted turns or a short circuit to the core.

Shorted turns in the input choke may reduce the value of inductance below the critical value of inductance; this will result in excessive peak-rectifier current, accompanied by an abnormally high output voltage, excessive ripple amplitude, and poor voltage regulation. Shorted turns in the smoothing choke (in the case of a multisection filter) will reduce the effective value of inductance; this will result in less filtering efficiency, with an attendant increase in the output ripple amplitude. An open filter choke, or a choke winding which is shorted to the core, will result in a no-output condition. A choke winding which is shorted to the core may cause overheating of the tubes, blown fuses, etc.

The shunt capacitor(s) in the choke-input filter is not subjected to extreme voltage surges because of the protection offered by the input inductor; however, the capacitor can become open, leaky, or shorted. An open capacitor results in excessive ripple amplitude in the output voltage; a leaky capacitor results in a lower-than-normal output voltage, and a shorted capacitor results in a no-output condition.

With the supply voltage removed from the input to the filter circuit, one terminal of the capacitor can be disconnected from the circuit. The capacitor should be checked, using a capacitance analyzer, to determine its effective capacitance and leakage resistance. It is important that correct polarity be observed at all times. A decrease in effective capacitance or losses within the capacitor can cause the filtering efficiency to decrease and produce excessive ripple amplitude.

If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter. Resistance measurements can be made across the terminals of the capacitor to determine whether it is shorted, open, or leaky. When testing electrolytic capacitors, set the ohmmeter to the high range and connect the test prods across the capacitor, being careful to observe polarity. This is important because current flows with less opposition through an electrolytic capacitor in one direction than in the other. If the correct polarity is not observed, an incorrect reading will result. When the test prods are first connected, a large deflection of the meter takes place, and then the pointer returns slowly toward the infinite-ohms position as the capacitor charges. For a good capacitor with a rated working voltage of 450 volts, dc, the final reading on the ohmmeter should be over 500,000 ohms. (*A rough rule of thumb for high-voltage capacitors is at least 1000 ohms per volt.*) Low-voltage electrolytic capacitors (below 100 volts rating) should indicate on the order of 100,000 ohms.

If no deflection is obtained on the ohmmeter when making the resistance check explained above, an open-circuited capacitor is indicated.

A steady full-scale deflection of the pointer at zero ohms indicates that the capacitor being tested is short-circuited.

An indication of a leaky capacitor is a steady reading on the scale somewhere between zero and the minimum acceptable value. (Be certain this reading is not caused by an in-circuit shunting part.) To be valid, these capacitor checks should be made with the capacitor completely disconnected from the circuit in which it operates.

In high-voltage filter capacitor applications, paper and oil-filled capacitors are used, as are also mica and ceramic capacitors (for low-capacitance values). In this case, polarity is of no importance unless the capacitor terminals are marked + or −. It is, however, good maintenance practice to use the output polarity of the circuit as a guide, connecting positive to positive and negative to negative. Thus any effects of polarity on circuit tests are minimized and the possibility of damage to components or test equipment is avoided. **Remember**—an undischarged capacitor retains its polarity and holds its charge for long periods of time. To be safe, discharge the capacitor to be tested with the **power OFF** before connecting test equipment or disconnecting the capacitor.

A simple check which can be used to quickly determine whether a capacitor is at fault is to substitute a known good capacitor of the same value and voltage rating and note whether the circuit operation returns to normal.

RESONANT FILTER.

APPLICATION.

The resonant filter is quite limited in its application to power-supply filter systems. It is normally used in conjunction with L-type or pi-type filter sections, rather than by itself, since it is designed to offer maximum attenuation only to the fundamental ripple frequency.

CHARACTERISTICS.

Parallel-resonant filter is composed of an inductor and a capacitor in parallel; series-resonant filter is composed of an inductor and a capacitor in series.

Filter is resonant at fundamental frequency of ripple voltage.

Parallel-resonant filter offers maximum impedance at resonance; series-resonant filter offers minimum impedance at resonance.

Parallel-resonant filter requires constant load current.

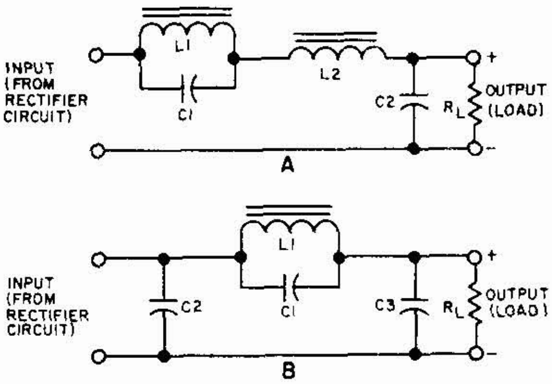
CIRCUIT ANALYSIS.

General. For special applications where maximum attenuation of the ripple frequency is desired, a resonant filter is sometimes used in power-supply circuits. This filter may be either the parallel-resonant or the series-resonant type, and is always tuned to the fundamental ripple frequency. Since the filter is tuned only to the fundamental ripple frequency, harmonics of the fundamental frequency are attenuated very little, if at all. For this reason, the resonant filter is seldom used by itself; it is normally used in conjunction with other filtering sections. A disadvantage of the parallel-resonant filter is that the inductance is subject to change when the load current is changed. Since the load current must flow through the inductor of the parallel-resonant filter, this current determines the value of inductance and, consequently, affects the resonant frequency of the tuned circuit.

Parallel-Resonant Filter. The accompanying illustration shows a parallel-resonant filter, sometimes called a **parallel-resonant trap,** used in two typical power-supply filter circuits.

The circuit in part A shows a parallel-resonant filter, L1 and C1, used with an L-section filter, L2 and C2; the the circuit in part B shows a parallel-resonant filter, L1 and C1, used in conjunction with a shunt input capacitor, C2, and a shunt output capacitor, C3. Note that in both filter circuits the load current must flow through inductor L1 of the parallel-resonant filter.

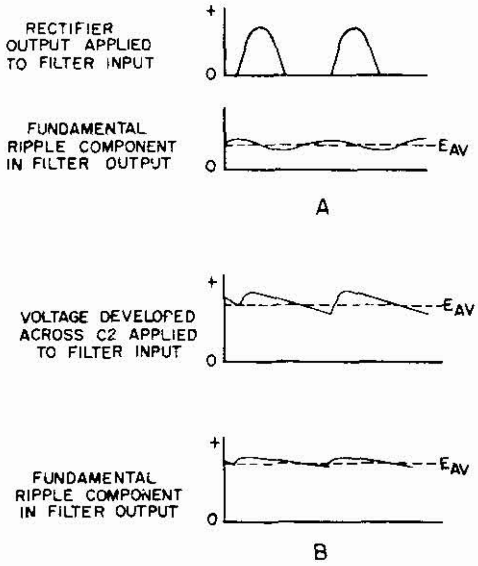
The parallel-tuned circuit, L1 and C1, is made resonant at the fundamental ripple frequency. When this is done, the fundamental ripple-frequency component is greatly attenuated because of the extremely high impedance offered by the parallel-resonant circuit. In a practical filter circuit, the inductor is fixed in value and one or more specific-value capacitors are selected and placed in parallel with the inductor to obtain exact resonance at the ripple frequency. In a few special cases, and also when the ripple frequency is relatively high, the capacitor is fixed in value and the inductor is made variable. In either case, however, if the load current through the inductor should change from the design value of current, the inductance of L1 will change and the circuit will no longer be resonant at the ripple frequency. The circuit loses its effectiveness rapidly as the load current is changed from the design value and the circuit is detuned from resonance. At resonance, the filter offers maximum impedance to the ripple-frequency component. The filter provides less attenuation at other frequencies; it has a progressively lower impedance, both above and below the resonant frequency, the farther the frequency is from resonance. Therefore, the parallel-resonant filter is nearly always used with additional filters to overcome this disadvantage and effectively attenuate harmonic frequencies.



Typical Power-Supply-Filter Circuits Using a Parallel-Resonant Filter

In the circuit shown in part A, the parallel-resonant filter, L1 and C1, is connected in series with the output of the rectifier circuit and ahead of an L-section filter, L2 and C2. The L-section filter circuit has the general characteristics previously described for the L-C CHOKE-INPUT FILTER, in this section of the handbook. The ripple-frequency component from the rectifier output is attenuated by the high impedance offered to the ripple frequency by L1 and C1, and the remaining fluctuations in the form of harmonic frequencies of the fundamental ripple frequency are attenuated by the L-section filter, L2 and C2. The upper waveform in part A of the accompanying illustration shows the shape of the output voltage obtained from a single-phase, half-wave rectifier. The frequency of the a-c input voltage is assumed to be 60 cps. When the rectified output is applied directly to the input of the parallel-resonant filter, the fundamental ripple component is highly attenuated in the output of the filter. This is shown by the lower waveform in part A.

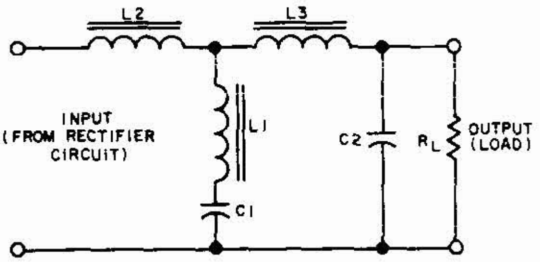
In the circuit shown in part B, the parallel-resonant filter, L1 and C1, is located between two shunt capacitors, C2 and C3. This filter circuit has the general characteristics previously described for the L-C CAPACITOR-INPUT FILTER, in this section of the handbook. The ripple-frequency component which remains after being reduced in amplitude by the action of shunt capacitor C2 is further attenuated by the impedance offered by the parallel-resonant filter and any remaining fluctuations are smoothed by shunt capacitor C3. The upper waveform in part B of the illustration shows the shape of the output voltage of a single-phase, half-wave rectifier, developed across C2. The frequency of the a-c input voltage is assumed to be 60 cps. When the voltage developed across C2 is applied to the input of the parallel-resonant filter, the fundamental ripple component is greatly attenuated and appears in the filter output as shown by the lower waveform in part B.



Typical Output Waveforms for Two Different Types of Input to the Parallel-Resonant Filter

The circuits shown in parts A and B of the illustration above have one important disadvantage, mentioned previously; that is, changes in load current affect the filtering efficiency of the parallel-resonant filter by changing the inductance and thus detuning the circuit from resonance. In a practical filter circuit, this effect can be tolerated for small changes in load current by making inductor L1 small as compared with capacitor C1, so that the detuning will be minimized.

Series-Resonant Filter. The accompanying illustration shows a series-resonant filter, sometimes called a **series-resonant shunt filter,** used in a typical power-supply filter circuit.



Typical Power-Supply-Filter Circuit Using a Series-Resonant Filter

The series-resonant filter is composed of L1 and C1 in series. The filter is used in conjunction with an input inductor, L2, and an L-section filter, L3 and C2. Note that the circuit is essentially a choke-input filter with two L-sections; the first L-section includes the series-resonant filter used as a shunt element instead of a shunt capacitor. The series-tuned circuit, L1 and C1, which is made resonant at the fundamental ripple frequency, offers extremely low impedance to the ripple frequency at resonance. The bypassing action of the resonant filter to the fundamental ripple-frequency component is, therefore, much better than that obtained with a shunt capacitor alone, since the capacitive reactance (X_C) of a shunt capacitor alone will normally be greater than the impedance of the series-resonant filter. The filter circuit illustrated has the same general characteristics previously described for the L-C CHOKE-INPUT FILTER, in this section of the handbook. The ripple-frequency component which remains after passing through inductor L2 is bypassed by the resonant filter, L1 and C1; the remaining fluctuations are further smoothed by the L-section filter, L3 and C2.

The series-resonant filter must always be used with an input *inductor* (L2) in series with the rectifier output. If the series-resonant filter were shunted directly across the rectifier output, the filter would act as a short circuit (low impedance to the fundamental ripple frequency) and cause extremely high rectifier peak currents to flow; these currents, in turn, would damage the rectifier. In a practical filter circuit, the inductor (L1) is fixed in value, and one or more specific-value capacitors (C1) are paralleled and placed in series with the inductor to obtain exact resonance at the ripple frequency. At resonance, the filter offers extremely low impedance to the ripple-frequency component, but the filter provides very little bypassing action at other frequencies; it has a progressively higher impedance, both above and below the resonant frequency, the farther the frequency is from resonance. Therefore, the series-resonant filter is always used with additional filter sections to overcome this disadvantage and effectively attenuate harmonic frequencies.

FAILURE ANALYSIS

General. When analyzing the failure of a resonant filter to perform satisfactorily, it should be remembered that *resonance of the filter is most important,* and that any change in the inductance, capacitance, load current, or applied ripple *frequency will directly affect* the filtering efficiency. The inductors used in a resonant filter can be checked for the proper value of inductance (*no* dc) by using an impedance bridge; the capacitors can be checked by using a capacitance analyzer.

As previously mentioned, the inductance of the inductor (L1) employed in a parallel-resonant filter depends on the load current which flows through it; therefore, the load current must be measured to determine that the current is within tolerance in order that the parallel-resonant filter operate effectively and remain tuned to the fundamental ripple frequency.

Because a resonant filter offers little attenuation to higher-order ripple frequencies (harmonics), it is normally employed in conjunction with other filter sections, such as choke-input or capacitor-input filter sections. Therefore, the failure analysis procedures for a power supply filter system which contains a resonant filter are essentially the same as those given earlier in this section of the handbook for the applicable choke-input or capacitor-input filter circuit.