UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Superior d'Enginyeries Industrial, Aeroespacial i Audiovisual de Terrassa

DEPARTAMENT D'ENGINYERIA ELÈCTRICA

STUDY OF THE ELECTRICAL SYSTEM OF A COMMERCIAL AIRCRAFT: DEVELOPMENT OF A NUMERICAL SIMULATION MODEL

FINAL BACHELOR DEGREE PROJECT

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STUDENT: JAKUB TOMASZ BEDNARCZYK TOBIASZ

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MENTOR: JOAN MONTAÑA PUIG

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Abstract

In this thesis a study, modelling and simulation-based methodology is proposed to inquire the knowledge about how the electrical system on aircraft works, detailed into the commercial such as the Airbus A320. This study was done by creating a MATLAB/Simulink model based on all crucial elements of the electrical system of an aircraft such as the generating system and distribution system.

Indeed, this work tries to clearly expose the different elements that make up the electrical system of a commercial aircraft, including, as said before, the different systems of generation and distribution of electrical energy, for this we will rely on several examples belonging to the one of the most outstanding model, as is the Airbus A320, through these examples it is possible to observe the evolution that the electrical system of aircraft has undergone and how these are increasingly dependent on electrical energy.

The considerations for this work where crucial, each component was analysed, such accuracy was given and ease of usage in order for a better understanding. Each component has its function and is corelated with any other one for a better functionality. However, all this work was done followed by several important manners in order to simplify the understanding.

As mentioned before, this work was done by a programme named MATLAB/Simulink as this was the main resources learned in the university and the best that fits for my usage. This model was made based on a basic-model aircrafts electrical system.

All components are detailed during the work and simulated trying to resemble the real Airbus A320 model. As this model is really into detail compared to simple aircraft, all development of the model was done with careful attention trying to get the best results possible.

Gratitude

This thesis was all done by myself, however there are many people to thank who helped me doing this project and helped me grow as a person and engineer.

First of all, I would like to thank Joan Montaña Puig, my main mentor, advisor and professor for his help, support, guidance, knowledge and a lot of patience. I will always be thankful for this tremendous work.

Moreover, I would like to thank all the university professor members in general, for teaching me this knowledge. Specially I would like to thank the electrical engineering department for all this wisdom and proficiency taught during these last years.

Finally, I could never have never arrived to this point without my closest, my family. I would love to give huge thanks to my parents Agata and Krzysztof for their love and support in all these moments.

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List of abbreviations

AC Alternating Current

AD Airworthiness Directive

AMOS Aircraft Maintenance and Repair Management Software

APN Amos Program Number

APU Auxiliary Power Unit

ATU Auto Transfer Unit

AWG Aviation Working Group

A320 Airbus A320

BAT Battery

BCL Battery Charge Limiter

BPCU Bus Control Unit

BTC Bus Tie Contactor

C/B Circuit Breaker

CFRP Carbon Fiber Reinforced Plastic

CS Certification Specification

CCS Commercial Cabin Systems

CSD Constant Speed Drive

DC Direct Current

DOA Design Organization Approval

EASA European Aviation Safety Agency

ECMU Electrical Contactor Management Unit

ECS Environmental Control System

EHA Electro-Hydrostatic Actuator

ELA Electrical Load Analysis

ELMF Electrical Load Management Function

ENG Engine

ESN Electrical Structure Network ESS Essential

ETOPS Extended-range Twin engine aircraft Operations

EPS Electrical Power System

EPDS Electrical Power Distribution System

EPDC Electrical Power Distribution Centre

EXT External

EWIS Electrical Wiring Interconnection System

FAA Federal Aviation Administration

FCS Flight Control Systems

FTIS Fuel Tank Inerting System

FUS Fuel System

GEN Generator

GLC Generator Line Contactor

GND Ground

GPU Ground Power Unit

HPS Hydraulic Power System

IDG Integrated Drive Generator

IFE In Flight Entertainment

LGS Landing Gear Systems

MEA More Electric Aircraft

PPS Pneumatic Power System

RCCB Remote Control Circuit Breakers

RAT Ram Air Turbine

SB Service Bulletin

TCCA Transport Canada

TR Transformer Rectifier

TR Line Contactor

VAC Voltage Alternating Current

VDC Voltage Direct Current

VFG Variable Frequency Generator

WIPS Wing Ice Protection System

XWB Extra Wide Body

1. Introduction

Electricity is the fundamental mainstay of today's modern life. It is basically an uttermost necessity for everything we would like to do in our daily life. From basic to specific necessities. However, when flying and operating with aircrafts, especially commercial aircrafts, their systems require energy. In most aircrafts we find different systems, from hydraulic to pneumatic and most important in this project, the electrical power system, used for different purposes, such as aircraft lighting, navigation or communication.

Since the Wright brothers made the first powered flight aboard an almost uncontrollable airplane the 17^{th} of December 1903 and later the first commercial flight in 1914, after that during World War II, the use of electrical power in aircrafts commenced. Little more than a century has passed and advances in aviation have been exceptional, although outwardly the current aircraft shapes and some technology is similar to what it was even 4 decades ago, however we still find some issues such as avionics, fuel consumption or more efficient systems causing operating costs to have fallen, this has had repercussions in favour of consumers by making it cheaper to travel in airplane which led to study and recreate those systems.

During the past years, even decades, commercial aircraft have evolved drastically in their electrical system which means a significant performance and efficiency gains. An aircraft electrical system is a self-contained network of components that generate, distribute and store and transmit electrical energy. This project will require an intense work with significant technical and engineering minded hard work.

Nowadays, the design of this aircrafts is very sophisticated, aiming for huge improvements, such as the More Electric Aircraft (MEA) design. In order to achieve these, all systems are being replaced for electrical components.

All this advances in technology have helped the electrical system in commercial aircrafts which helps me as well with this study. With these new references I will manage on doing this project and achieve all my objectives that will be mentioned in the following paragraphs.

1.1 Purpose of the project

This thesis aims to study the electrical system of a commercial aircraft and develop a simulation model in MATLAB. This programme named MATLAB, is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

The MATLAB/Simulink environment was chosen because of its availability and its capability. It provides a wide source of functions for professional engineering studying. It mainly allows to create graphic overlays to guide the user for running the system.

This thesis will document the result of a whole term studying the concepts related to aviation and electrical branch of engineering specialising in the electrical system of a commercial aircraft from a theoretical point of view to a more practical one.

1.2 Objectives

The overall main objective of this thesis is the full-bodied investigation of the advanced electrical system used in today's aircrafts and developing a model of this electric power system.

The project shall identify all main concepts related to the electrical system, from the **theoretical part** to a **practical** one. These two parts may include a really specific study.

First, the theoretical part must be related more to a training for the practical part. Such as understanding each component to insight the history behind the electrical system of the first commercial aircrafts. Reviewing if existing models based on the certification EASA CS-25.

Second, the practical part I must implement what I have learnt from the practical part and creating a simulation such as in MATLAB of the actual system. This model will allow the simulations of operation in normal conditions and preliminary simulations of faults or abnormal conditions. This main model can be used in other subjects such as an activity.

Finally, a really important objective is handling all I have learnt in my 4-year degree and include it in this project.

1.3 Origin of the project

The opportunity of doing the enrolment in this university was already the start of new ideas, especially in the electrical branch. However, since I was young, I have always wanted to become a pilot or at least work in the aviation sector. In my second university term I have started working in Iberia, at Barcelona Josep Taradellas el Prat airport as a flight dispatcher, this work gave me the opportunity to start thinking of new ideas for my final project which I must enjoy doing it as is somehow the topic I actually like.

My involvement in this project will give me the opportunity to learn new aspects and specially apply many of the expertise acquired during my degree.

1.4 Ground rules and assumptions

For correct application of the study, a good understanding of the basic rules and assumptions is crucial. In the following paragraphs will be discussed.

Research success: all main subjects and knowledge learnt during this degree must be applied for a good future development. Taking into account the time scale, certifications and finally economics.

Time scale: In this part the study must be held in a concrete period of time, obviously not including the theoretical part in which I will study from the earlier time until now. Despite that, the main period chosen is this decade.

Certification: All this study must be done following all certification rules approved. These present rules are written in terms of current available technology.

Economics: In this part there is no attempt on creating an actual electrical system that will be used in real life for commercial aircrafts. However, if this project goes further may some economics be necessary.

2. The electrical system of an aircraft

The electrical system of an aircraft is a self-contained network of components that generate, transmit, distribute, utilize and store electrical energy not only that but also a complex mix of components of AC and DC intending to form a reliable system. However, this part is more 'academic' which means more theoretical. This theory will be applied for a future model created in MATLAB.

The electrical system can be divided into four important sections: power sources, power distribution, power conversion, and electrical loads. Beginning with where does the power come from to where this power goes to and finally how this power is distributed [1]. All this concept easily seen in the following figure.

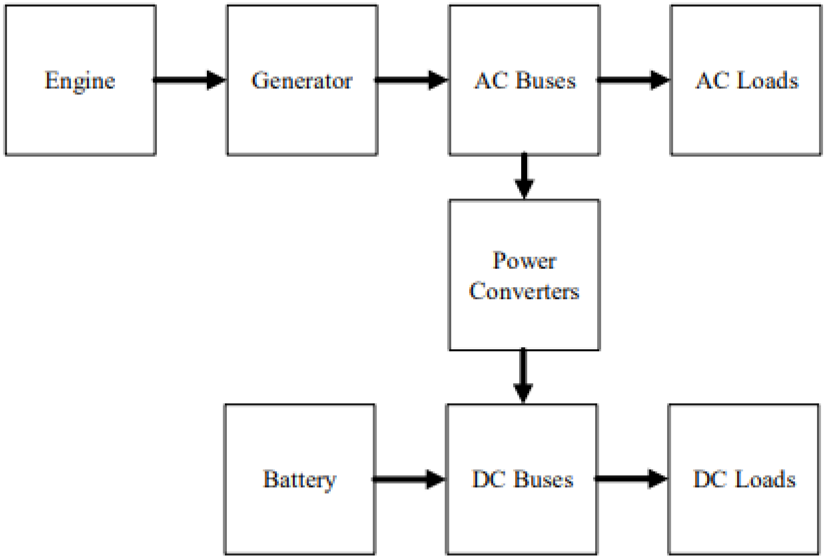


Figure 1- Typical electrical aircraft scheme [1]

First of all, the power comes from a generator and the battery. Those generators take the power from the engines through a gearbox. Then this power is being distributed through the buses, in this case AC and DC buses. Finally, this power is being converted by the power converters such as transformers, rectifiers and inverters.

In addition, this theory will be applied to a MATLAB model. The main objective of the project, to develop and design not only a more detail file for the electrical system of a commercial aircraft but also a student-friendly MATLAB file for students in different subjects related to the field.

In the following figure is given the actual PDS of a commercial aircraft. This system will be projected into a MATLAB workspace illustrating all components that are formed.

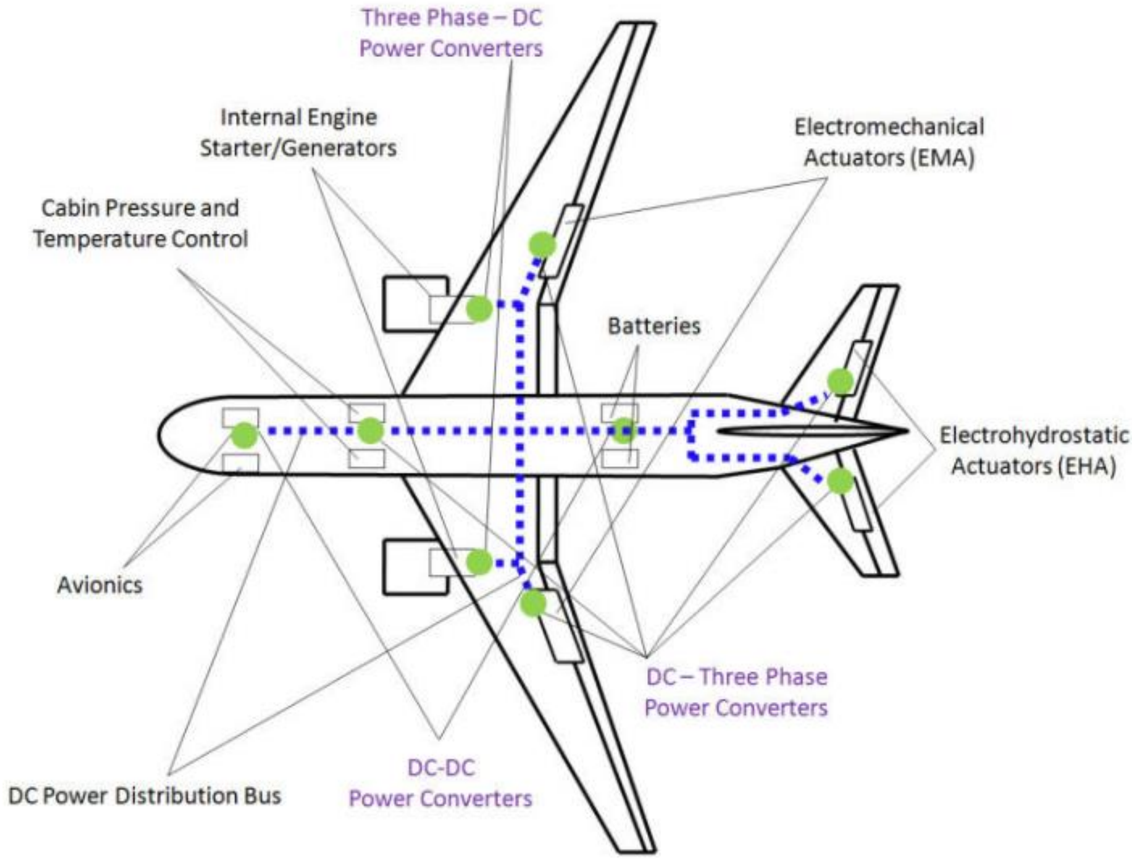


Figure 2- Power distribution system (PDS) of a commercial aircraft [31]

Being this part more generic on how the electrical system works, later on I will enter into detail on how the actual electrical system of a commercial aircraft is. Explaining every detail, from general aspects to each system integrated.

2.1 Electrical system of a commercial aircraft

A typical electrical system in an aircraft consists of a number of components that generate and distribute electrical power. A generator, alternator, or hydraulic motor can supply power to an EPS. In addition to an alternator, an aircraft's electrical system also includes a battery, switches, fuses, and lights used for display purposes. To understand the components of an aircraft's electrical system, consider these examples. These three types of equipment are important in aviation and are used in all commercial aircraft.

The electrical system of an aircraft consists of two basic components: an alternator and a battery. The alternator is connected to the electrical distribution bus at the beginning of the flight and disconnected at the end of the flight. The electrical distribution bus connects the batteries in each module. Magnetic contacts control both the alternator and the battery control switch. However, there are some things you should know before flying a commercial aircraft.

Aircraft electrical system components include generators and alternators that produce electrical power. These are driven by the engine and have a single distribution bus. They may also be driven by an APU, hydraulic motor, or ram air turbine [2]. The output voltage from these components is typically 115-120V/400Hz AC and can be routed through a transformer. The generators and generator output are connected to a distribution bus, which is the power source for the individual components of the aircraft. The wiring is equipped with a circuit breaker or fuse to protect the system from damage.

The electrical systems in an airplane are essential to keeping the airplane operating properly and staying in the air. In a commercial aircraft, the electrical system provides power to the passenger cabin. All components are wired for specific purposes.

2.1.1 Origins and evolution

Electricity grids are used to generate and conduct electrical current into our homes so that we can use it to power our appliances and lamps. These elaborate networks of wires, generators, breakers, and all the other components stretch across every country, connecting everyone to a source of electricity. All of this started very humbly in England in the late 1800s.

The beginnings of electrical power as we know it today date back to 1881, when a couple of electricians in England decided to harness the power of water to create a current that could be used to light things like lamps. So, they started building the first of these stations. The two men built their station and ran several lamps on the electricity generated by the two water wheels. The supply was not really constant, but they were on the right track.

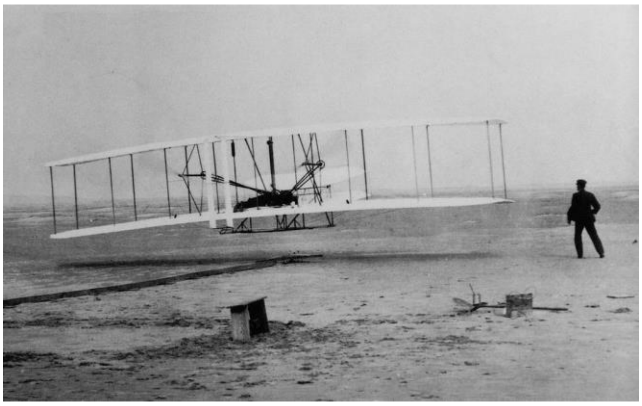


Figure 3- First flight by the Wright brothers [29]

This track managed to evolve during the last decades, until now. Nowadays we are using the electrical system in different fields, such as in aviation.

The first electrical system in aviation was added at the beginning of the 20th century. In the early days of aviation, electrical requirements were symbolic. The electrical energy to ignite the engines through the spark plugs was represented by devices called magnets, which are no longer used today. As technology advanced, systems such as radios were introduced, which meant an increase in the aircraft's electrical requirements, so small batteries were installed that required a dynamo to recharge them. The generator was driven by an external turbine, which was moved by the air movement and set the dynamo in motion. The power supplied by these generators was no greater than 500 W.

Not only the electrical system was important for an aircraft, but also the construction itself, for example the construction of sustaining wings, trying to solve the problem of lifting the aircraft. Then the problem of propulsion, related to the application and generation of power and also the problem of balancing and steering the machine, which was the problem of control.

Through the aviation history we had and still have different pioneers, like the Wright brothers or Henri Farman. However not only the aviation pioneers are the main character but also the select of pioneer aircrafts which were created by those pioneers. For example, the Ader Éole or the Farman III.

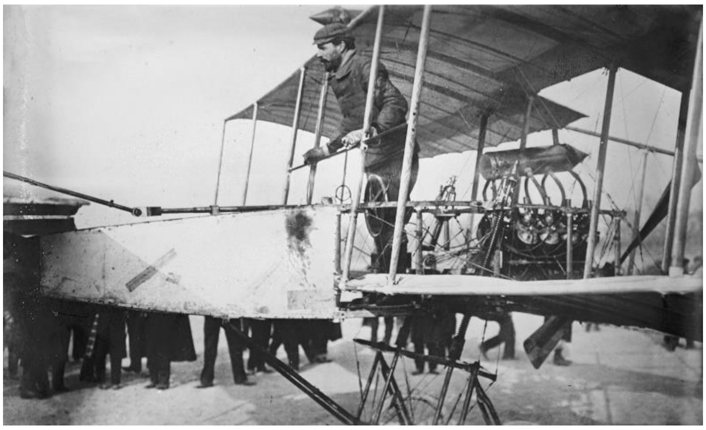


Figure 4-Farman III a pioneer aircraft [29]

After all World Wars, the aviation industry was still developing until the first airlines organizations came in. Those days big investments were made to improve the aviation sector until today. Nowadays all aspects in aviation have evolved drastically big airlines like KLM or Lufthansa, even Iberia from Spain existed for decades. The aeronautical infrastructure made huge steps for this evolution.

Figure 5 - Air France Concorde [26]

The following figure shows actually how those steps were done during the beginning of the 20th century, showing exactly each most common model start its work.

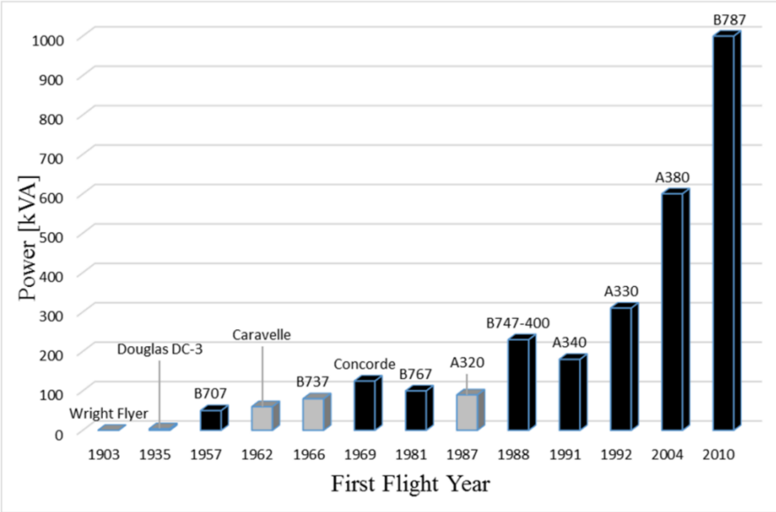


Figure 6 – Evolution of the first flights base on aircrafts models and power usage [28]

Not only the power usage is important but also the generation system and at what voltage and frequency worked. It was the Second World War that really caused a great development of aviation thanks to the great technological advances such as the appearance of the first radars together with the development of jet engines that allowed the construction of large military and commercial aircraft with important electrical requirements. remarkable.

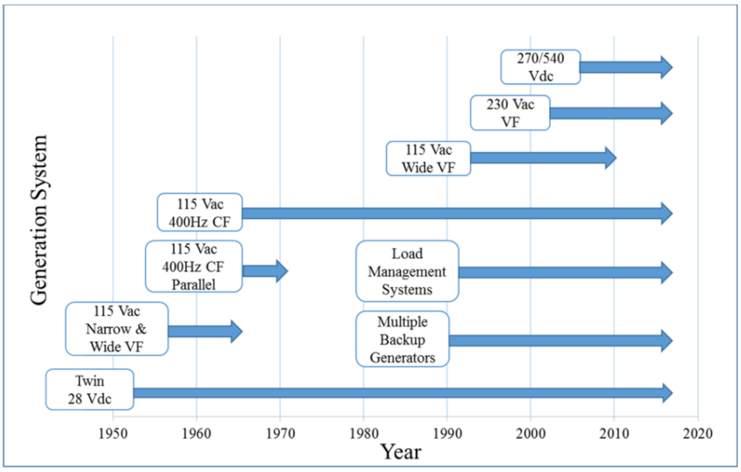


Figure 7 - Evolution of the generation system [28]

Currently, electrical energy needs are very high due to the large number of elements and subsystems that require it for the proper functioning of the system as a whole. Below is a graph of the evolution in electrical energy consumption of some of the most representative commercial aircraft models from the 1960s to the present.

In recent years, aircraft have been developed that far exceed these figures, one of them is the Airbus A380, the largest commercial aircraft in the world with a power generation of more than 800 kVA, as shown in figure 6.

2.1.2 Basic aircraft electrical system

An aircraft is a large, highly complex system involving many equally complex systems, such as electrical, pneumatic, or hydraulic, which are closely interconnected. In the following figure we can observe four main systems underlined in yellow. These four are the main for an aircraft to work properly in all conditions.

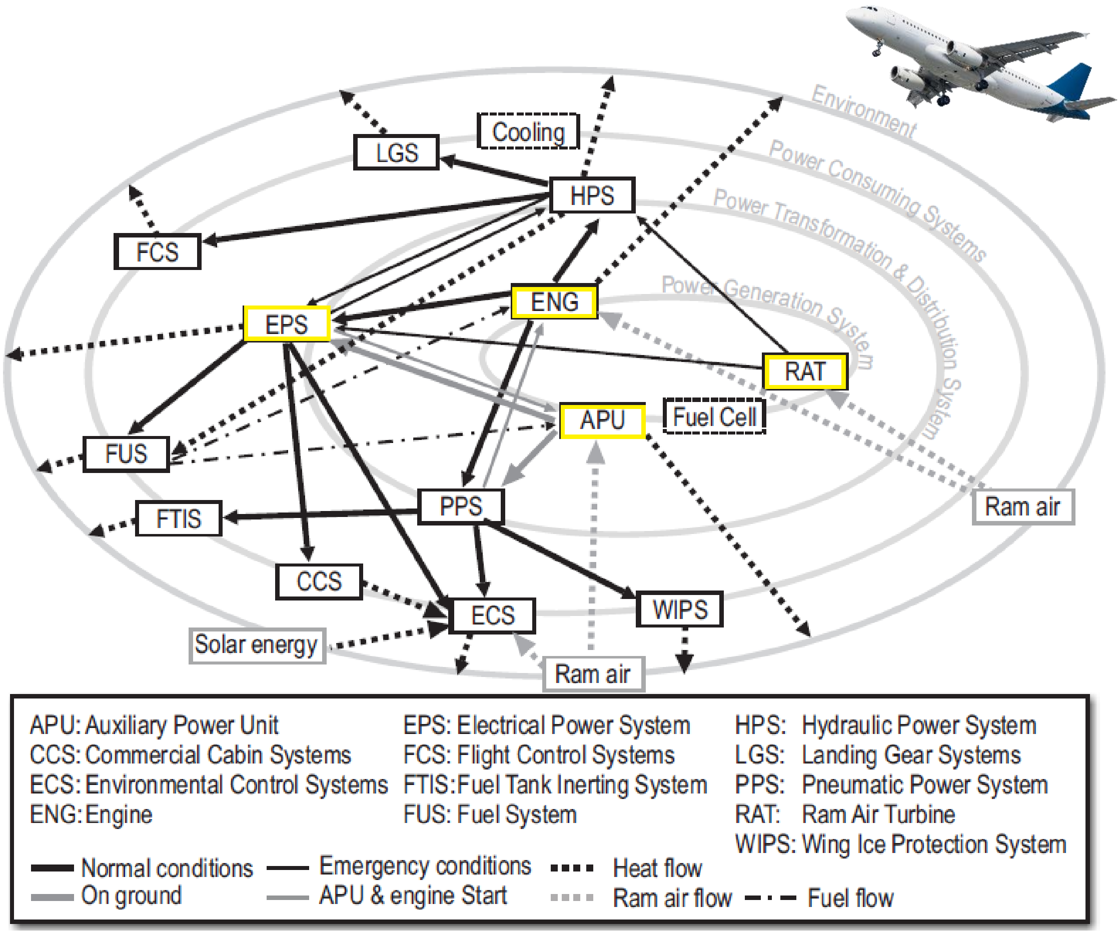


Figure 8- Aircraft systems [24]

Aircraft electrical design is influenced by two basic requirements: the equipment must be lightweight and extremely reliable. These requirements can be met in several ways.

To begin with, the electrical parameters are chosen to minimize weight so that the aircraft can lift off the ground with its payload and gain altitude without consuming unnecessary energy and fuel.

One technique is to reduce the size and weight of magnets (generators, transformers, motors) by using a higher frequency power system. Ground power systems are usually 50 or 60 Hz. Aircraft electrical systems that use AC power normally operate at 400 Hz. So basically, as I explained before the output voltage from these components is typically 115-120V/400Hz AC.

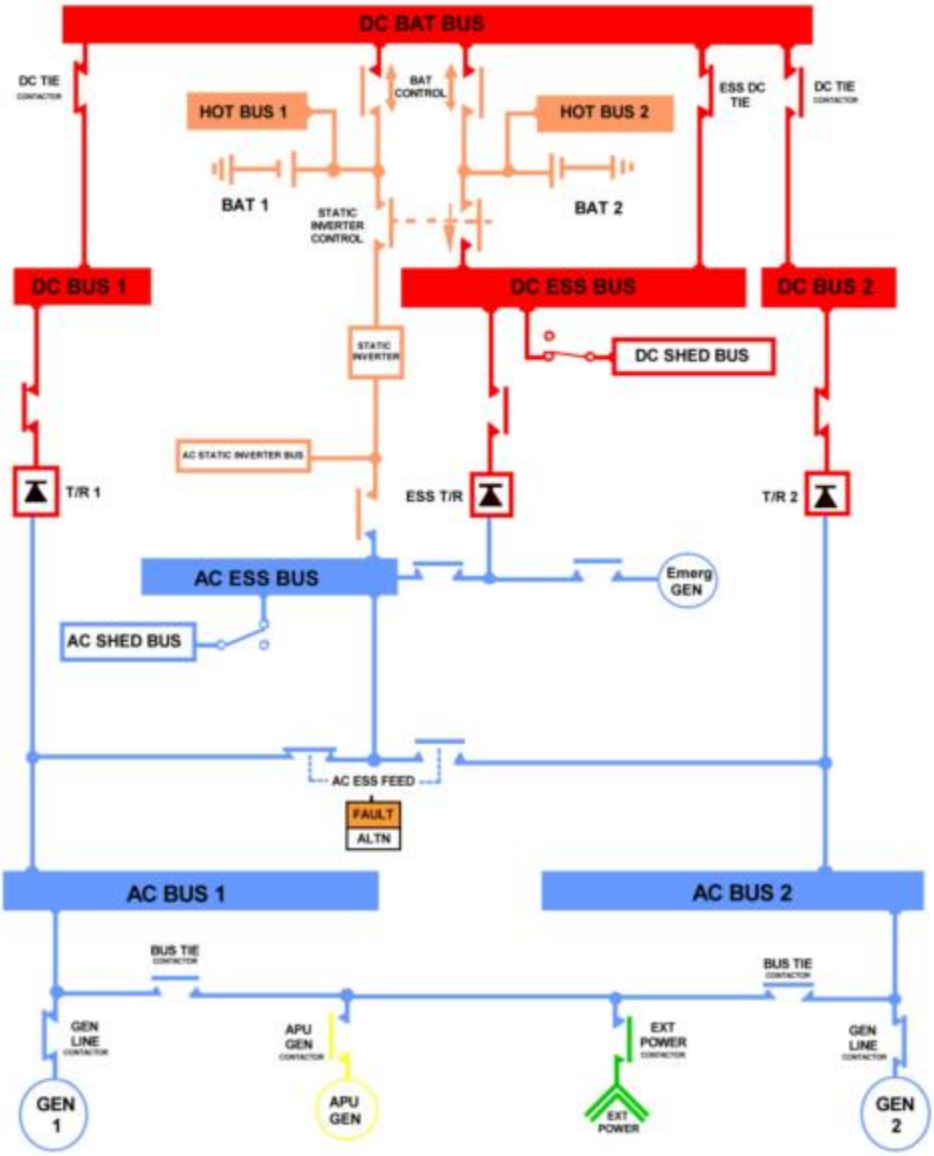


Figure 9 - Electric system schematic [27]

The previous figure represents the main train of an electrical system of an aircraft. Its task is to generate the necessary energy so that all elements that need to be supplied with electricity can function. It must also have redundant and emergency systems so that under no circumstances can the aircraft's basic systems be left without power, for example the RAT (Ram Air Turbine) system which helps in emergency conditions the hydraulic system.

Because certain electrical systems require alternating current, small aircraft are equipped with an inverter, which was originally rotary but is now this has changed. Aircraft that consume a large amount of electrical power are equipped with alternators, such as the A320.

In addition, most aircraft in this category have another backup power source, such as an inverter or a small alternator driven by a ram air turbine, which I mentioned before also known as the RAT in order to provide a high level of redundancy. This is necessary because flight control is electrical rather than hydraulic. If all electrical power were to fail, the crew would not be able to control the aircraft at all.

In fact, not only the RAT turbine is the main part of an electrical system. There are loads of systems associated to the functioning of an aircraft, we can find three basic categories related to the power needed for the machine in which the first two have a subsystem:

- **Power generation systems:** this group includes aircraft engines, the APU auxiliary power unit, the RAT air-impact turbine. However, in the near future fuel cell might be implemented.

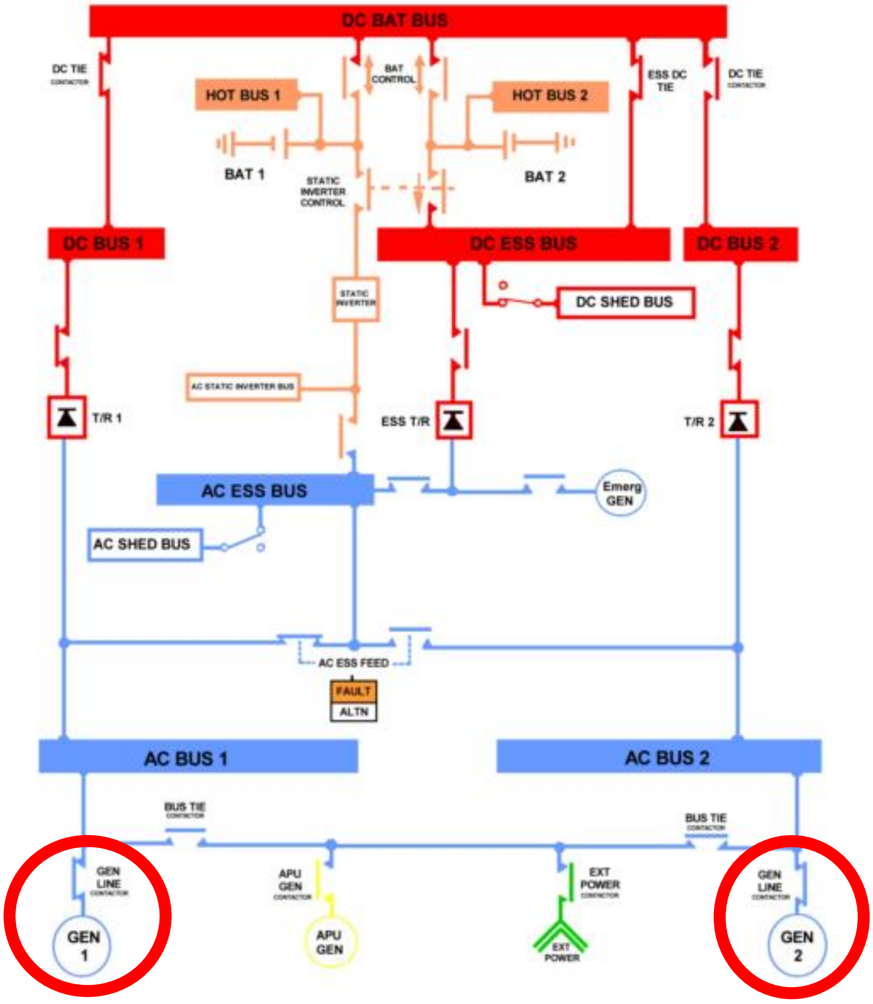


Figure 10- Generation system detailed on an electrical system schematic [27]

- **Energy conversion and distribution systems:** are the systems responsible for converting and distributing the energy coming from the generation systems to the consumer systems. The electrical and hydraulic systems belong to this group, since they convert the mechanical energy of the engine into electrical and hydraulic energy, respectively. In the following figure, the distribution are the wires.

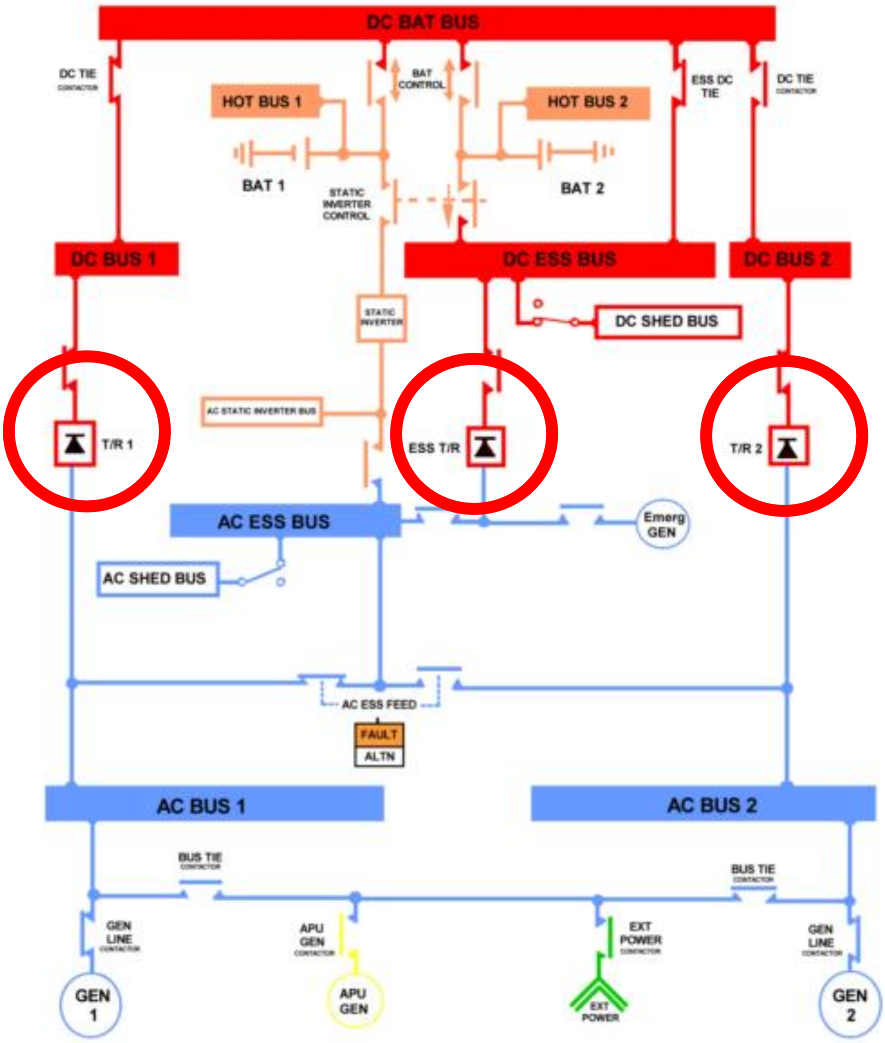


Figure 11 - Energy system detailed on an electrical system schematic [27]

- **Power consumes systems:** in an aircraft, there are a variety of consumer elements with different purposes that are powered by different types of electricity. The most important are: flight control system, lighting systems, anti-ice protection system, environmental control system, fuel system and also all entertaining systems. Basically, all component that requires consumption. I could underline all the previous figures in one, because of the consumption produces from each. However, the following figure is more accurate.

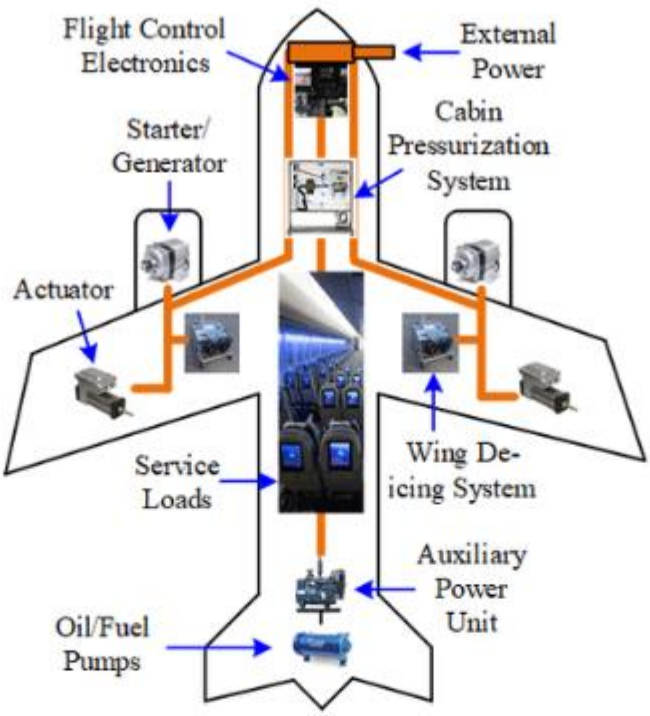


Figure 12 - Power consumption systems [25]

The power generation system and the power consume system have two subsystems. The aircraft electrical system consists of a series of electrical and electronic devices designed to generate, control, and distribute electrical power under normal or emergency conditions to all elements that require it, in accordance with the margins established in the regulations and standards. We can find two important subsystems:

- **Generation subsystem:** power is generated by various gensets installed in the aircraft, such as the main generators, the auxiliary power units GPU (Ground Power Unit) for ground power and APU (Auxiliary Power Unit), which can be used both on the ground and in flight, the emergency power units are responsible for supplying power in case of failure of the main and auxiliary systems.

  Batteries can also be included in the power generation system because they allow for the storage of energy that can be used in the event of a total failure of the electrical system in which all main, auxiliary, or emergency power generation systems fail.

- **Distribution subsystem:** the distribution system can be divided into two blocks, the primary distribution and the secondary distribution, both of which have the equipment necessary for distribution, such as busbars, protection devices, load switching elements and drivers.

  In this subsystem is based on two main distribution, the primary and secondary distribution.

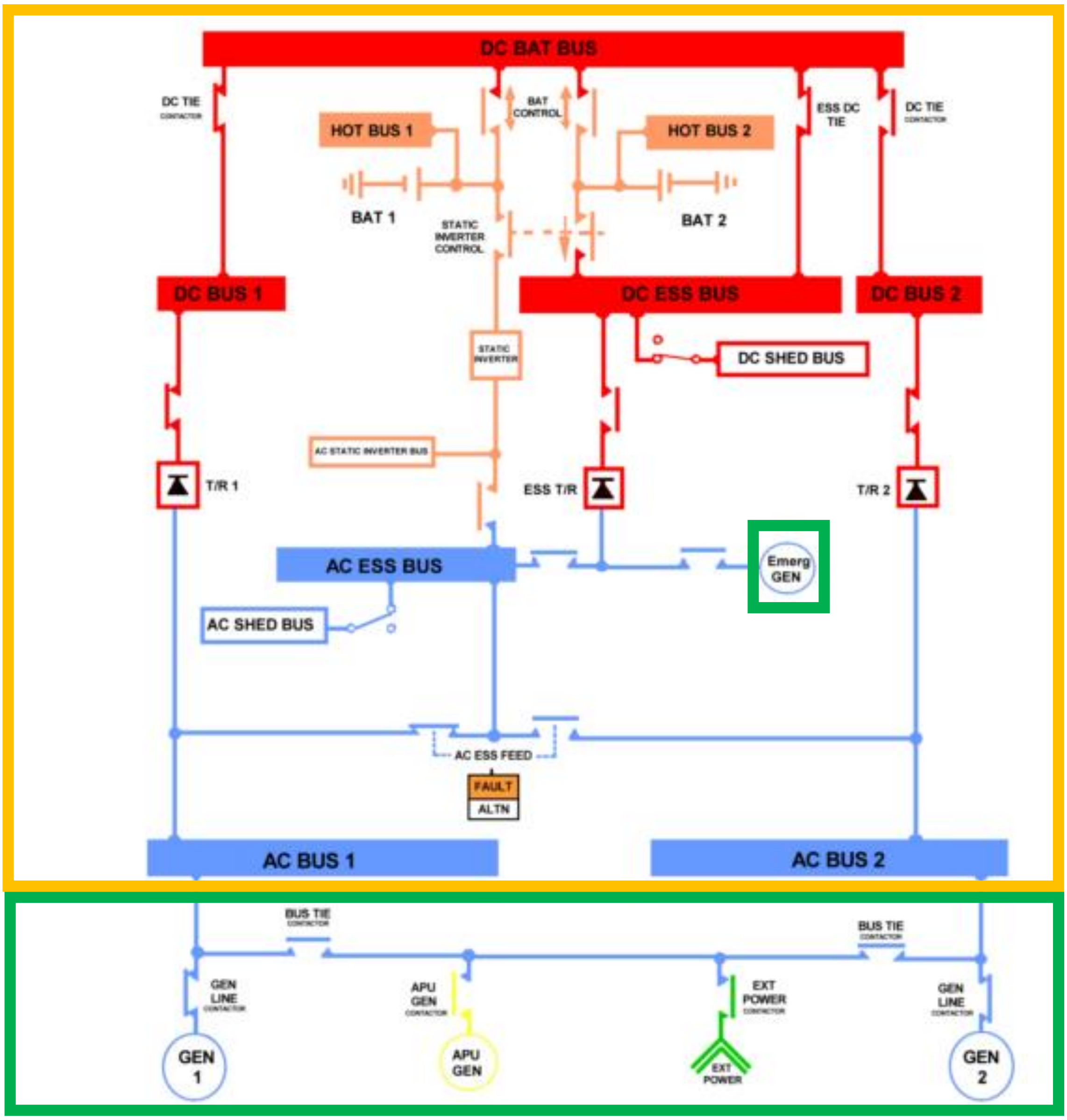


Figure 13 - Electrical system schematic divided in two parts [27]

Distribution system   Generation system

It is really important to add, that all the electrical system scheme is a generating system, but there are several parts which main objective is to distribute that energy generate.

In order to secure a perfect functioning of the electrical system is necessary to implement new devices which are going to control the actual condition of both systems mentioned before. However, we need to install the GCU (Generator Control Unit) panel for the generation system and the BPCU/ECMU (Bus Control Unit) / (Electrical Contactor Management Unit) panel for the distribution system.

Summarising, the electrical system's main objective is to deliver electricity through all the devices installed in the aircraft.

2.1.3 Electricity on board

The increase in electricity consumption and the importance in many cases of the loads it feeds have made the electrical system one of the most critical and demanded systems, which is why the energy it supplies must be quality energy.

All started from the origin of aviation, when electrical systems were based on continuous current voltages of 12 Vcc, furthermore become to be 24 Vcc which were connected in serial connection with the batteries.

Through time those 24 Vcc became 28 Vcc, which is the value that is mainly used in actual aircrafts. For these current voltages we have some requirements that are mandatory to follow. Mainly DC/DC and AC/DC converters and rectifiers are used to provide a continuous power supply for the devices that require it.

Alternating generation is carried out by means of alternators that generate a three-phase power signal with normalized levels of 115/200 Vac, the first value corresponding to the phase-neutral voltage value and the second to the phase-to-phase voltage. The negative terminal for both systems (continuous/alternating) is constituted by the structure of the aircraft, the negative terminal of both generators and electrical equipment is attached to the chassis of the aircraft, making it the neutral conductor of the system.

Nowadays we have had an enormous evolution on this concept. Now all aircraft have higher voltage levels, 230/400 Vac and ±270 Vdc.

The main objective of this increase is to reduce all currents that are supported from the electrical system and the main reason for that is to reduce the weight. A weight reduction is essential, especially for fuel consumption and further costs.

The international standard ISO 1540-2006(E) and the military standard MIL-STD-704(F) [3] define the admissible margins in terms of voltage and frequency levels used in aviation, differentiating between different situations depending on the state of operation of the system electric. The aircraft can work in several conditions, such as:

- Normal operation
- Abnormal operation
- Emergency operation

2.1.4 High frequency performance

When we talk about commercial aviation, we talk about typical alternating current generation systems with standard values of 115/200 Vac and at 400 Hz, this frequency value may seem very high to us accustomed to the typical values of 50 Hz and 60 Hz typical of the European and American power grids respectively.

The main reason why we are using high frequency is because of cost reduction, especially in material usage. Copper and steal are the main materials in use, such as for the core or winding.

However, high-frequency electrical systems reduce the efficiency of power transmission; One of the main problems it presents is that they are more prone to voltage drops, particularly because the line becomes more resistive. Increasing the frequency translates into an increase in the film effect or skin effect that decreases the useful section of the conductors to transport the electric current. Another negative effect is that working with high frequencies, typical copper conductors behave like antennas, radiating current out of the conductor and causing the corresponding power losses and electromagnetic interference to susceptible equipment such as radio and navigation.

Despite the fact that the standard frequency of 400 Hz is installed in most commercial aviation, in recent years systems have been developed that operate with variable frequencies (PV) between 380-800 Hz.

2.2 Certifications

Before a newly developed aircraft model may enter into operation, it must obtain a type certificate from the responsible aviation regulatory authority. Since 2003, EASA is responsible for the certification of aircraft in the EU and for some European non-EU Countries. This certificate testifies that the type of aircraft meets the safety requirements set by the European Union.

We must follow 4 main steps of a type-certification process:

- Technical familiarisation and certification basis
- Establishment of the certification programme
- Compliance demonstration
- Technical closure and issue of approval

Technical familiarisation and certification basis

The aircraft manufacturer presents the project to EASA when it is considered to have reached a sufficient degree of maturity. The EASA certification team and the set of rules that will apply for the certification of this specific aircraft type are being established (Certification Basis).

Establishment of the certification programme

EASA and the manufacturer need to define and agree on the means to demonstrate compliance of the aircraft type with each requirement of the Certification Basis. This goes hand in hand with the identification of EASA's "level of involvement" during the certification process.

Compliance demonstration

The aircraft manufacturer must demonstrate compliance of its product with regulatory requirements: the structure, engines, control systems, electrical systems and flight performance are analysed against the Certification Basis. This compliance demonstration is done by analysis during ground testing (such as tests on the structure to withstand bird strikes, fatigue tests and tests in simulators) but also by means of tests during flight. EASA experts perform a detailed examination of this compliance demonstration, by means of document reviews in their offices in Cologne and by attending some of these compliance demonstrations (test witnessing).

This is the longest phase of the type-certification process. In the case of large aircraft, the period to complete the compliance demonstration is set at five years and may be extended, if necessary.

Technical closure and issue of approval

If technically satisfied with the compliance demonstration by the manufacturer, EASA closes the investigation and issues the certificate. EASA delivers the primary certification for European aircraft models which are also being validated in parallel by foreign authorities for operation in their airspaces, e.g., the FAA for the US or TCCA for Canada. Conversely, EASA will validate the FAA certification of US aircraft models (or TCCA certification of Canadian models) according to applicable Bilateral Aviation Safety Agreements between the EU and the concerned Third Country.

2.2.1 Operation without normal electrical power

The current regulation, § 25.1351(d), Amendment 25-72, "Operation without normal electrical power," states that the airplane must be operated safely in visual-flight-rules conditions for a period of not less than five minutes after loss of all normal electrical power.

This rule was structured around a traditional design of mechanical control cables for flight control that allowed time for the crew to remedy an electrical failure, start the engine(s) if necessary, and re-establish some or all of the electrical power-generation capability.

2.2.2 EASA CS-25

The certification specification (CS) is, in aeronautical law, a standard that specifies the certification needs of an aircraft imposed by the European Aviation Safety Agency [4]. They accompany Development Regulations and unlike these and the Base Regulation, considered as Hard Law, they are considered as Soft Law. The number of these specifications coincides with the number of the equivalent FAR regulation.

The European Aviation Safety Agency issues these specifications to be used as a means of demonstrating that products, components and equipment meet the requirements specified in Annexes I, III and IV of Regulation (EC) No 216/2008. The specifications are presented with a sufficient degree of detail and specificity to indicate to applicants the conditions under which the certificates are issued, corrected or supplemented.

There are Certification Specifications for a multitude of Development Regulations, such as the regulations associated with Initial Airworthiness or Crew

The CS-25 (Abbreviation for Certification Specification 25) applies to large aircraft powered by turbine engines. Within this CS no limit to the weight of the aircraft is specified, as is done in CS-23 [5].

2.3 Forecast and load analysis

As happens in any electrical installation on land, the first step in the design of a new installation is to know what loads we are going to feed and what sources we are going to use to do so; Something similar happens in the aeronautical industry, it is necessary to make a detailed analysis of the loads that are going to be part of the system and from this determine which are the generating sources that must be installed to guarantee the supply in any flight situation.

The main propose of the load analysis is to determine the capacity of the electrical system that will be needed for different flight operations. Furthermore, for different inflight failures.

After deep research, from current to the number of unities or the functional category we can create the label for those load analysis.

2.4 Main electrical system parts

Your aircraft's electrical system has these main primary components: batteries, generators or alternator, transformers, inverters and an electrical bus to distribute electrical power. The spark plugs in certified piston aircraft engines are powered by engine-driven magnetos, so no additional electrical power is required for the engine to run.

Obviously more parts are important, however during this part I will enter into detail for the main ones, such as I mentioned before.

2.4.1 Generators

The main source of electrical power on an aircraft is a generator. A generator. converts mechanical energy to electrical energy via applications of electromagnetics. The. mechanical energy input for a generator comes from the engine in the form of a rotating.

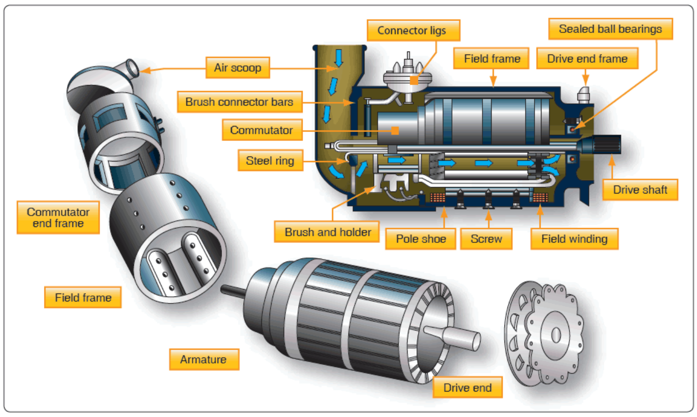


Figure 14 - Aircraft generator parts [23]

During the process of choosing the right generator we must take into account the following considerations:

- Power and voltage supply
- Synchronous
- Wound field
- Multistage
- Rotor and stator design
- Materials
- Torque density
- Air gap
- Rotor pole
- Number of phases
- Slots per pole and phase
- Winding
- Final circuit test
- Losses

Beginning with the **power and voltage supply**, it is strictly important to follow these parameters for the equation, all the following equations in this part 2.4.1 were extracted from the same source [42]:

$$P \; \alpha \; (f_b \,, B_L, A, D^2, Ls, N) \quad (1)$$

P = power [W]

f_b = form factor

B_L = magnetic load [A]

A = electrical loading [W]

D = rotor diameter [mm]

Ls = stack length [mm]

N = shaft speed [rpm]

However, the general output rms voltage equation stands for:

$$E = \sqrt{2}\pi f_b \, N' f \Phi \quad (2)$$

E = rms voltage [V]

f_b = form factor

N' = number of phase turns

f = frequency [Hz]

Φ = magnetic flux [Wb/m²]

The equation number 2 is obtained from the Fourier series representation equation of air gap magnetic flux density and the form factor.

Continuing with **synchronous,** the aircraft generator are 100% synchronous machines. However, before that, we must know what a synchronous machine is.

A synchronous electric motor is an AC electric motor in which, at steady state, the rotation of the shaft is synchronized with the frequency of the supply current; the rotation period is exactly equal to an integral number of AC cycles. In first the magnetic field is created on the rotor. Then an external driving force is applied. Then a voltage is induced and finally the output frequency is directly proportional to the shaft rotational speed. All this explanation followed by this equation:

$$f = \frac{N\,P}{120} \quad (3)$$

f = frequency [Hz]

N = shaft speed [rpm]

P = number of poles

After the synchronous we have the **wound field,** generally generators a part from being synchronous, they are wound field machines, which means that the magnetic field is produced by electromagnets. The main electromagnet can be found on the rotor. Since thus magnetic fields can be adjust, we can find some advantages, such as using it to regulate the output voltage view higher ease. However, as always there are some disadvantages, for example using wound field machines there is high probability of having a complex design due to the large number of coils. In addition, the large number of coils limits its performance. Despite thus advantages and disadvantages aircrafts prefer this wound field machines.

Then we have the **multistage,** since generally all aircrafts are wound fielded, the main electromagnet is the rotor, DC excitation must be given by and DC exciter via slip rings mounted on the stator. However, new ones have the supply through brushless excitation system.

In the multistage we can avoid having slip string, this elimination allows the physical connection between the rotor and stator to be shaft bearings. However, as always, some difficulties we can find, such as measuring the amp-turns on the main field when testing the generator.

Now we must concentrate on how **the rotor and stator design** must be.

First the **rotor design**, its ratio is defined by the length to diameter ratio (L/D). The normal aerospace design for this ratio is between 0.3 and 2.0, as higher the ratio is, the lower inertia and faster mechanical response. Having a higher speed, stresses the mechanical out, reducing end-turn conductor losses and allowing for smaller shaft. However, a lower ratio allows for a deeper stator slot depth.

Secondly, the **stator design** is mainly the armature windings. An important aspect of the stator is that, being made of steel, helps direct magnetic flux and completes the flux path for the magnetic circuit. This means they are slot-less and slotted.

Another important aspect are **the materials,** all aircrafts generators have copper windings. This copper windings have existed since always, during many decades. Copper is high conductive, constant and low costed. However, disadvantages never stop, it includes significant losses at higher speeds due to eddy current losses and skin effects. Aluminium could be a replacer; it has a higher coefficient of thermal expansion (CTE) but its low volumetric density can be problematic.

The materials for the rotor and stator are the magnetic steel. It allows the flux to go direct to the machine. The type of steel chosen is based on different criteria such as core, saturation or losses.

Then we have the **torque density,** it has a very important role to do. Mainly it plays as a physical sizer. The torque per rotor volume (TRV) is higher it yields a smaller rotor volume, while a lower TRV yields to a larger rotor volume. All these criteria are important for a better aspect, such as better cooled machine. This torque can be determined by air gap shear stress:

$$\sigma \; \alpha \; AB \quad (4)$$

σ = shear stress [Pa]

A = current density [A/m²]

B = flux density [T]

$$\tau = \frac{T}{Vr} = \frac{\pi}{\sqrt{2}} k_w AB \quad (5)$$

τ = torque density [J·m³]

T = torque [Nm]

Vr = rotor volume [m³]

Continuing with the **air gap,** the air gap of a generator is the gap between the rotor and stator. A larger air gap allows for a better voltage regulation and performance. This allows a high respond which depends of the amount of energy stored in the air gap. This stored energy can be calculated with this equation number 6.

$$Stored\ Energy = \frac{B^2\ x\ Volume}{2\mu o} \quad (6)$$

μo = permeability of air [cm³/s/cm²]

B = flux density [T]

It is important to remark that, a narrow air fap increases its performance and minimizes the flux leakage, this allows for a more powerful machine usage.

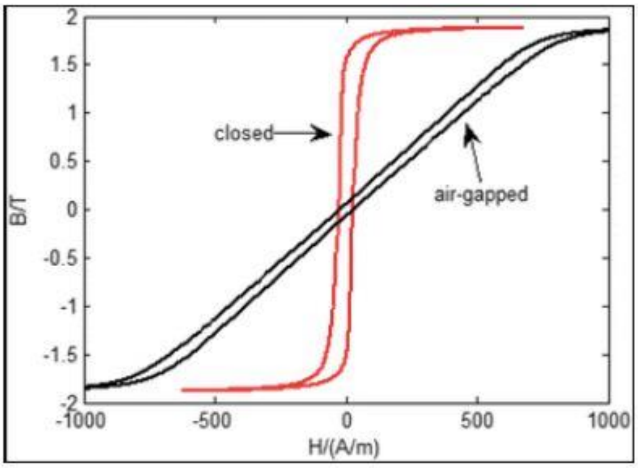


Figure 15 - Air gap curve on magnetics effect [23]

Another important consideration is the **rotor pole**, which refers to the number of magnetic poles. This aspect affects a lot to the machine, for example to its frequency, which is directly proportional to the number of poles, the magnetic area gap per pole and pole pitch. Increasing the number of poles reduces required rotor and stator yoke thickness, as follows:

$$t_y = \frac{B}{By}\frac{\pi D}{4P} \quad (7)$$

B = magnetic loading [A]

By = peak yoke flux density [T]

D = rotor outer diameter [mm]

P = number of poles

The number of poles is really important, because a higher number of poles increases stator iron losses, as iron losses density is roughly proportional to the square of the frequency. The type of rotor can be by its shape, for example cylindrical or salient.

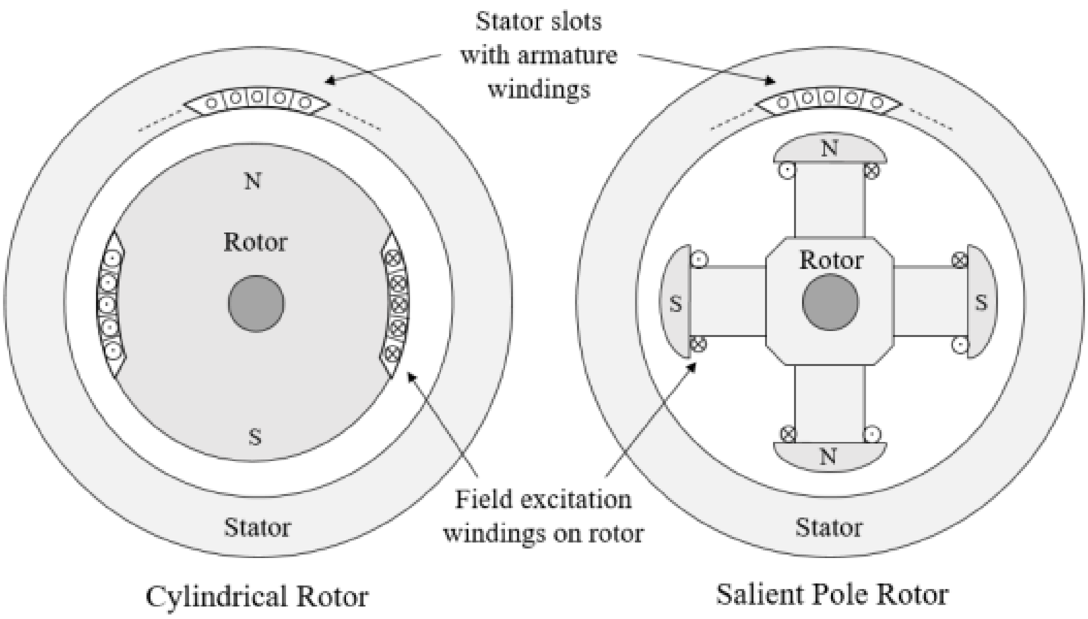


Figure 16 - Comparison between cylindrical and salient pole rotor [32]

Such as the number of poles, the **number of phases** is as important is the pole ones. The number of phases affects the machine in different ways, such as stator slots, the slots per pole per phase and the per-phase rms current [6]. The number can be calculated with:

$$Ns = N'Np \quad (8)$$

Ns = number of stator slots

N' = number of phase turns

Np = number of phases

However, the per-phase rms current is calculated by:

$$I_{\phi,rms} = \frac{P}{V\,Np} \quad (9)$$

$I_{\phi,rms}$ *= per-phase rms current [A]*

P = power [W]

V = voltage [V]

Np = number of phases

While the diameter is being held constant, an increase in the number of stator slots will decrease the available slot width, this may cause a decrease in coil and the permitted current. In corelation with equation 9, as the phase is in parallel, a current decrease is needed.

Then the **slots pole per phase,** another aspect that is really important, which helps govern the association between poles and windings.

$$m = \frac{Ns}{2Pq} \quad (10)$$

m = slots per pole per phase

Ns = number of stator slots

P = number of pole pairs

q = number of phases

The parameter *m* is an integer and a fractional slot machine. The number of slots per pole for assumptions used here should be a whole number plus ½. This allows flux, the pole and total reluctance of the air gape be barely the same.

And finally, before the final circuit test, we have the **winding configurations**, these windings are configured as to help create the sinusoidal back electromotive force (EMF) in order to eliminate harmonics beyond the first harmonic. These harmonics are normally presented within a machine.

Traditionally, there are three winding types of configuration factors: pitch, distribution and skew. But before talking about each of them we must know the total winding factor equation:

$$k_w = k_p k_d k_{sk} \quad (11)$$

k_w = *winding factor*

k_p = *pitch factor*

k_d = *distribution factor*

k_{sk} = *skew factor*

The pitch factor is the ratio of the back EMF of a fractional-pitch winding to a full-pitch one.

$$k_p = \frac{back\ EMF\ of\ fractional-pitch\ winding}{back\ EMF\ of\ full-pitch\ winding} \quad (12)$$

$$k_{p(n)} = \sin[(n)(\%pitch)(\tfrac{\pi}{2})] \quad (13)$$

The pitch ratio is the ratio of the pitch angle to a full 180 degrees displacement of two coil sides.

$$pitchRatio = \frac{pitchAngle}{180} \quad (14)$$

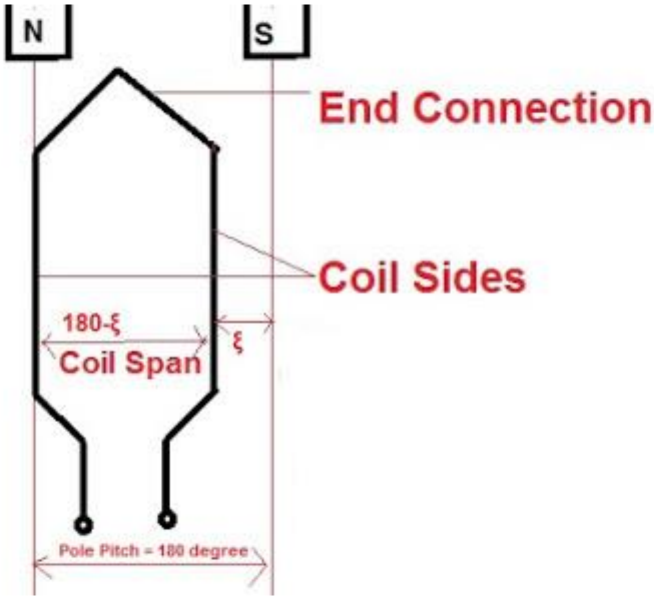


Figure 17 - Coil span factor [22]

The distribution factor is the ratio of the induced EMF in a distributed winding way.

$$k_d = \frac{back\ EMF\ in\ distributed\ winding}{back\ EMF\ in\ concentrated\ winding} \quad (15)$$

$$k_{d(n)} = \frac{\sin(\frac{n\alpha}{2})}{(m)\sin(\frac{n\alpha}{2m})} \quad (16)$$

m = slots per pole per phase

α = phase belt angle [Degrees]

n = harmonic

Skew factor is the derived winding factor that takes into account skewed windings.

$$k_{sk(n)} = \frac{\sin(n\frac{skewAngle}{2})}{n(\frac{skewAngle}{2})} \quad (17)$$

2.4.2 Converters, transformers and inverters

The need to convert large amounts of electrical energy requires the use of high-efficiency converters to avoid excessive heat dissipation. For these reasons, all modern power converters are based on solid state technology, known as solid state power converters (SSPC). The key components of the SSPC are the power switches with a high switching frequency: 20-40 kHz. This frequency is necessary to produce forms of voltage and current waves that are necessary for sensitive avionics systems. Otherwise, this switching frequency is a source of electromagnetic interference (EMI). The most suitable switches for such fast switching are MOSFETs and IGBTs. Modern power converters are based on solid state technology. The components listed in the SSPC are power switches with a high switching frequency: 20-40 kHz. This frequency is necessary to produce forms of voltage and current waves that are necessary for sensitive avionics systems.

Figure 18 - A320 static converter [33]

The transformer, typically used in conjunction with the rectifier or inverter on an aircraft, boosts or bucks the ac voltage depending on the number of windings.

A steady-state electrical model is implemented where only winding resistances are considered. Inductances, including leakage and mutual inductances, are neglected. Some additional assumptions are that there is no phase shift error in the transformer, no eddy currents, and the transformer is never saturated.

It is important to add the TRU as it is actually the transformer rectifier unit, which converts the 120V AC power generated by the engine or APU generators or provided by a Ground Power Unit (GPU) to 28V DC power for use by various electrical components.

Figure 19 - A320 transformer [33]

The power inverter in an aircraft is used to convert the dc voltage of the battery to three phase ac voltage to supply power to the ac loads in case of emergencies.

Voltage and current drops were not used to calculate the output voltage and current as they are small and negligible. Pulse-width modulated (PWM) voltage source inverters are used in commercial aircraft.

Figure 20 - A320 inverter [33]

2.4.3 Distributors

Once the necessary energy has been generated and transformed into conditions of use, it is necessary to take it to all consumption points. The elements that are used for distribution of tensions by the different zone are:

- Distribution bars
- The wiring
- Accessories (support trays or connectors)

From the point of view of installation design, the element that requires special attention is the cabling. It is necessary to know the behaviour of said wiring in each of the conditions. It is also important to take into account while wiring the aircraft the type of line working on, the length, the intensity and installation conditions.

How to ensure that equipment is powered at the voltages specified in the MIL-STD-704, the maximum voltage drops accepted will come defined from the tension applied in the distribution bars and consumption.

Table 1 - Federal Aviation Administration (FAA) voltage drops

NOMINAL VOLTAGE	CONTINUOUS SERVICE	INTERMITTENT SERVICE
28 V (CC)	3,5% to 1 V	7% to 2 V
115 V (AC)	3,5% to 4 V	7% to 8 V

This are just some brush strokes; all distribution calculations will be given further in this project.

2.4.4 Protections

Before we get into aircraft lightning protection, it's important to understand why it exists. These tools, systems, and policies are necessary because lightning often strikes planes both in the air and on the ground.

At any given moment, there are approximately 150 lightning bolts happening throughout the world. Lightning strikes are an everyday occurrence on planet earth. And while approximately 80% of those strikes stay in the clouds (in-cloud lightning), they still pose a risk to airborne objects, like aircrafts.

Most aircrafts have a thick, external metal that is sufficiently thick enough to resist lightning strikes.

The thick exterior metal prevents a lightning strike's electromagnetic energy from entering critical spaces, including:

- Interior of the aircraft
- Electrical wires

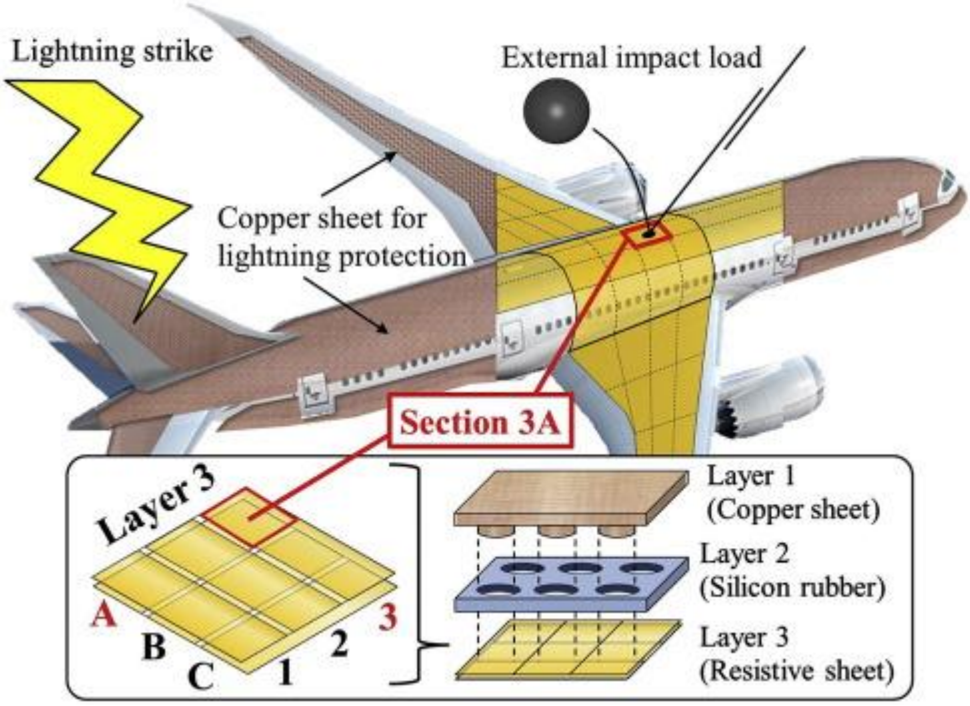


Figure 21 - Aircraft lightning strike sections [33]

Th question is, how often does a lightning strike the aircraft? For commercial jetliners, the answer to that question is about once per year. It sounds like a lot, but it is how it is. The United States Federal Aviation Association (FAA) estimates that lightning strikes a commercial plane once every 1,000 flight miles.

And where do they normally strike? Normally it strikes through one of the external places [7], such as:

- Wing
- Nose
- Tip
- Rudder

Obviously, nowadays for everything there is a solution, same for lightning strikes on ground. In this case, the best way to protect everyone is to follow the safety and operations solution, which consists of detecting, alerting and protecting.

It starts with accurately detecting total lightning, which is the combination of in-cloud and cloud-to-ground strikes. While cloud-to-ground strikes are the only ones that can injure people on the ground at airports, in-cloud lightning is a dangerous precursor to severe weather like microbursts, hail, and tornadoes.

On the other hand, air traffic control would better benefit from a real-time lightning strike map. Once these two areas are taken care of, it's time to protect ground crew from lightning with detailed, practiced safety procedures. Airport safety lightning policies should outline how to secure at-risk infrastructure and move personnel to safety quickly.

In addition, we have the overcurrent protection, which protects from high current than permitted. The voltage has surpassed the nominal conditions. We can find three important causes:

- an overload.
- a short-circuit.
- or a ground fault.

This produces a rise on the temperature of operation. The overload is a slight excess current due to excessive power demand. There is a progressive heating of the cable. However, the short-circuit is a large increase in current due to the union of two elements at different voltages, without any resistance between them.

2.5 Evolving for more electrical aircraft

So, first of all, we must know what actually an electrical aircraft is. An electric aircraft is an aircraft powered by electricity, almost always via one or more electric motors which drive propellers. Electricity may be supplied by a variety of methods, the most common being batteries.

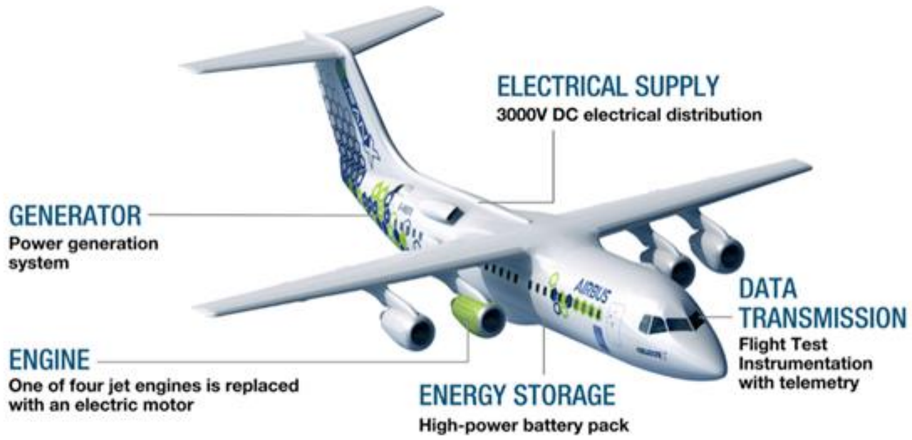


Figure 22 - Airbus electrical aircraft concept [34]

Commercial aircraft since its inception have been made up of a mix of systems: pneumatic, mechanical, hydraulic and electrical, a combination that has always been under debate and even more so in recent years when the idea of building larger aircraft has caused these systems to become increasingly complex and the interaction between them makes the entire aircraft an inefficient system.

In this way, the idea of manufacturing a more electric aircraft (MEA) or even an all-electric aircraft (AEA) has arisen in recent years. A clear example of the evolution towards more electric aircraft is the incorporation of the "Fly by Wire" (FWB) system introduced in the Airbus A320.

2.5.1 More electrical aircraft concept (MEA)

The MEA concept emerged in the middle of the 20th century, during World War II, with the approach of some military aircraft designers to reduce the weight of aircraft, whose drive systems were fundamentally based on mechanical principles. It seemed possible. The electrical systems made their way efficiently.

In addition to weight reduction, the electrical systems made it possible to obtain better control, monitoring, tolerance to system failures, reduction in maintenance costs or an increase in the reliability of the aircraft in general.

The general objective, before and now, is to achieve the reduction and even elimination of traditional drive systems so that the electrical system is the largest or the only one in the aircraft. The objectives pursued in the manufacture of more electric aircraft are not only technical but also have an environmental impact, air transport is booming.

Aviation has fundamentally transformed society over the past 40 years. The economic and social benefits throughout the world have been immense in 'shrinking the planet' with the efficient and fast transportation of people and goods. The growth of air traffic over the past 20 years has been spectacular, and will continue in the future.

Europe is home to approximately 448 airlines and 701 commercial airports which in 2010 supported 606 million passengers allowing the free movement of people and goods across borders. Aviation creates economic growth, wealth and provides highly skilled jobs it is a massive way of money generation.

The Group of Personalities also agreed to establish a new Advisory Council for Aeronautics Research in Europe (ACARE) to develop and maintain a Strategic Research Agenda (SRA) that would help achieve the goals of Vision 2020. However, over the same period a number of boundary conditions changed that prompted ACARE members to reconsider the sufficiency of the existing Vision 2020 with the view to extend it to a new horizon towards 2050 [20-21].

3. Studying a concrete model. Structure of the electrical system of an Airbus A320

The Airbus A320 is a narrow-body commercial jet aircraft for short to medium-haul flights developed by Airbus SAS, a French company currently controlled by the Dutch corporation Airbus SE. There are several models derived from the A320, including the short versions A318 and A319, the long version A321, and the ACJ business jets.

Models derived from the A320 have a maximum capacity of 220 passengers and a range that goes from 3,100 to 12,000 km, depending on the model [8].

Figure 23 - Airbus A320 [35]

However, this project is not based on how this aircraft looks like or similarities. Exactly I am studying the electrical system of it.

Before starting with the electrical system, it is important to know that all begins with the turbofan engine system. In the Airbus A320 the turbofan engine model is the **CFM56-5B.** Today, it is the only engine that can power every model of the A320 family with one bill of materials. The engine's broad-based market acceptance has been because of its simple, rugged architecture, which gives it the highest reliability, durability and reparability in its class.

Figure 24 - CFM56-5B engine

Inside of that engine we can find different important parts:

- Splitter fairing
- Radial drive shaft
- Fuel nozzles
- N1 shaft
- N2 shaft
- Oil vent tube

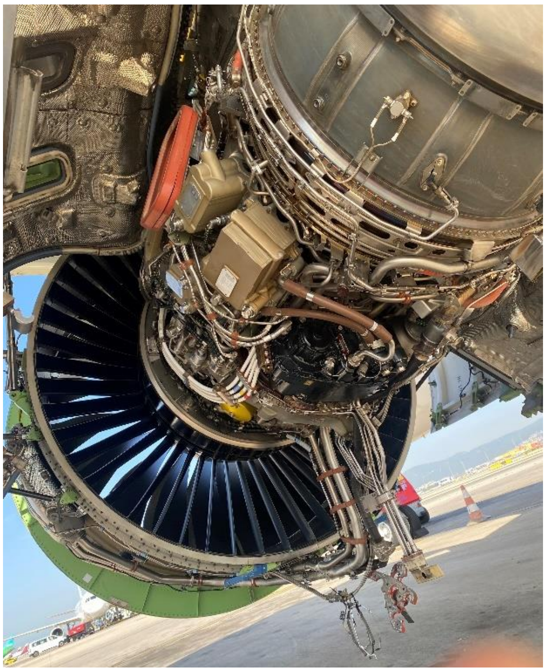


Figure 26 - Inside of the CFM56-5B engine (left side)

Figure 25 - Inside of the CFM56-5B engine (right side)

The electrical power system consists of a three-phase 115/220V 400Hz constant-frequency AC system and a 28-volt DC system.

The electrical transient is acceptable for equipment. The commercial supply has secondary priority. Normally, this system produces alternating current, some of which it then transforms into direct current for certain applications.

The whole network is being supplied by three generators. However, if all normal generation system were in loss, an emergency system generator can supply the AC power. If all AC generation is lost, the system can transform into DC power from the batteries into AC power.

In the following figure we can see how the electrical system is structured:

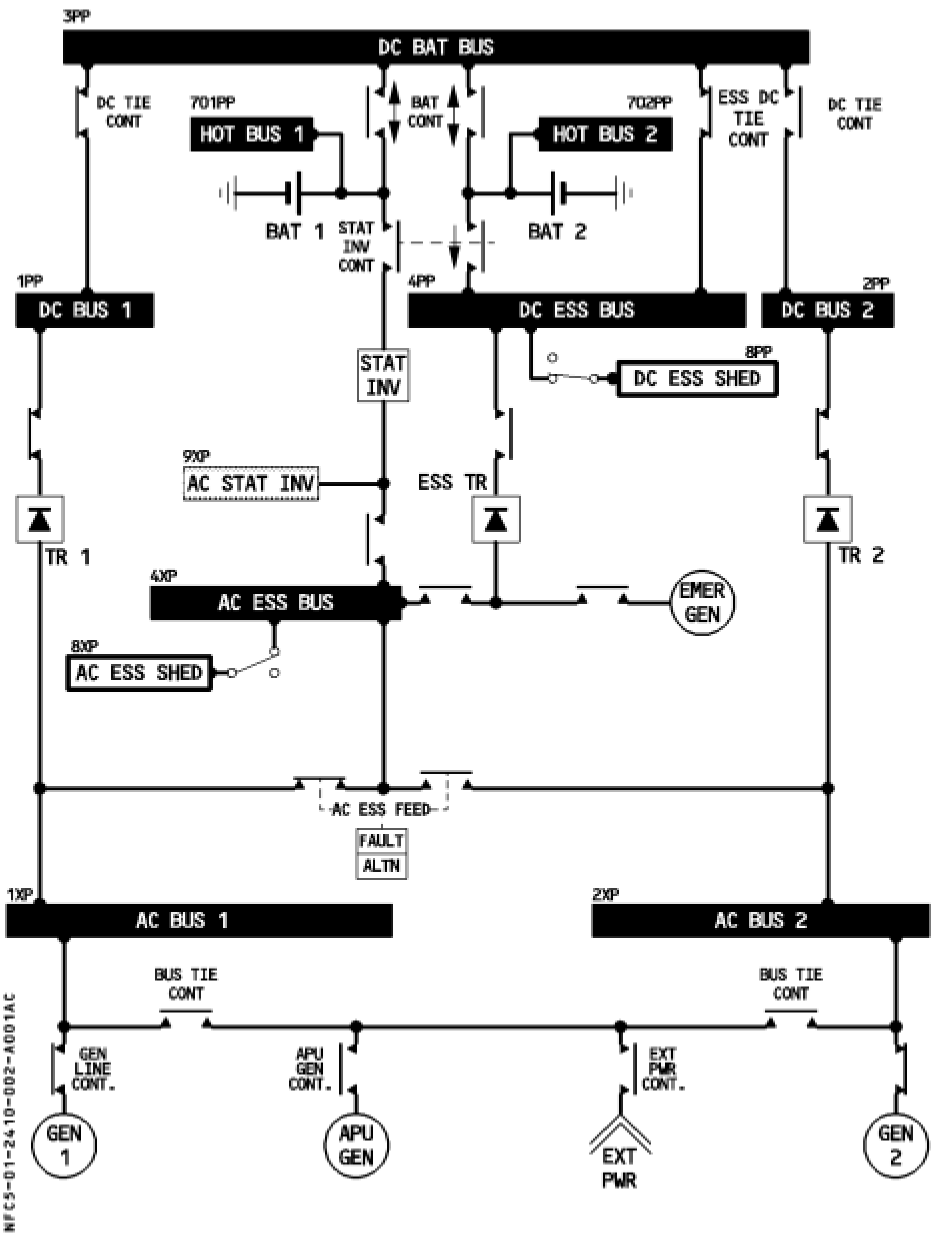


Figure 27 - Airbus A320 electrical system scheme [38]

3.1 Flight deck and main features for the electrical system

Before starting with all the electrical system of the Airbus A320 explanation, it is important to get familiar with its flight deck and main features, because all system work through there which are commanded by a pilot.

Starting with the flight deck layout:

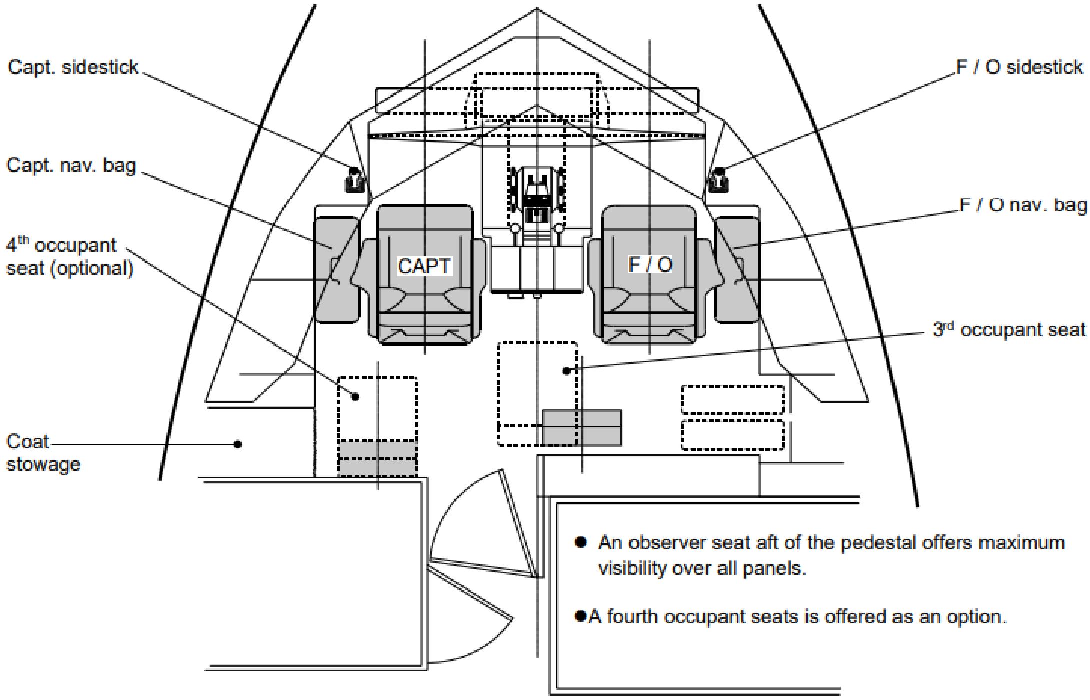


Figure 28 - Flight deck layout Airbus A320 [39]

As seen in figure 24, the A320 cockpit is quite simple from this point of view. However, it is actually a small place full of push-buttons that give functionality to the aircraft.

The following figure shows how it look from the back side, really focusing on the circuit brakers.

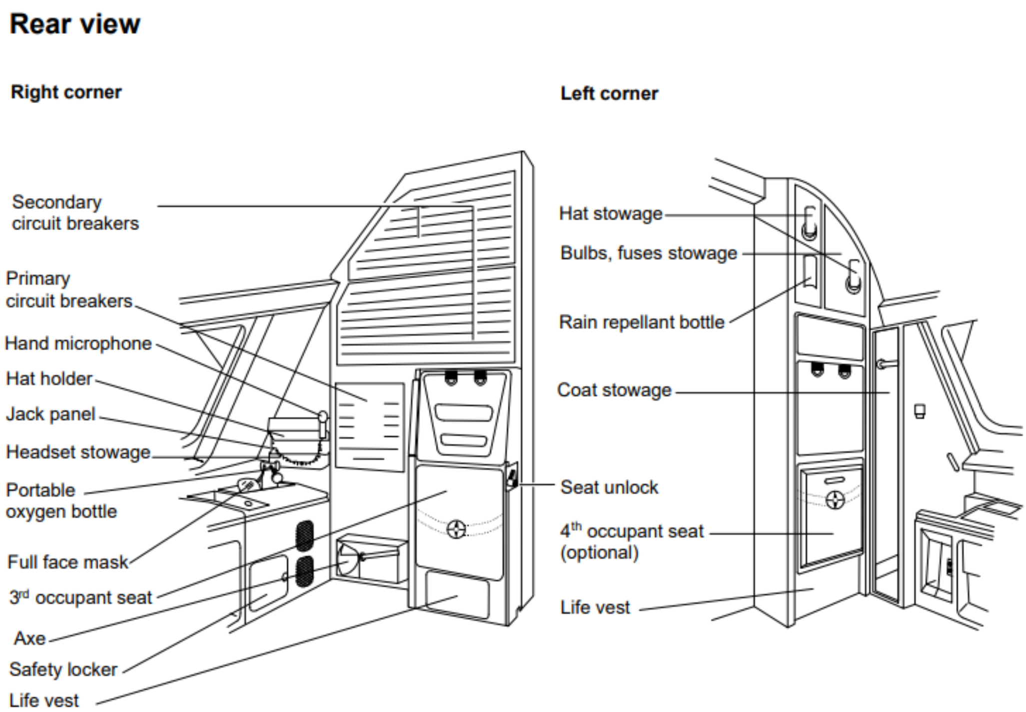


Figure 29 - Rear view of the Airbus A320 cockpit [39]

Now, the main flight deck with all its features. In bold are outlined the main control and indications panels:

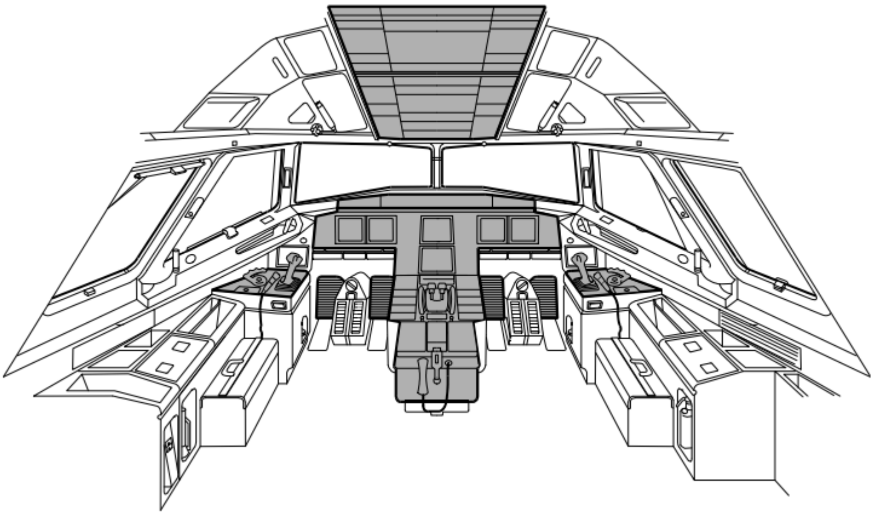


Figure 30 - Flight deck of an Airbus A320 [39]

In figure number 26, we can find the main features and other ones.

On the one hand, the main features are the sidestick controllers which leave the main instrument panel unobstructed and the six display units (DU) interchangeable, switchable and integrated into the same system (ECAM).

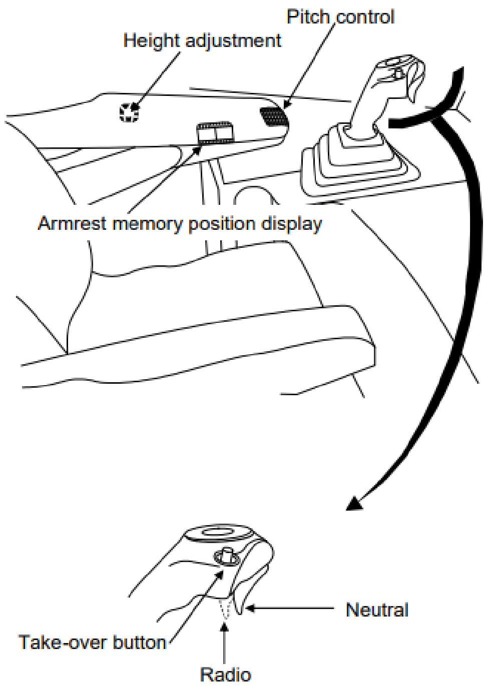


Figure 31 - Sidestick arrangement of an Airbus A320 [39]

I will not enter into detail on how the sidestick works, as is not really related to this thesis. However, here is a simple figure explaining it.

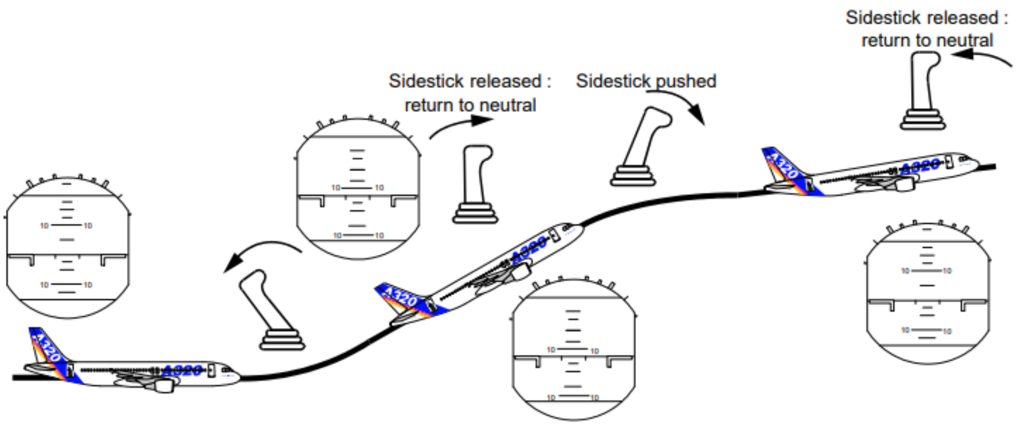


Figure 32 - Sidestick operation of an Airbus A320 [39]

Then we have the main instruments panel, included in the main features of the flightdeck. As the following figure shows, how it is all distributed.

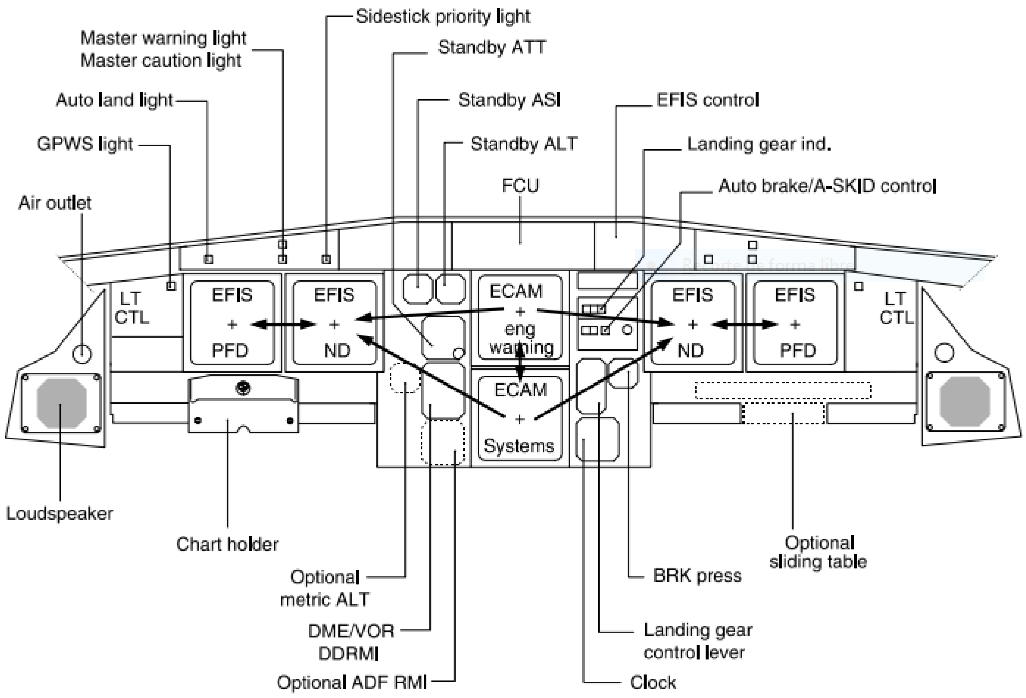


Figure 33 - Main instruments panels of an Airbus A320 [39]

All those displays allow the pilots to control the whole aircraft in case of any emergency, especially the navigation displays.

On the other hand, we have the other features such as the ergonomic layout of panels, synoptically arranged according to frequency of usage (normal, abnormal and emergency). Other important points of the flight deck are, the glareshield (AUTOPILOT), the pedestal and overhead panel. In the following three figure we can see how it looks like:

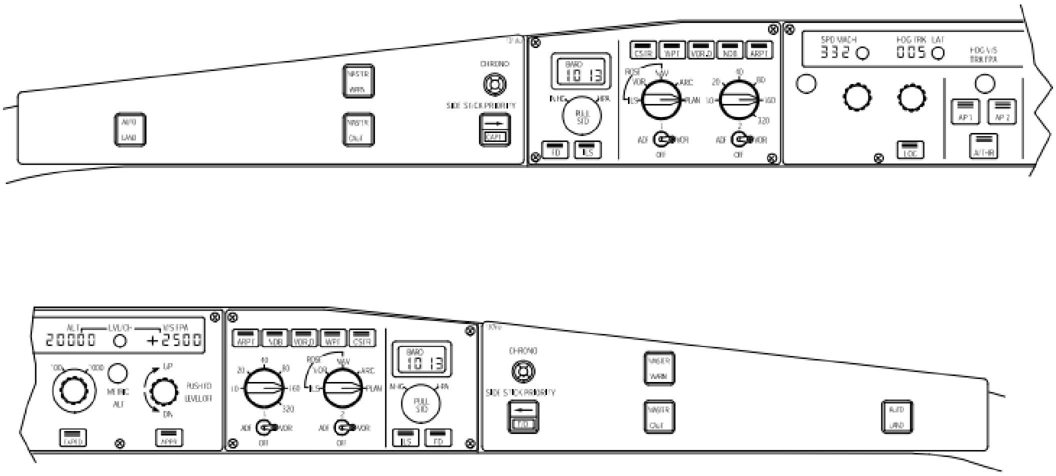


Figure 34 - Glareshield of an Airbus A320 [39]

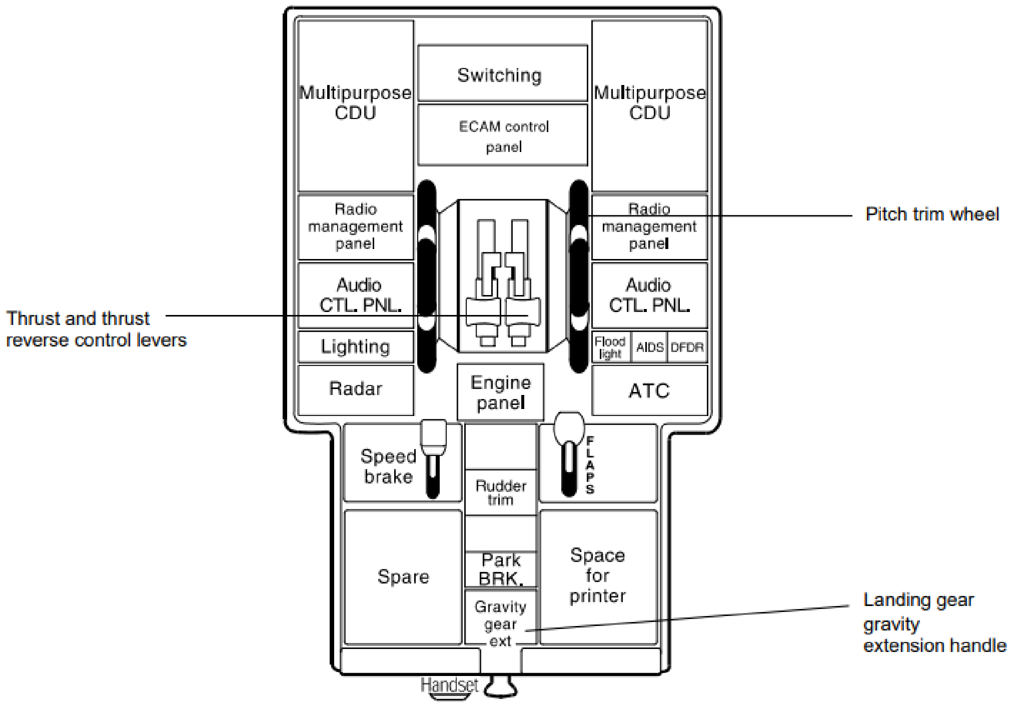


Figure 35 - Pedestal of an Airbus A320 [39]

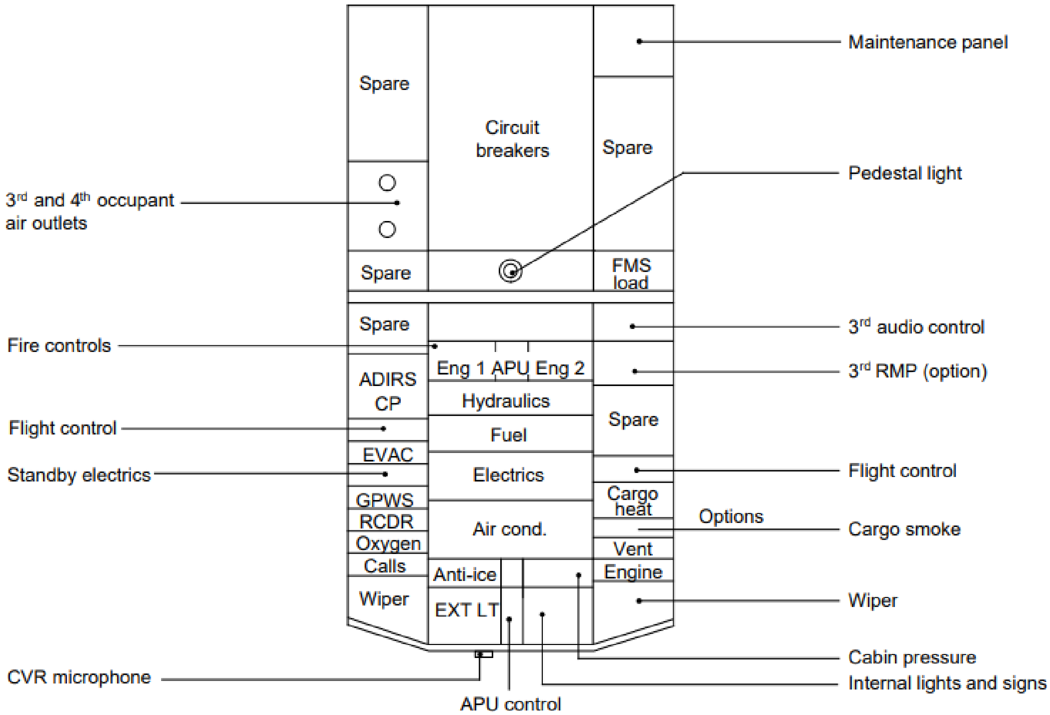


Figure 36 - Overhead panel of an Airbus A320 [39]

This last one really important for this project, as all main systems are controlled from this side.

3.2 Generating system

Going back to figure number 10, where I divided the electrical system scheme into two parts, now let's begin with the first one, that is the generation system.

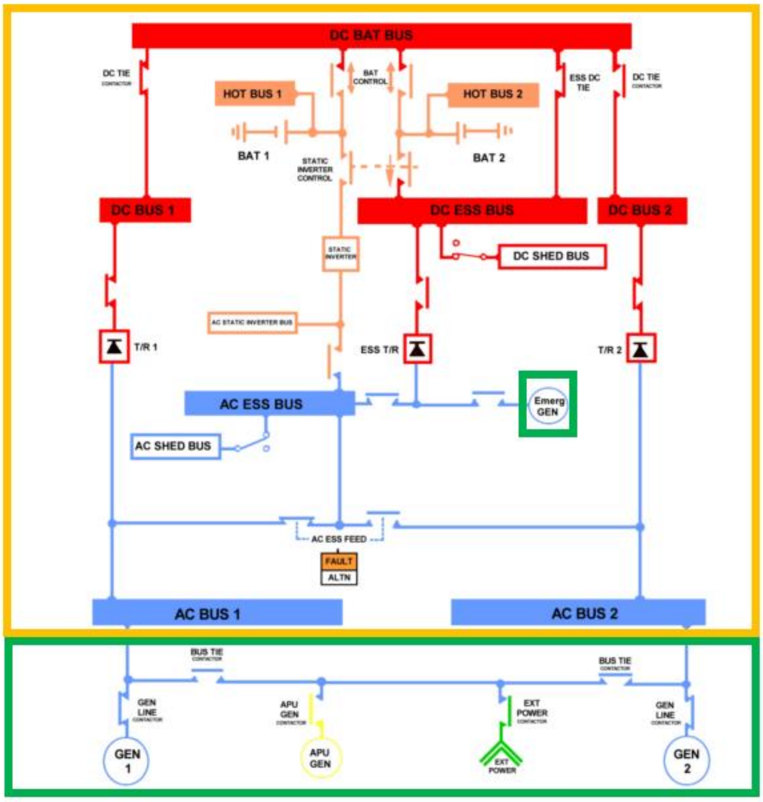


Figure 37 - Electrical system schematic divided in two parts [27]

Distribution system Generation system

This part includes aircraft engines, the APU auxiliary power unit, the external power (outside the aircraft) and the RAT air-impact turbine (not include in the following figure).

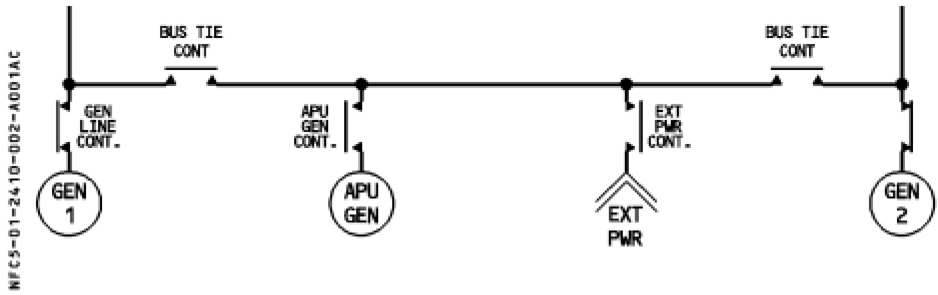


Figure 38 - Generating system of an Airbus A320 [38]

As I explained before, during the main electrical parts of an aircraft, the main source of electrical power on an aircraft is a generator. A generator. converts mechanical energy to electrical energy via applications of electromagnetics. The. mechanical energy input for a generator comes from the engine in the form of a rotating.

During this part, I have divided each segment as follows:

- AC generation system.

- DC generation system.
- Auxiliary generation system.
- Emergency generation system.
- Transformation of the generation systems.
- Location of the generation system in the aircraft.

3.2.1 AC generation system

The AC generator is a machine that converts mechanical energy into electrical energy. The AC Generator's input supply is mechanical energy supplied by steam turbines, gas turbines and combustion engines. The output is alternating electrical power in the form of alternating voltage and current.

As mentioned before, the electrical system consists of a three-phase 115/220V 400Hz AC system.

Two three-phase **AC generators** (GEN1 and GEN2) marked in red in the following figure, one driven by each main engine through an integrated drive that supplies electrical power to the aircraft. In this case the primary AC supply is from two 90 KVA engine driven integrated drive generators (IDGs). Each IDG has an associated generator control unit (GCU) which provides frequency, voltage and generator line contactor (GLC) control. A third 90 kVA generator is driven by the APU. This generator, along with ground power, is controlled by the Ground and Auxiliary Power Control Unit (GAPCU). Each of the three main generators is capable of supplying the power requirements of the entire system. The generators cannot be connected in parallel, and are automatically brought on line according to priority rules. The IDGs are highest priority, followed by EXT PWR when connected, followed by the APU generator.

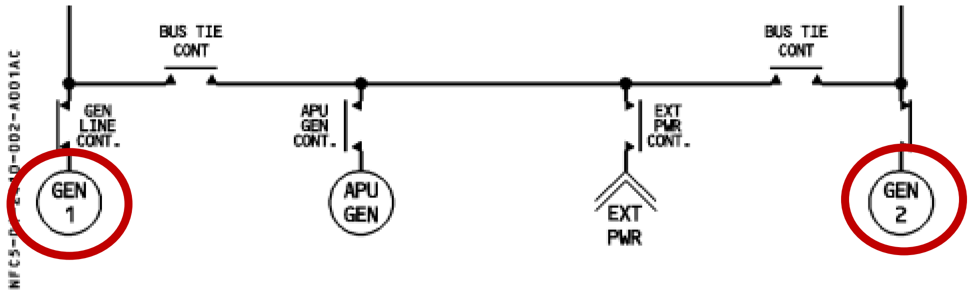


Figure 39 - Generating system of an Airbus A320 (GEN 1 & GEN2) [38]

That would be the main generators, however, there are three more very important. First is the **external power unit**. It is a ground power connector neat the nose wheel allows ground power to be supplied to all bus bars. This ground power control unit (GPCU) protects the network by controlling the external power contactor.

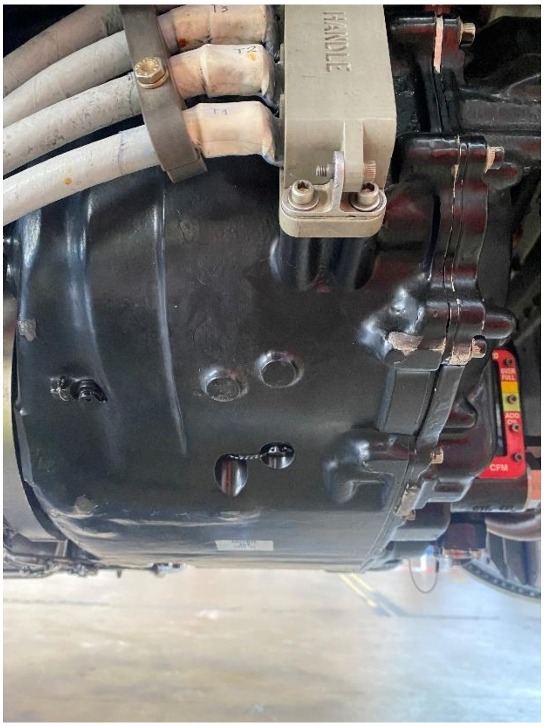


Figure 40 - IDG from the inside of the Airbus A320

For this IDG, the oil, a hydraulic fluid, is one of the vital components of the IDG. Oil is used for cooling and lubrication, and is also used to by the CSD to regulate the rotation speed of the generator mechanically. IDG is driven by the engine Accessory Gearbox. It is Accessible in the Engine Nacelle. The following figure shows how the level is measured:

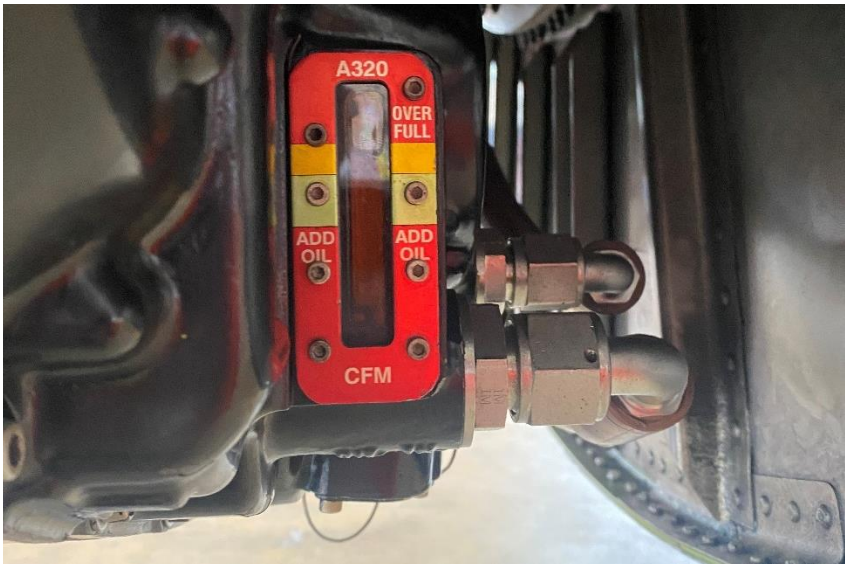


Figure 41 - Oil indicator for the IDG in the Airbus A320

This oil indicator must be between green level, which is the ideal quantity.

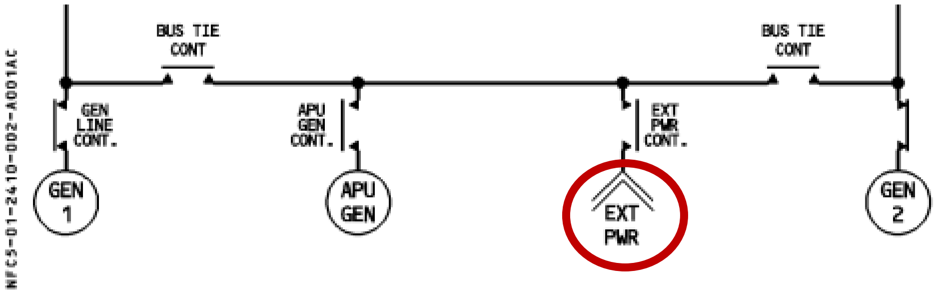


Figure 42 - Generating system of an Airbus A320 (EXT PWR) [38]

Then we have the **emergency generator**, the blue hydraulic circuit drives an emergency generator that automatically supplies emergency AC power to the aircraft electrical system if all main generators fail. This emergency generator can supply 5KVA of three-phase 115/220V 400Hz power. This generator can keep the emergency generator at constant speed, controls the output voltage, protects the network and control the start-up.

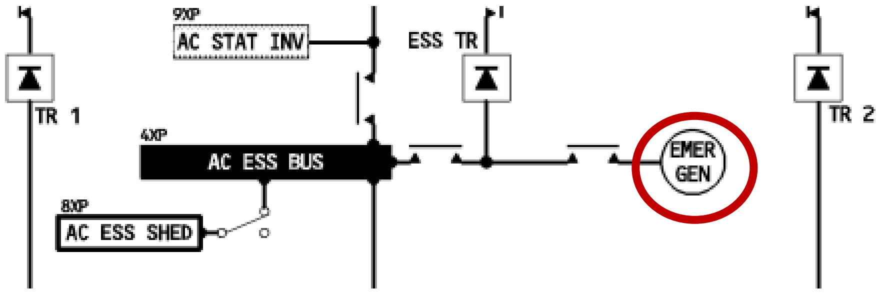


Figure 43 - Generating system of an Airbus A320 (EMER GEN) [38]

Finally, for the AC generators we have the **static inverter** which transforms DC power from BAT1 into one KVA of single-phase 115V 400Hz AC power, which is then supplied to part of the AC essential bus. When the aircraft speed is over 50kt, the inverter automatically is activated, but if the speed is under 50kt it will only activate if the BAT1 and BAT2 pushbuttons are both in auto.

3.2.2 DC generation system

The DC generator is an electrical machine whose main function is to convert mechanical energy into electricity. When conductor slashes magnetic flux, an emf will be generated based on the electromagnetic induction principle of Faraday's Laws.

Primary DC power is provided by two 200A transformer rectifier units with automatic protection circuits that disconnect the TR in the event of overheat or minimum current. A third identical TR, the "essential" TR provides power for the DC Essential bus in the event of loss of all normal AC generators (the Ess Tr is capable of drawing power from the emergency AC generator) or in the event of loss of one or both of the main TRs.

Two 23Ah batteries are also provided for emergency DC power. Each has an associated battery charger limiter (BCL) to monitor charging and control its battery contactor. The minimum required offline battery voltage is 25.5V. If the battery voltage is below minimum, they can be recharged by connecting the batteries to the battery bus and applying external power for approximately 20 minutes. In the event of failure of all other power sources, the batteries can provide emergency power for approximately 30 minutes.

The batteries are really important for this part, it is impeccable for the electrical system for any aircraft, they act as wildcard item as they can provide their stored energy for different tasks like.

The types of batteries mounted on an aircraft are diverse and the choice of one or the other will depend fundamentally on the service they are going to provide, as we have said before, in modern aviation batteries are almost reserved for emergency situations, so the most indicated They are the so-called stationary batteries characterized by having low levels of self-discharge during long periods of inactivity, remaining in float with a high level of accumulated charge, waiting for the moment in which they have to work.

The other basic characteristic of the battery is the material from which its main elements are made (electrolyte and plates); Although there are different types such as Lead-Acid, Ion-Lithium or Silver-Zinc [10], currently most aircraft use Nickel-Cadmium batteries due to their good characteristics.

Figure 44 - Battery and charger [37]

Some important features about the batteries for the A320:

- Nº of batteries: 2
- Type: Ni-Cd
- Capacity (Ah): 23
- Nominal V: 24V
- Weight: 25.5kg

Other aircrafts, such as A330 or B777 have similar characteristics, only its capacity and weight must change because of the aircrafts size.

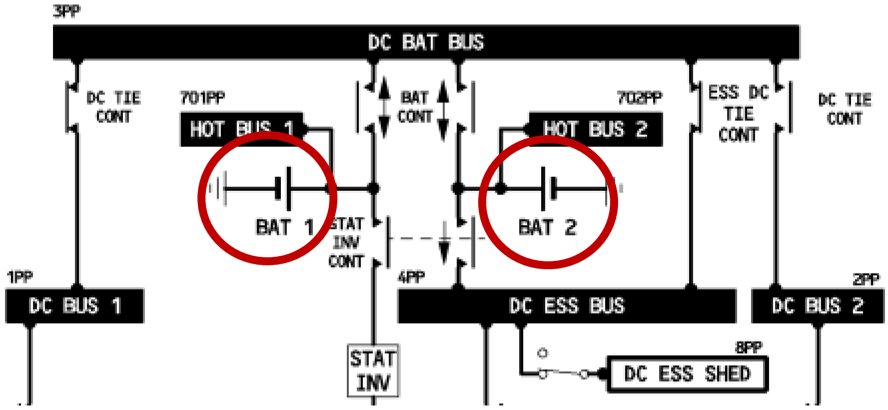


Figure 45 - Generating system of an Airbus A320 (BAT 1 & BAT2) [38]

A part from the batteries, the transformer rectifiers (TRs) are really important too. We have two main TRs, TR1 and TR2, which supply the aircrafts electrical system with up to 200A of DC current.

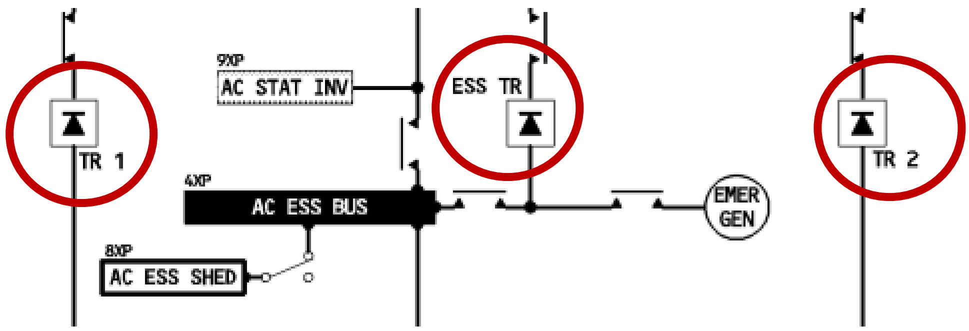


Figure 46 - Generating system of an Airbus A320 (TR1, TR2 & ESS TR) [38]

Finally, the circuit brakers known as C/Bs. In the A320 we can find two types, the monitored (green) and non-monitored (black).

The Wing Tip Brakes (WTB) C/Bs have red caps on them to prevent from being reset and the C/B TRIPPED warning are monitored.

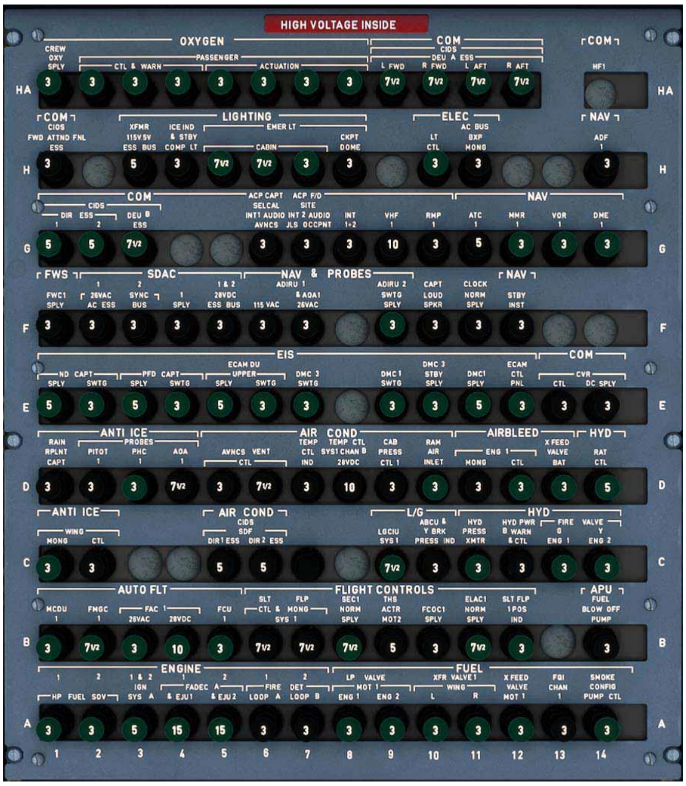


Figure 47 - Circuit brakers from an Airbus A320

3.2.3 Auxiliary generation system

Auxiliary generation systems are those that serve as support for different systems such as pneumatic or electrical and are totally independent of the main generators. This group includes the APU auxiliary power unit and the GPU external or ground power systems for powering the aircraft at the airport. The auxiliary power unit generates a three-phase alternating signal 115/200 V at 400 Hz

For the auxiliary generation system, we observe to main units. The first is the Auxiliary Power Unit (APU) and then the Ground Power Unit (GPU).

Beginning with the APU, this unit is a self-contained gas turbine engine that operates on the ground and in flight (on most models) and whose primary function is to supply backup or emergency electrical and pneumatic power, if needed. Pneumatic and electrical power supply is possible simultaneously or independently.

In no case will the function of the APU be to propel the aircraft, but rather it is reserved for tasks such as: starting the engines, supplying electrical and pneumatic energy with the main engines off, and providing energy during the flight in cases of emergency. The power unit is generally installed in the tail of the aircraft so that the combustion gases generated are evacuated.

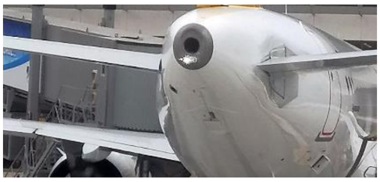


Figure 48 – APU (exterior) from an Airbus A320

Going more in depth, the APU has 3 important sections:

- **Charge section (green box):** It is formed by the compressor destined to supply the bled air for its use in the pneumatic system of the aircraft.
- **Power section (red box):** constitutes the gas turbine engine itself, it usually has one or two stages of centrifugal compressor or one centrifugal and one axial compression rotor in series.
- **Accessories box section (blue box):** In this section, different devices are connected, such as: the starter motor, the cooling fan, the oil pump or the electric generator that supplies electrical power to the plane.

All sections remark in the following figure:

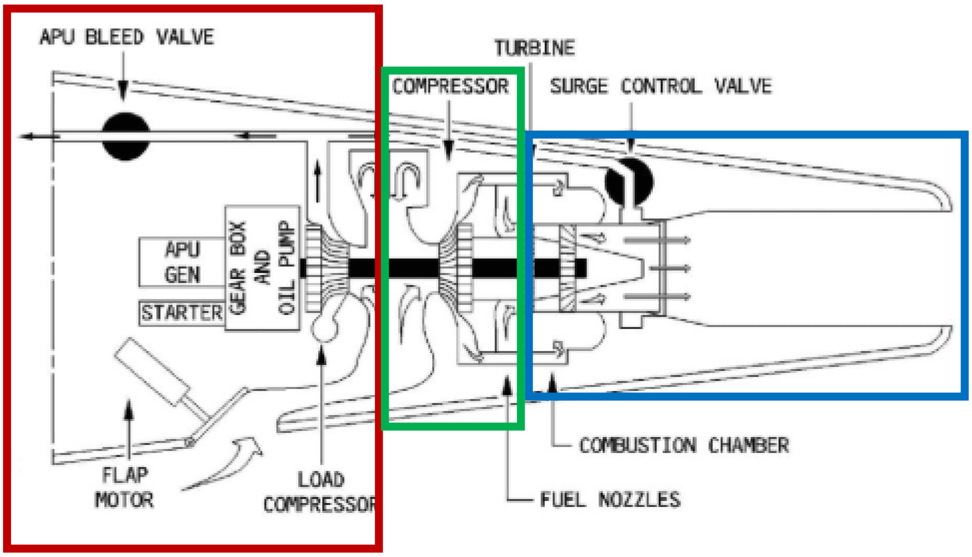


Figure 49 - APU parts and sections [36]

Generally, the starting of this unit is produced through an electric starter motor powered by the aircraft's batteries, by external power units when the aircraft is on the ground, or from the electrical system of the aircraft itself. In flight, as there is no external power available, the unit can only be started using the aircraft's own electrical system if it is operational, otherwise the batteries, which in many aircraft have a battery dedicated to starting the unit, it would power the starter motor.

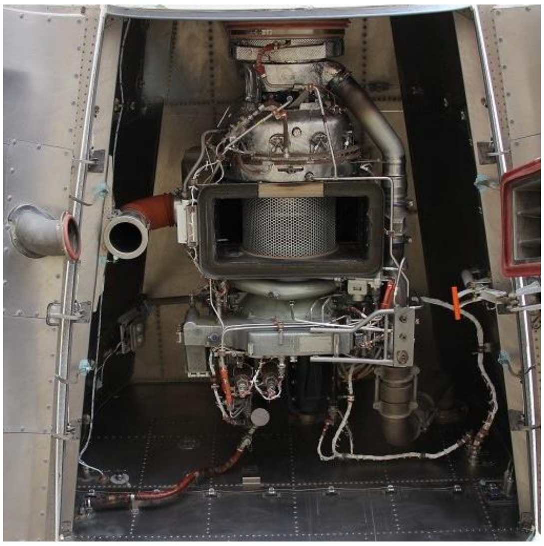


Figure 50 - APU from an Airbus A320 (interior)

The future of these devices is to replace their gas turbines with fuel cells in order to reduce fuel consumption and polluting emissions.

On the other hand, we have the Ground Power Unit (GPU). When aircraft are parked at the airport with their engines stopped, they need energy for proper maintenance and fine-tuning. As indicated above, this energy demand can be supplied by the APU, although fuel consumption and both environmental and noise pollution that it produces makes its use only necessary when the airport does not have GPU ground power systems.

The ground systems to provide three-phase electrical energy 115/200 V at 400 Hz are diverse and can be classified into fixed installations and mobile devices. Sometimes it may also be necessary to have direct current power at 28 V, in these cases the voltage level is achieved by connecting batteries or by processing the alternating signal.

In the airport we can find different type of parking's or stands for the aircrafts. Some of them have external ground power units some other have them integrated in the stand.

Let's have a look at the integrated GPU first. The fixed installations notably reduce the congestion of vehicles on the runway and in the aircraft transit areas, allowing service periods and stopovers to be shortened; they are also quieter and do not produce the environmental pollution caused by APUs or GPUs powered by diesel engines.

Some might come fixed in fingers some other fixed into the ground.

Figure 51 - Ground fixed GPU

All of them connected directly to the aircraft.

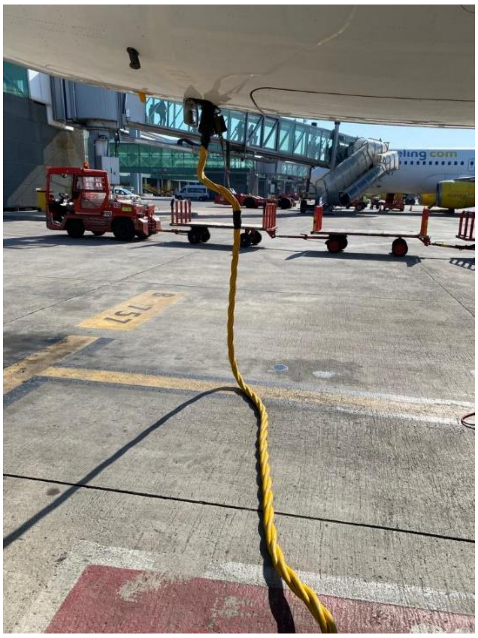


Figure 52 - Cable connection to the aircraft GPU

Finally, this fixed GPU goes to the aircraft connection lot. All of the devices described above provide electrical power to the aircraft through connectors that plug into a receptacle located generally forward of the landing gear. These connectors are standardized according to the IATA manual, Airport Handling Manual AHM 960 appendix C (use in North America 3x 230/133V - 60Hz) and appendix D (use in Europe 3x 400/230 -50Hz).

Figure 53 - Ground electric lot connection

However, fixed-type installations have very high initial costs and lack the flexibility that ground teams have to adapt to possible changes or different types of aircraft. Fixed installations can be very diverse and each airport will choose one or the other depending on its electrical energy requirements. Some of the most typical configurations are briefly outlined below.

The energy supplied by the airport or by the devices that operate in it is subject to a series of requirements included in the following regulations; IATA AHM972, ISO6858, Euro standard DFS400Hz, SAE ARP1148A, MIL-STD-704, MIL-STD-461, VDE 0875 N and others specific to each airport.

On the other side, remote stands or parking spots, have an external GPU. These types of machines are very common in airports and have the characteristic that they can move or be moved to the place where they are needed.

The most used is based on a diesel engine that drives a three-phase alternator that generates a signal of 115/200 V at 400 Hz, both elements are mounted on a chassis with wheels to be able to move it. The power range of these units is varied, but the equipment used to supply power to a standard commercial aircraft is usually 90 kVA. These units are equipped with electronic devices responsible for the regulation, control and protection of both the diesel engine and the alternator and the electrical energy they generate.

Figure 54 - External GPU

3.2.4 Emergency generation system

During a flight, at any moment, any issue could happen that can become a catastrophe and this is the reason why all aircraft must have an emergency system for everything. In this case, the emergency generation system. When an aircraft flies over 10,000 m high, any failure can lead to a catastrophe, which is why redundant equipment is installed in aircraft, sometimes duplicated or tripled, and their failure rate is very low as they are oversized.

In aviation, one of the golden rules consists of assuming that neither systems nor human beings are infallible, for example, the calculations made before each take off are based on the assumption that an engine will fail and, furthermore, it will do so at the most unfavourable moment (take off, landing). Regardless of possible human error, there are external factors such as atmospheric factors that can cause an emergency situation. The main factors can be for example, running out of fuel or lightning strikes, as I explained before.

This is how a normal and a loss of main electrical generators scheme would look like:

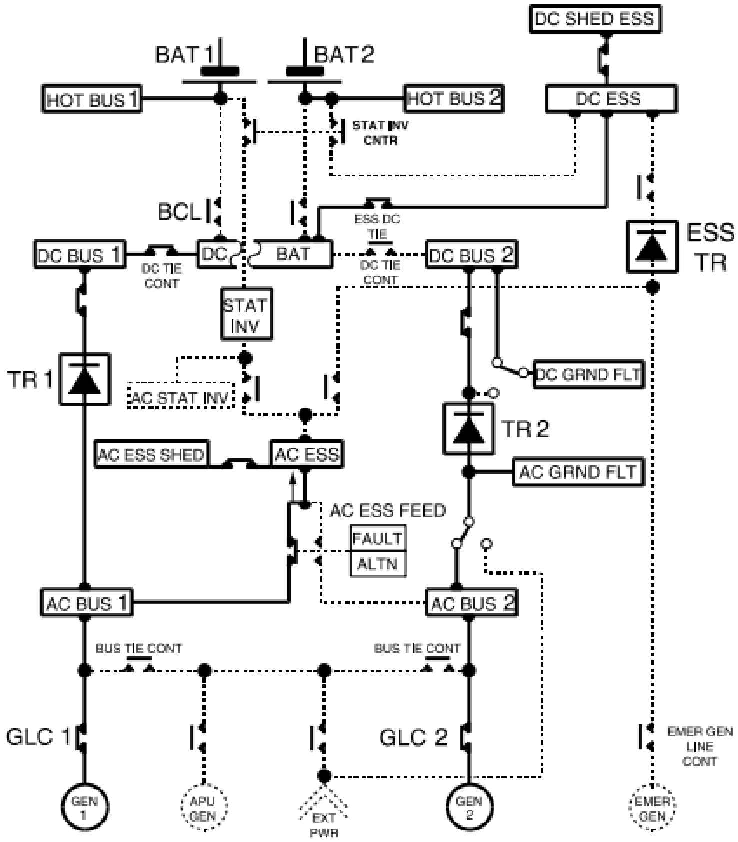


Figure 55 - Normal electrical flight configuration scheme [38]

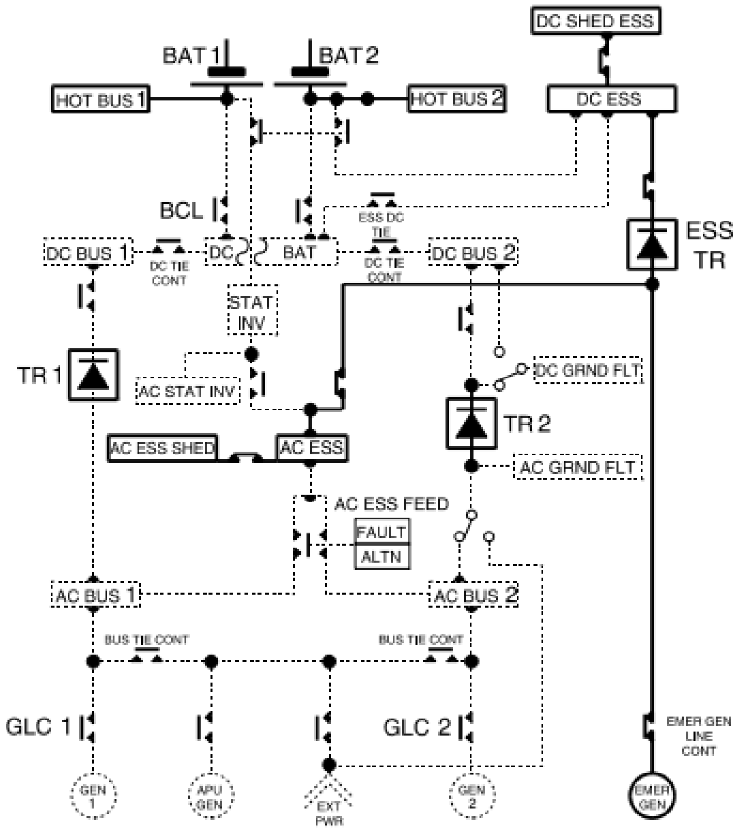


Figure 56 - Loss of main electrical generators scheme [38]

As far as the electrical system is concerned, the most critical case would be the simultaneous loss of the main engines and the APU in flight, leaving the main alternators and power generation sources of the aircraft out of service. In the event that this situation arises, the aircraft has sufficient elements to generate energy and make an emergency landing. These elements are:

- Backup generators.
- Ram Air Turbine (RAT).

Starting with the **backup generators**, this emergency power generation system is developed from the entry into force of the ETOPS regulation which, as explained above, applies to twin-engine aircraft that cover long routes or these are through environments such as deserts or oceans where the nearest airport is hundreds of kilometres away [11].

The backup generators are driven by the main engines and are mounted on the same fairing, but they are completely independent from the primary alternators, that is, their drive shaft is different although they share the same gearbox. If the main alternators or the APU are not operational due to a fault, the backup generators are responsible for supplying power to the vital loads of the system.

Then we have probably the most important one, the **RAT system**. A ram air turbine (RAT) is a small wind turbine that is connected to a hydraulic pump, or electrical generator, installed in an aircraft and used as a power source. The RAT generates power from the airstream by ram pressure due to the speed of the aircraft.

Figure 57 - Ram Air Turbine of an Airbus A320

The speed of the plane in the air makes the turbine rotate and move the pump that provides hydraulic energy. This energy can be used to power some hydraulic circuit of the plane and also to provide energy to the hydraulic motor in charge of moving the emergency electric generator, this generator is being fed up with an output voltage of 115/200 Vac and 400 Hz frequency.

The RAT provides two main parts, the electrical one and hydraulic. This system is different from the other because of low maintenance cost and high usage.

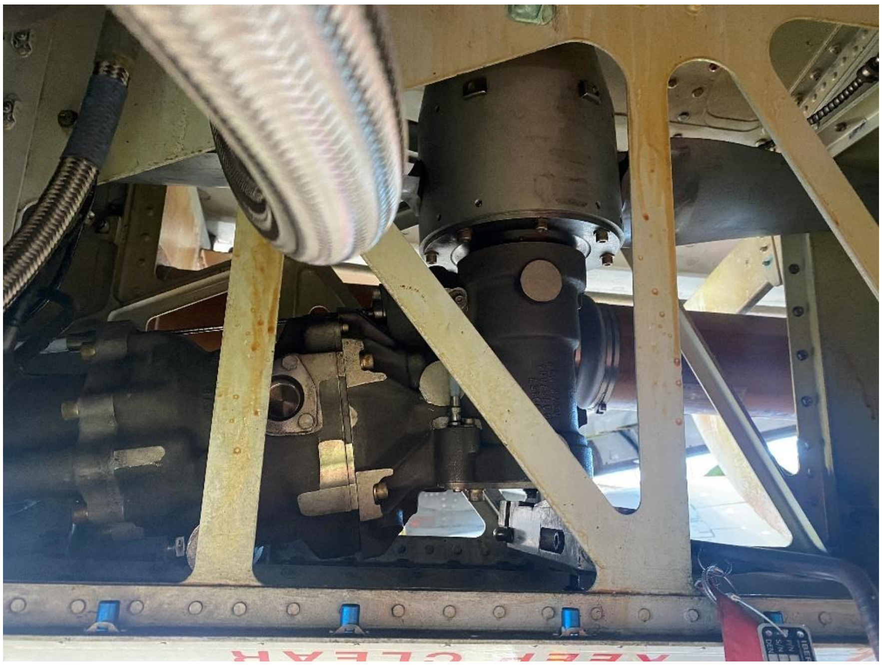


Figure 58 - Inside the RAT of an Airbus A320 (not deployed)

3.2.5 Transformation and conversion devices

The electrical system of an aircraft feeds different loads that work in direct or alternating current with different voltage levels than those obtained in the generation, this requires the availability of devices capable of adjusting the electrical power generated at the different voltage levels. required by electrical loads and busbars. As always working in the standard conditions, already given before.

In addition, we have to take into consideration several devices, such as the transformers and autotransformers, rectifiers and inverters.

Starting with the **transformers and autotransformers,** these devices are widespread throughout the generation and distribution system and their development has largely allowed the widespread use of alternating current in on-board systems.

Continuing with the **rectifiers**, a Transformer Rectifier Unit (TRU) combines the functions of a Transformer and a Rectifier into one unit. In aircraft applications, the TRU converts the 120V AC power generated by the engine or APU generators or provided by a Ground Power Unit (GPU) to 28V DC power for use by various electrical components.

Last but not least, the **inverters**, these devices are responsible for converting direct current from batteries into alternating current at a frequency of 400 Hz.

3.2.6 Location of the generation system

The following figures are showing how all the generation system is being distributed through the aircraft Airbus A320:

Figure 59 - Airbus A320 generation system distribution [40]

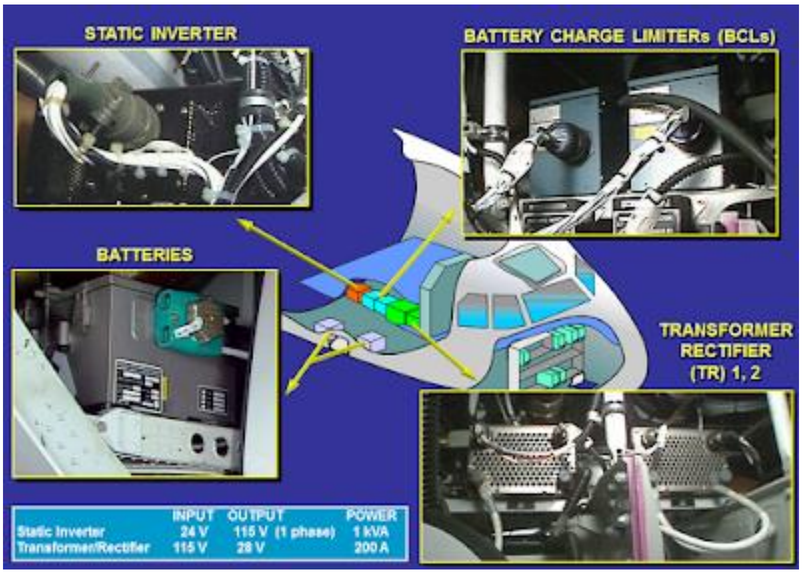


Figure 60 - Airbus A320 generation system distribution next to flightdeck [40]

The static inverter converts the direct current from battery 1 into an AC current if no other source is available. However, the Battery Charge Limiters (BCLs) control the battery coupling and uncoupling to the DC BATTERY BUS to ensure battery charging and protection. Each battery is rated at 24 V with a capacity of 23 Ah when all TRs are identical and interchangeable.

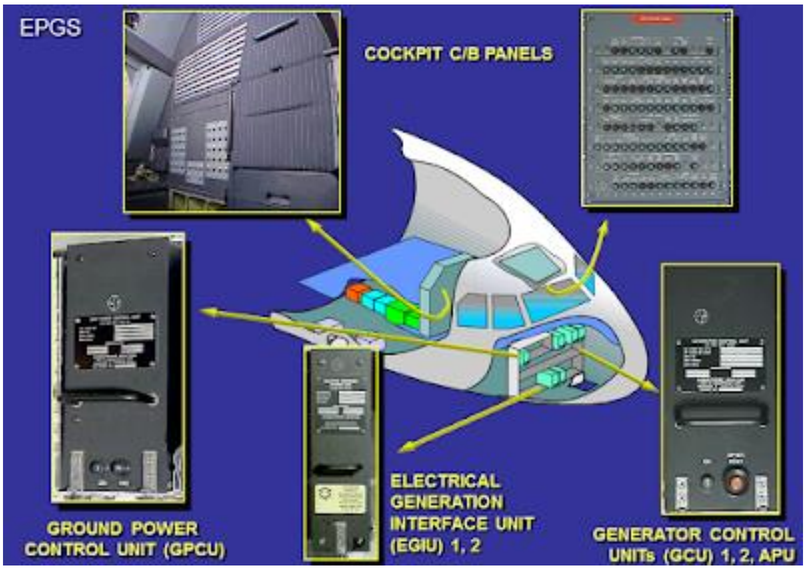


Figure 61 - Airbus A320 generation system distribution EPGS [40]

The Ground Power Control Unit (GPCU) connects the external power to the A/C network if all parameters are within the limits. It is also the central unit connected to the Centralized Fault Display Unit for on-board maintenance purposes. The Electrical Generation Interface Units (EGIU) used by the ECAM to display the AC electrical power parameters when the Generator Control Units (GCUs) protect and control the A/C network and generators and finally the main C/B panels are located in the cockpit.

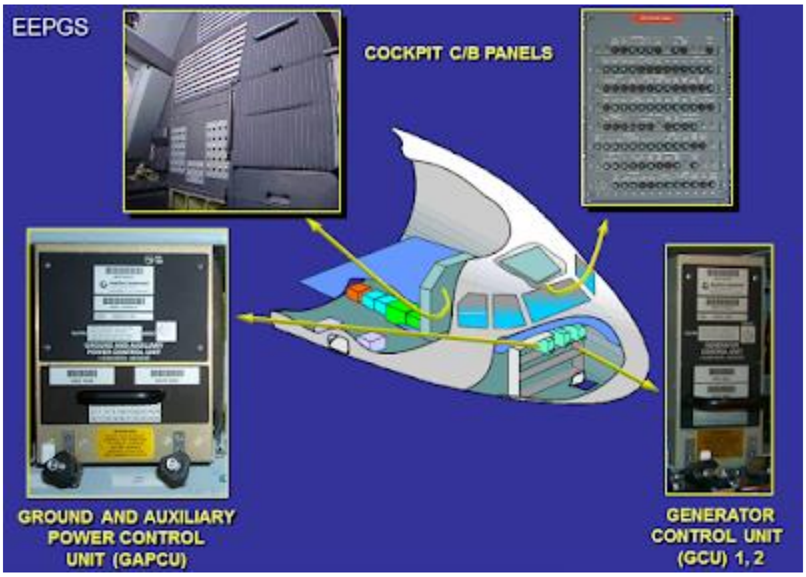


Figure 62 - Airbus A320 generation system distribution of the EEPGS [40]

In the EEPGS, the GPCU is replaced by a Ground and Auxiliary Power Control Unit (GAPCU). The GAPCU controls the APU Gen and the external power channels.

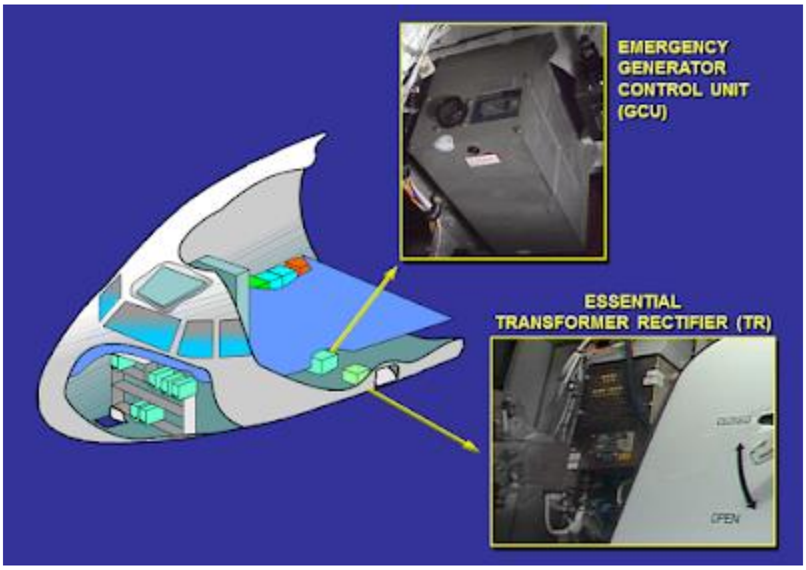


Figure 63 - Airbus A320 generation system of the EGCU [40]

3.3 Distribution system

Going back to figure number 10, where I divided the electrical system scheme into two parts, now let's begin with the second and last one, that is the distribution system.

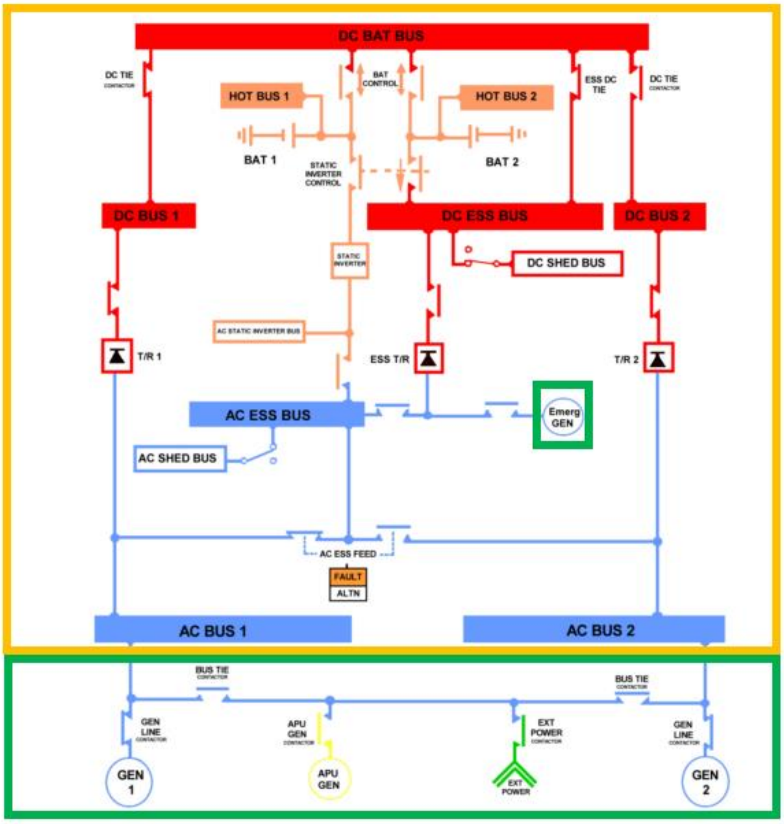


Figure 64 - Electrical system schematic divided in two parts [27]

Distribution system　　Generation system

The distribution system is in charge of transporting the current either in direct or alternating current to the different consuming loads of the system, the distribution of energy in an airplane is carried out by means of distribution bars or collectors, these elements are formed by plates of low impedance copper installed in connection boxes or distribution panels from where the current is distributed to the circuits or other distribution bars.

It is important to remember what was said at the beginning of the thesis and it is that the previous figure is just an idea of how the electrical system is divided. However, the following figure will show more into detail how the distribution system is divided into primary and secondary.

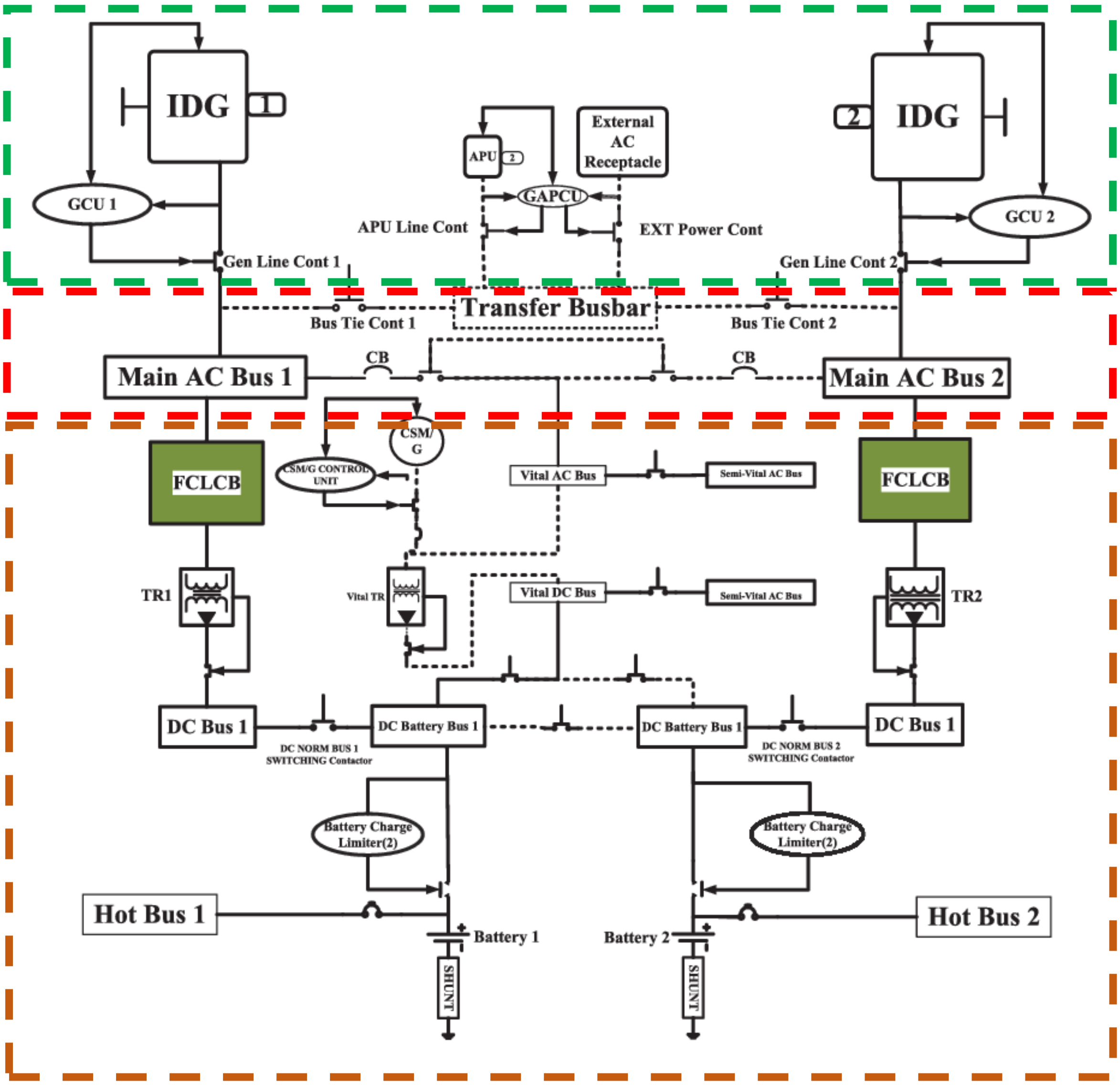


Figure 65 - Division of the electrical system [41]

Generation   Primary distribution   Secondary distribution

In the following page I will summarize the operation of the distribution system of an aircraft with the aim of explaining how the different bars of the system are fed depending on the importance of the services to which they supply energy.

In the first place we have the generation sources that would be the main generators, in our case GEN 1 and GEN 2. These generators are in charge of feeding the main alternating current bars. However, if a fault occurs in one of the two generators or in both, the APU will be activated by closing the corresponding BTB (Bus Tie Breaker) contactor depending on which generator is damaged.

On the other hand, analysing the power supplies in the upper part of the figure, we observe the external power supply, which are fed from the GPU airport power groups and provide power to the aircraft through the main bars to power all the aircraft circuits or service bars responsible for supplying a reduced number of loads when the aircraft is stopped, although these bars can also supply loads that work during the flight, therefore they must be connected in such a way that they can receive power in both situations.

The main alternating current bars in normal conditions are in charge of feeding the essential alternating current bar on which all the essential systems of the airplane that work with alternating current depend. Due to the importance of the equipment dependent on this bus to ensure safe flight, the essential AC bus can also receive power from the RAT emergency generator in the event that the main AC busses are unable to supply power (power failure). the GEN 1, GEN 2 and APU); In the event that the emergency generator cannot feed the essential alternating bar either, the batteries through the inverter are responsible for providing energy. In addition, the main buses also supply non-essential services such as the kitchen and entertainment devices for passengers, but these can stop being supplied automatically or manually from the cabin if necessary due to power requirements.

If the battery bar cannot feed the essential DC bar, it can receive energy from the essential AC bar through the TRU transformation and rectification unit. If it could not be fed in this way, the battery would provide it with energy.

Finally, we have the reserve bars which are those that are dedicated to powering vital equipment. Reserve DC buses connect directly to aircraft batteries, while AC buses can be powered by either the essential AC bus or batteries.

So, to conclude with how it actually works, we must acknowledge one important concept, and it is basically how the distribution system is divided. We can find two main parts, the primary and secondary one.

	AC BUS 1	AC BUS 2	AC ESS BUS	AC SHED ESS	AC STAT INV	TR1	TR2	ESS TR	DC BUS 1	DC BUS 2	DC BAT BUS	DC ESS BUS	DC SHED ESS	HOT BUS 1	HOT BUS 2
NORM CONF	GEN1	GEN2	GEN1	GEN1	–	GEN1	GEN2	–	TR1 GEN1	TR2 GEN2	TR1 GEN1	TR1 GEN1	TR1 GEN1	BAT1	BAT2
ONE GEN INOP AVAIL X (1,2 or APU)	GENX	GENX	GENX	GENX	–	GENX	GENX	–	TR1 GENX	TR2 GENX	TR1 GENX	TR1 GENX	TR1 GENX	BAT1	BAT2
EMER CONF · BEFORE EMER GEN AVAILABILITY (about 8 sec)	–	–	ST INV BAT1	–	ST INV BAT1	–	–	–	–	–	–	BAT2	–	BAT1	BAT2
· EMER GEN RUNNING	–	–	EMER GEN	EMER GEN	–	–	–	EMER GEN	–	–	–	ESS TR EMER GEN	ESS TR EMER GEN	BAT1	BAT2
TR1 FAULT	GEN1	GEN2	GEN1	GEN1	–	–	GEN2	GEN1	TR2 GEN2	TR2 GEN2	TR2 GEN2	ESS TR GEN1	ESS TR GEN1	BAT1	BAT2
TR2 FAULT	GEN1	GEN2	GEN1	GEN1	–	GEN1	–	GEN1	TR1 GEN1	TR1 GEN1	TR1 GEN1	ESS TR GEN1	ESS TR GEN1	BAT1	BAT2
TR1 + 2 FAULT	GEN1	GEN2	GEN1	GEN1	–	–	–	GEN1	–	–	–	ESS – TR GEN1	ESS – TR GEN1	BAT1	BAT2

ON GROUND BAT. ONLY	AC BUS 1	AC BUS 2	AC ESS BUS	AC SHED ESS	AC STAT INV	TR1	TR2	ESS TR	DC BUS 1	DC BUS 2	DC BAT BUS	DC ESS BUS	DC SHED ESS	HOT BUS 1	HOT BUS 2
Speed > 100kt	–	–	EMER GEN	EMER GEN	–	–	–	EMER GEN	–	–	–	ESS TR EMER GEN	ESS TR EMER GEN	BAT1	BAT2
rat stall or 50 kt ≤ speed ≤100 kt	–	–	ST INV BAT1	–	ST INV BAT1	–	–	–	–	–	BAT 1-2	BAT2	–	BAT1	BAT2
speed < 50 kt	–	–	–	–	ST INV BAT1	–	–	–	–	–	BAT 1-2	BAT2	–	BAT1	BAT2

Figure 66 - Distribution table of an Airbus A320 [12]

3.3.1 Primary distribution

The primary distribution system is the first link between the generation system and the consuming loads, the output of the generation sources is carried through conductors called feeder or feeders to the main current distribution bars. alternate. The primary distribution is responsible for the management and distribution of energy from the primary generators (alternators), the auxiliary generators (APU and GPU) and also the RAT emergency generators or Backup generators. The entire electrical system of the aircraft starts from the primary distribution, feeding the loads of great consumption, different alternating current bars and the transformation and conversion units to provide energy to the system's direct current circuits.

The primary distribution also includes all the contactors responsible for switching and configuring the system status, such as the main generator contactors, the BTB bus link contactors, and the APU power unit and external GPU contactors. To control the contactors, it is usually done automatically through the GCU generator control units and the BPCU/ECMU electrical system operation control units, which work together to determine the opening/closing of these in each situation. Specifically, the BPCU controls the operation of the two BTB junction switches. The BTBs allow the left and right buses to connect to each other in the event of a left or right main generator failure. In addition, they also allow power from the APU or ground power supply to be switched to the main AC bars.

3.3.2 Secondary distribution

The secondary distribution system is responsible for distributing the power from the primary distribution system to the different alternating current bars (essential bars, reserve bars...) and transformation and conversion devices such as the TRU transformation and rectification units to feed all the system direct current bars. This system is associated with both direct and alternating current circuits with medium and high consumption, but always lower than those that make up the primary distribution. The secondary distribution system is capable of self-configuring its status depending on the general status of the electrical system and which generation sources are operational at all times, for this it uses switching elements such as contactors or relays whose operation It is similar to that of the contactors responsible for distributing the current flow to the bars and loads that need power.

As in the case of primary distribution, all the elements that make up the secondary distribution (busbars, relays, protection devices...) are installed in panels or cabinets located in the electrical and electronic equipment compartment. The only exception is those protection devices, normally thermal circuit breakers that do not have remote control and cannot be remotely monitored, in these cases they must be installed in the cockpit to be supervised.

3.3.3 Control unities

All aircraft, including the Airbus A320 have the distribution bars through all the generator suppliers between them to switch the power flows in the appropriate way in each operation will depend on each type of aircraft and the architecture of its electrical system.

In current aircraft, the contactors and relays responsible for the interconnection between bars are managed by electronic units that allow global and automatic control of the entire electrical system. These control units are based on computers (microprocessors) and have replaced the complex logic relay circuits that were previously responsible for managing the contactors, making operation more efficient and, above all, automating it.

We need to highlight that the control unit system has several other main functions, such as, control the connection and disconnection between generators and distribution bars or detect the absence of current in the distribution bars. However, they also send all this information into the ECAM of the aircraft to follow its maintenance just in emergency [14-15].

3.3.4 Location of the distribution devices

Within the distribution system there are two configurations that determine the location of the cabinets or panels where the primary and secondary distribution elements are located, as well as other elements such as batteries or transformation and rectification units.

One would be the centralized (a), where it is characterized by being a point-to-point distribution system, it is made up of a single main distribution centre located in the front area of the aircraft. However, there is also a more distributed one or better said, decentralized (b), which is not used in the Airbus A320. In this configuration, the primary and secondary distribution panels are no longer installed in the same compartment but are distributed throughout different areas of the aircraft.

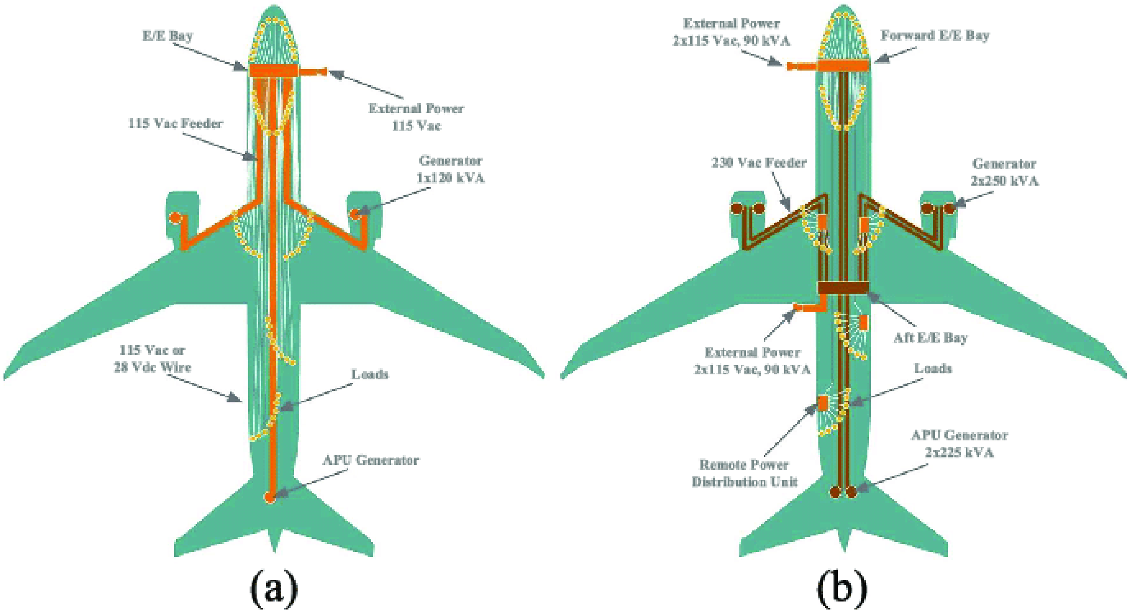


Figure 67 – Two types of distribution of an aircraft [41]

3.3.5 Conductors

The conductors constitute the skeleton of the electrical distribution system of an aircraft, they are responsible for transporting electrical energy or other types of signals such as data signals from the generators or sources to the loads and receivers.

The power distribution conductors used in an aircraft must have some technical characteristics that are common regardless of where they are installed.

Going back to one of the certifications, especially the MIL STD-704 which explains which are the values of the nominal voltage. The following table shows the values:

Table 2 - Maximum current drop for AC and DC circuits

NOMINAL VOLTAGE	CONTINUOUS REGIM	DISCONTINUOUS REGIM
28 V (DC)	3,5% -> 1V	7% -> 2V
115 V (CA)	3,5% -> 4V	7% -> 8V
200 V (CA)	3,5% -> 7V	7% -> 14V

The working conditions in which the drivers of an airplane operate are very diverse, from its design it is essential to determine which routes will be followed and the work atmosphere to which they will be exposed in order to choose the driver that best suits them. adapts to the needs and facilitates inspection and maintenance tasks. The most frequent conditions to which drivers are subjected on an aircraft are listed below. These conditions are included in the MIL-STD-810 standard and may be applicable to many electrical equipment on board the aircraft.

This main working conditions that may affect depending on the environment are:

- Humidity
- Vibrations
- Temperature variations
- Pollution
- Electromagnetic interferences

All conductors can be made out of barely any material, however, it is important that some of them have more advantages than others, such as copper and aluminium. Copper is an element of great conductivity and ductility in addition to offering great resistance to mechanical traction, for its part, aluminium has lower conductivity and less resistance to mechanical traction, so its use is not allowed in areas of high vibration and will never be used in conductors with a small section, as it has advantages that it is lighter and cheaper.

The vast majority of conductors installed on aircraft are made up of tin-coated copper wires. However, silver or nickel can provide better behaviour at high temperatures and prevent oxidation that can form between the contact surfaces and that limit the flow of electric current. Aluminium conductors are used when the connection distances are large and so are the sections in order to avoid breakage of the conductor due to vibration.

An important aspect is that for tinned copper conductors, the MIL-W-22759 and MIL-W-5086 standards apply, for aluminium the MIL-W-7072 standard is used.

The following values are normalized for standards use of conductors:

Copper:

- $\rho = 1.724 \cdot 10^{-2}\ \Omega mm^2 / m$
- $\alpha = 3.93 \cdot 10^{-3}$ degrees C^{-1}

Aluminium:

- $\rho = 2.826 \cdot 10^{-2}\ \Omega mm^2 / m$
- $\alpha = 4.03 \cdot 10^{-3}$ degrees C^{-1}

In aviation, the standard used to measure sections is the American AWG (American Wire Gauge) [16].

The sections range from 0000, which is the largest, to 40. In the case of copper conductors, the use of AWG sections less than 20 is not recommended since they do not offer security in terms of mechanical resistance, for aluminium conductors. the use of AWG sections less than 8 and their installation in areas exposed to corrosive fumes, strong vibrations or where there is a frequent need to connect and disconnect conductors is not recommended. The largest sections used in aviation are 2 AWG in copper and 0 AWG in aluminium. If larger sections are required, certification by the competent bodies is necessary [17].

For example, Airbus does not use conductors with a section smaller than 26 AWG and 24 AWG, respectively.

Table 3 - Section AWG

<table>
<tr><th>AWG</th><th>DIAMETER (mm)</th><th>SECTION (mm^2)</th><th>UNE SECTION (mm^2)</th><th>APLICATION TYPE</th></tr>
<tr><td>22</td><td>0.64</td><td>0.33</td><td rowspan="3">1</td><td rowspan="2">LOW POWER CHARGES</td></tr>
<tr><td>20</td><td>0.8</td><td>0.5</td></tr>
<tr><td>18</td><td>1</td><td>0.8</td><td rowspan="2">MEDIUM POWER CHARGES</td></tr>
<tr><td>16</td><td>1.29</td><td>1.3</td><td>1.5</td></tr>
<tr><td>14</td><td>1.63</td><td>2.1</td><td>2.5</td><td rowspan="2">SECONDARY DISTRIBUTION</td></tr>
<tr><td>12</td><td>2.05</td><td>3.3</td><td>4</td></tr>
<tr><td>10</td><td>2.6</td><td>5.26</td><td>6</td><td rowspan="10">PRIMARY DISTRIBUTION</td></tr>
<tr><td>8</td><td>3.26</td><td>8.37</td><td>10</td></tr>
<tr><td>6</td><td>4.1</td><td>13.3</td><td>16</td></tr>
<tr><td>4</td><td>5.2</td><td>21.15</td><td>25</td></tr>
<tr><td>2</td><td>6.54</td><td>33.6</td><td>35</td></tr>
<tr><td>1</td><td>7.35</td><td>42.4</td><td>50</td></tr>
<tr><td>0</td><td>8.25</td><td>53.5</td><td rowspan="2">70</td></tr>
<tr><td>00</td><td>9.27</td><td>67.4</td></tr>
<tr><td>000</td><td>10.4</td><td>85</td><td rowspan="2">120</td></tr>
<tr><td>0000</td><td>11.7</td><td>107</td></tr>
</table>

We can find two main effects that modify the material resistivity depending on the frequency:

- Skin effect
- Proximity effect

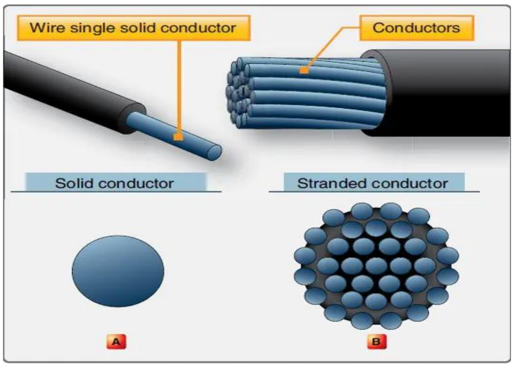


Figure 68 - Wiring types [27]

The current regulation proposes a modification of the resistivity as a function of these two effects, all equations extracted from the same bibliography [27]:

$$\rho'_t = \rho_t(1 + Yc + Yp) \quad (18)$$

$$Yc = \frac{x^4{}_c}{192+0.8x^4{}_c} \quad (19)$$

$$Yp = \frac{2.9x^4{}_p}{192+0.8x^4{}_p}\left(\frac{d}{D}\right)^2 \quad (20)$$

$$x^2{}_c = \frac{8\pi sf\cdot 10^{-7}}{\rho_t}\,kc \quad (21)$$

$$x^2{}_p = \frac{8\pi sf \cdot 10^{-7}}{\rho_t} kp \quad (22)$$

D = distance between conductors

d = diameter [mm]

s = section [mm]

f = frequency [Hz]

kc (skin) and kp (proximity) = constant values depending on conductor (follow table 4)

Table 4 - Recommended values for Kc and Kp

RECOMMENDED VALUES OF KC AND KP				
Conductor construction	**Coating on strands**	**Treatment**	**Kc**	**Kp**
Concentric round	None	None	1	1
Concentric round	Tin or alloy	None	1	1
Concentric round	None	Yes	1	0.8
Compact round	None	Yes	1	0.6
Compact segmental	None	None	0.435	0.6
Compact segmental	Tin or alloy	None	0.5	0.7
Compact segmental	None	Yes	0.435	0.37
Compact sector	None	Yes	1	(Check note)

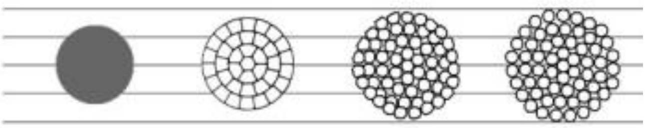


Figure 69 - Types of conductor construction [27]

3.3.5.1 Section calculation according to F.A.A

For the calculation of sections according to the F.A.A, a series of initial data must be obtained, such as:

- Line data:
  - Line voltage type:
    - In AC single-phase 115V. Three-phase and two-phase 200V.
    - In DC single-phase 28V.

- Charge data:
  - Power and intensity consumption.
  - Load service time.
  - Power factor.

- Environmental conditions:
  - Installation form.

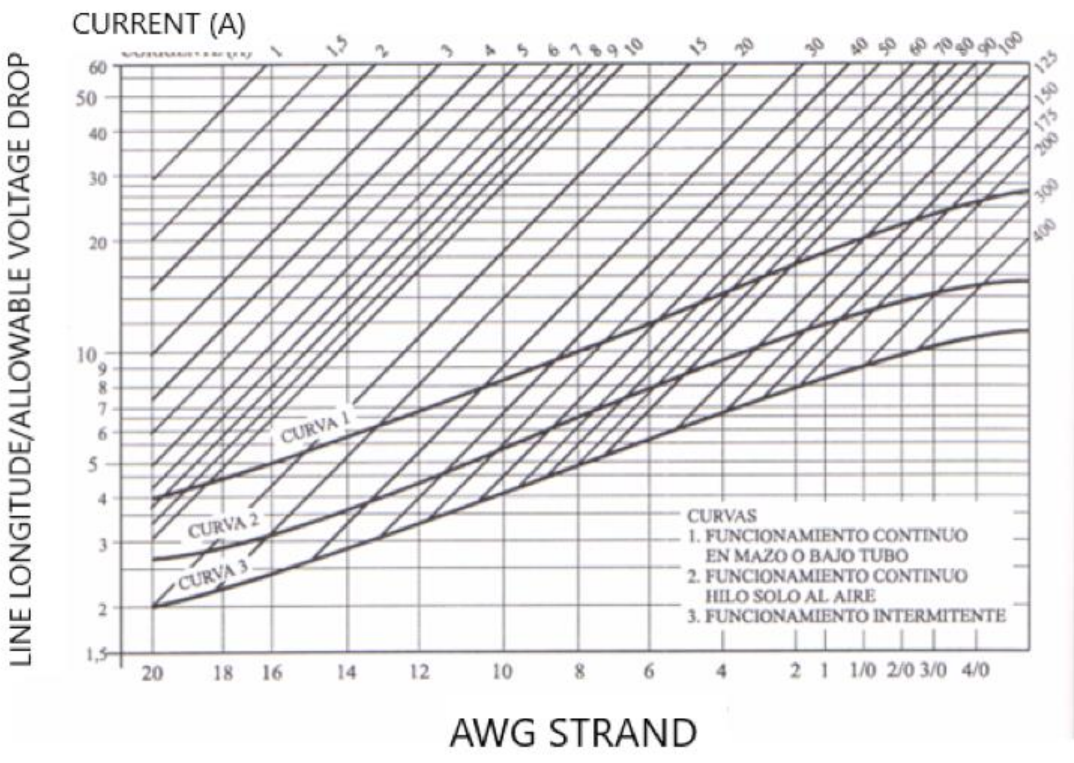


Figure 70 - Plot for the section calculation according to FAA [14]

Important to note, that this graph was found in Spanish, so 'curva 1', 'curva 2' and 'curva 3' stands for curve 1, curve 2 and curve 3 respectively.

The meaning of each curve stands for:

- Curve 1: continuous operation in bundle or under tube.
- Curve 2: continuous operation with strand on air.
- Curve 3: blinking operation.

To solve this method, it is important to follow figure number 62. In the first place, the type of curve (1, 2 or 3) is chosen depending on the type of installation, then the current values that the line will carry and the length/max ratio are known. admissible voltage drops (m/ΔVmax) on the ordinate axis, the cut-off point is obtained.

If the cut-off point obtained is above the chosen curve, then it is projected on the abscissa axis and the AWG section indicated just to the right is selected. Thus, the most restrictive criterion is the maximum voltage drop.

In the case in which the projection of the ratio (m/ ΔVmax) intersects the chosen curve before the intensity straight line, then said point is projected on the abscissa axis and the value of the immediately superior section is selected, in this case, the most restrictive criterion is that of maximum admissible intensity.

3.3.5.2 Section calculation according to MIL-1-5088

For the calculation of sections according to the MIL-1-5088, a series of initial data must be obtained, such as:

- Line data:
  - Line voltage type:
    - In AC single-phase 115V. Three-phase and two-phase 200V.
    - In DC single-phase 28V.

- Charge data:
  - Power and intensity consumption.
  - Power factor.

- Environmental conditions:
  - Installation form.

In this method, the criteria of maximum allowable voltage drop and maximum current must be met separately. First, a section S1 is calculated from the current or power data, as is done in a common installation. Once obtained, it is chosen. the AWG section immediately above the calculated one. In this way we obtain a section according to the criterion of maximum admissible voltage drop.

Next, a section S2 is calculated according to the criterion of maximum admissible intensity, for this a factor is taken into account that does not exist in an installation on land, such as altitude, an installation at height can present cooling problems due to the low density of the air and the inability to dissipate the heat by the machines or in this case the conductors, if we add to this that many of the lines are grouped in bundles, the problem is accentuated.

The following three graphics will show how the temperature rises up in each section AWG depending on the current.

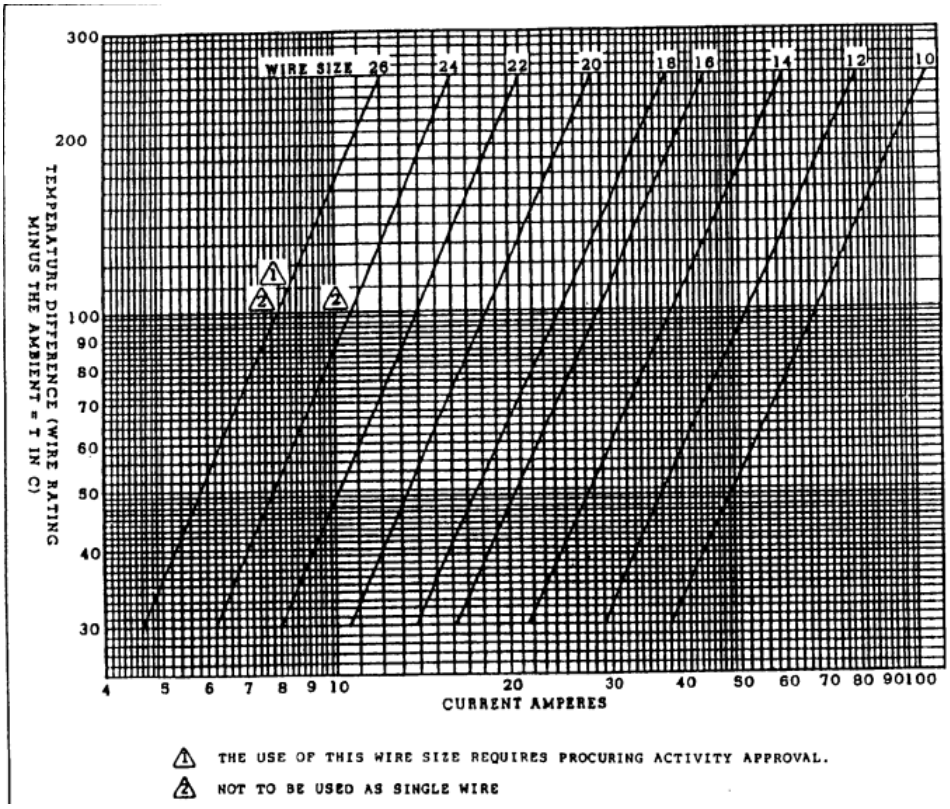


Figure 71 - Single copper wore om free air [3]

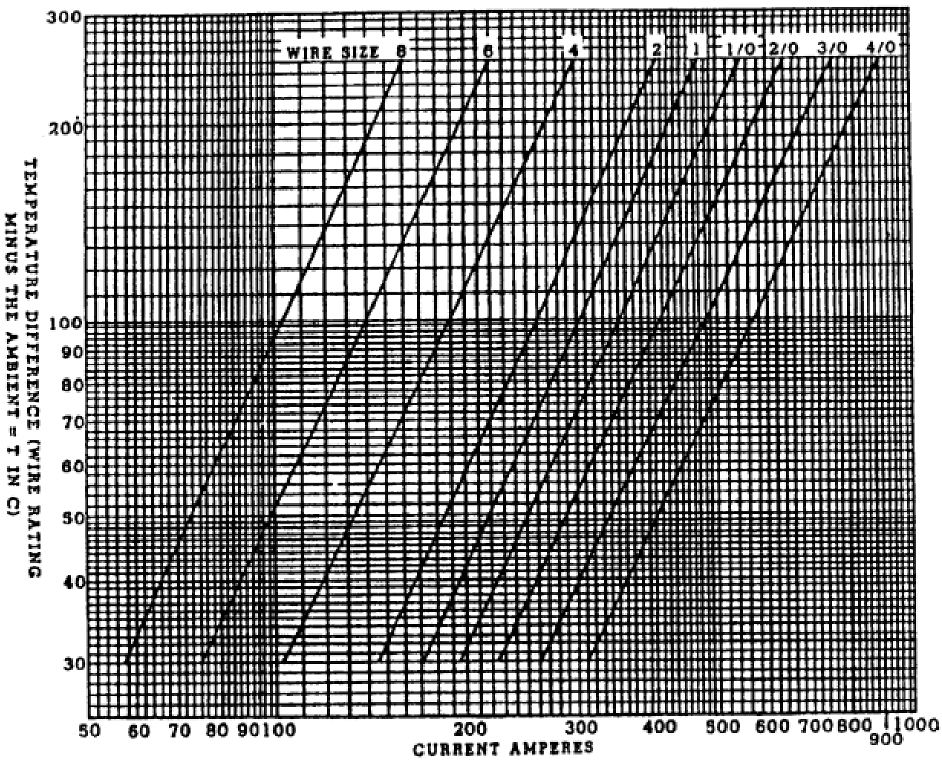


Figure 72 - Single copper wire in free air – continued [3]

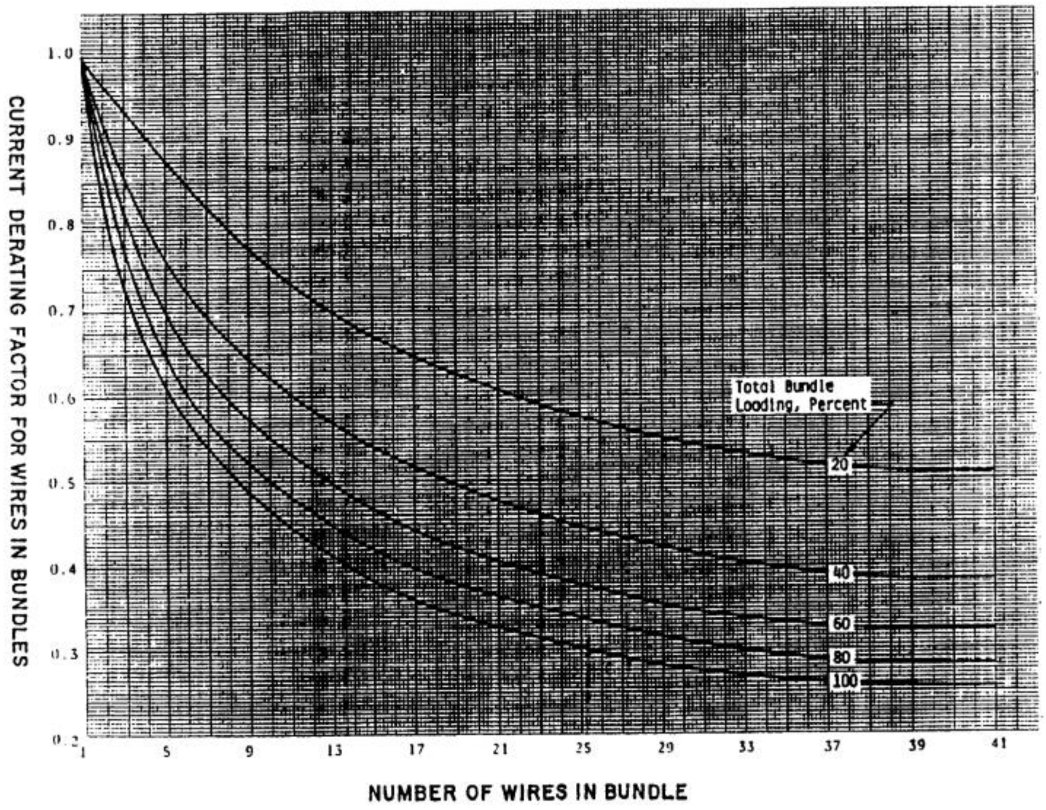


Figure 73 – Bundle derating curves [3]

With the two correction factors, the actual current value flowing through the conductor can be calculated Ieq with the following equation:

$$Ieq = \frac{I}{Km \cdot Ka} \text{ [A] (23)}$$

The equivalent current value allows us to use the graphs given before. The value of the AWG section is obtained from the resulting cut-off point between the increase in temperature (axis of ordinates) that is defined by the maximum temperature that the insulation of the conductor can withstand without losing its properties and the equivalent current calculated. In any case, the section immediately above that obtained by the cut-off point will be taken as the valid section in the event that it does not coincide on one of the section straight lines.

Finally obtained S1 and S2, the one that is greater of the two will be chosen as the definitive section.

Despite all these calculations, it is important to identify the conductors, such as MIL-W-5088-L includes a fairly clear methodology that is used by many manufacturers of aeronautical material. The method for coding conductors according to this standard is detailed below and in which it is necessary to determine:

- Number of unities
- Functional category
- Line section
- Conductor section

- Material of the conductor
- Special categories
- Conductor function
- Number of conductor's order

The following figure is a perfect example on how it is determined:

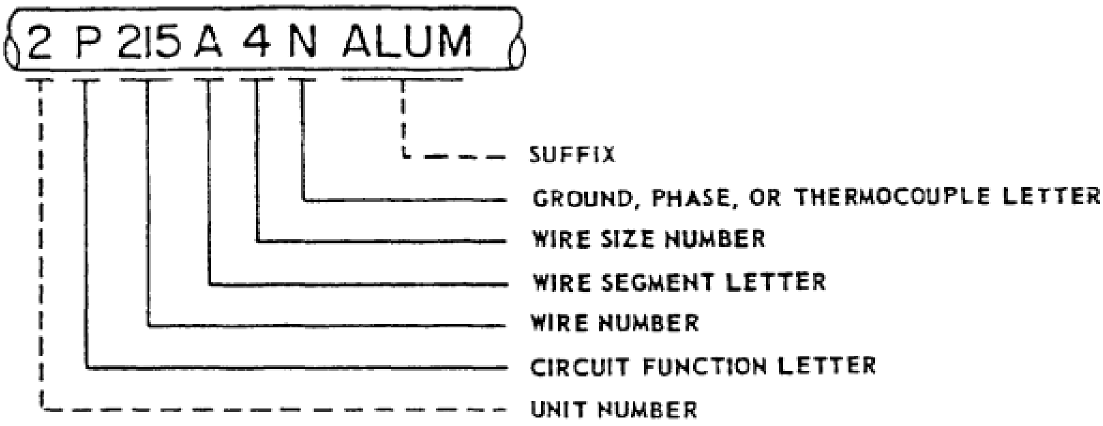


Figure 74 - Codification example [3]

3.3.5.3 Non-electric conductors

Apart from the conductors dedicated to the transport of electrical power on the plane, there are other types dedicated to the transport of different data signals, such as coaxial cables, thermocouples or specific conductors.

3.3.6 Protection devices

The main objective of the protection devices is to avoid damage due to overheating that can affect the conductors, if an abnormal situation occurs such as a very high current and it is not detected and corrected, the insulation of the conductor can melt. causing damage to nearby circuits and equipment or even causing a fire inside the aircraft. Such as the circuit breaker (CB) explained before.

3.4 Electrical load analysis

Electrical Load Analysis (ELA) is a record of the current state of an aircraft's electrical load, that is the individual and cumulative load an aircraft's systems place on the aircraft's power sources such as the APU, RAT even including engines, under various phases of flight and operational conditions.

A current Electrical Load Analysis (ELA) is used to demonstrate compliance with CFR 25.1351, AC 43.13-1B and FAA, Order 8300.16A for carriers who operate in or enter the US (and are therefore subject to FAA regulations). However, in Europe we have the EASA obligations and various CASAs (Civil Aviation Safety Authorities) [18].

It is important to note that the ELA is allowing the evaluation of the electrical system capacity required to supply different necessities of electrical loads, such as AC and DC loads. This is achieved by evaluating and calculating operational and maximum electrical values in different flight phases and this calculation allows to ensure different aircrafts equipment's to work properly. Aircrafts manufactures, such as Airbus, give the baseline ELA data for operators to calculate and maintain the numbers [19].

3.4.1 ELA calculations

The ELA calculations must be one, as said before, in different flight phases because the electrical loads are different depending on the phases of the flight, all being defined by EASA 2017 regulations.

The ground phase is defined by when all wheels are in ground contact, without the engines running and connected to the GPU or APU. After the ground phase we still have eight more phase to take into account:

- **Start phase** is from the start up when pushback is done to the start of roll.
- **Roll phase** begins when the aircraft is leaving the parking stand into the taxiing, to runways and finally the take-off roll. The roll last until the landing gear is not up.
- **Take-off phase** the moment when the aircraft rises from the surfaces and last altitude of 1500 feet.
- **Climb** starts above 1500 feet and ending in aircraft cruise level.
- **Cruise phase** is from the end of climb until the start of descent. This is the longest electrical consumption during the flight, which means it is the highest number consumption, from coffee makers to ovens.
- **Descent phase** start when aircraft leaves the cruising altitude and ends at 800 feet.
- **Landing phase** commences at 800 feet when landing gear is down until the touchdown and rollout.
- **Taxi phase** is from touchdown to the moment when the engines are not running anymore and the aircraft is on stand.

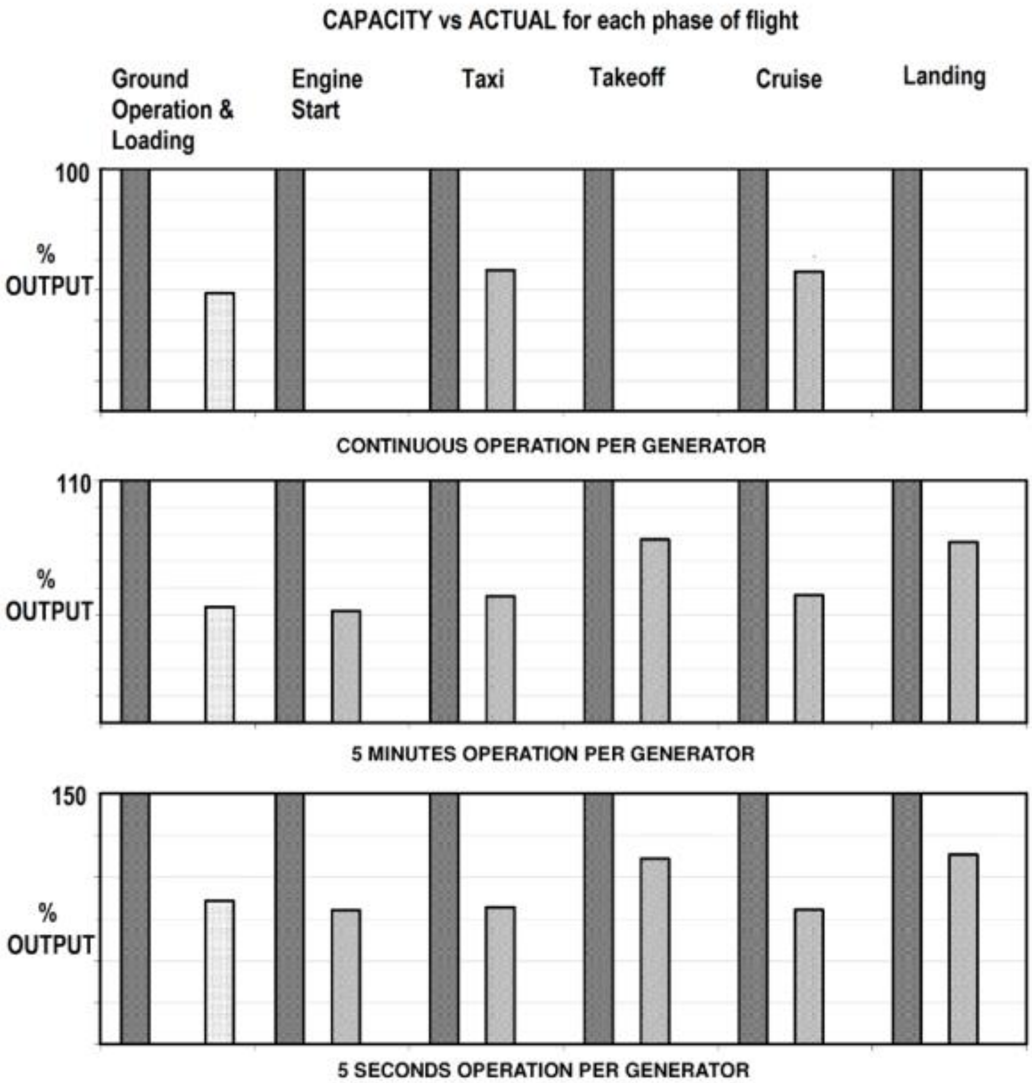


Figure 75 - ELA comparison in general aviation [3]

ELA analysis is achieved by evaluating and calculating operational and maximum values in different flight phases. A calculation method must be used to evaluate post-delivery modifications, such as Airbus service bulletin (SB), to confirm that the new modification will be within the limits of electrical power sources and network capabilities.

In our case, the Airbus A320 is divided in three important levels:

- Power source level.
- Distribution level.
- Converter level.

3.4.2 ELA maintenance solutions

There are three important solutions for ELA maintenance. The aircraft maintenance in general has a huge importance in aviation.

These three solutions are:

1. Outsource.
2. Adopt the spreadsheet approach.
3. Use of an industry solution.

On the one hand outsourcing all modifications delegates the effort to MROs and services firms with proven capabilities. For the airlines that use multiple mod vendors, especially STC mods, coordination between vendors can become an issue. However, the cost and effort for an MRO to revise a customer's ELA can be material. Regardless, responsibility remains with the operator to verify the ELA.

On the other hand, using spreadsheets is really practical for operators with single fleet, for example here in Spain Vueling or another solution could be if there were a large number of electrical engineers in the fleet.

Finally, the ELA manager should standardize and simplify the aircraft ELA maintenance.

4. Development of a numerical simulation model of the electrical system of an aircraft

Nowadays, having a more common-sensed or also called practical explanation of any topic, even this one, engineering is really important for a better understanding. In this case, the electrical system of an aircraft made on MATLAB.

Until now we have understood how the electrical system of an aircraft works, in detail, how the Airbus A320 electrical system works. In this part I will create a MATLAB model based on one already existing one named 'power_aircraft_distribution'.

The electrical system can be divided into four important sections: power sources, power distribution, power conversion, and electrical loads. Beginning with where does the power come from to where this power goes to and finally how this power is distributed. All this concept easily seen in the following figure.

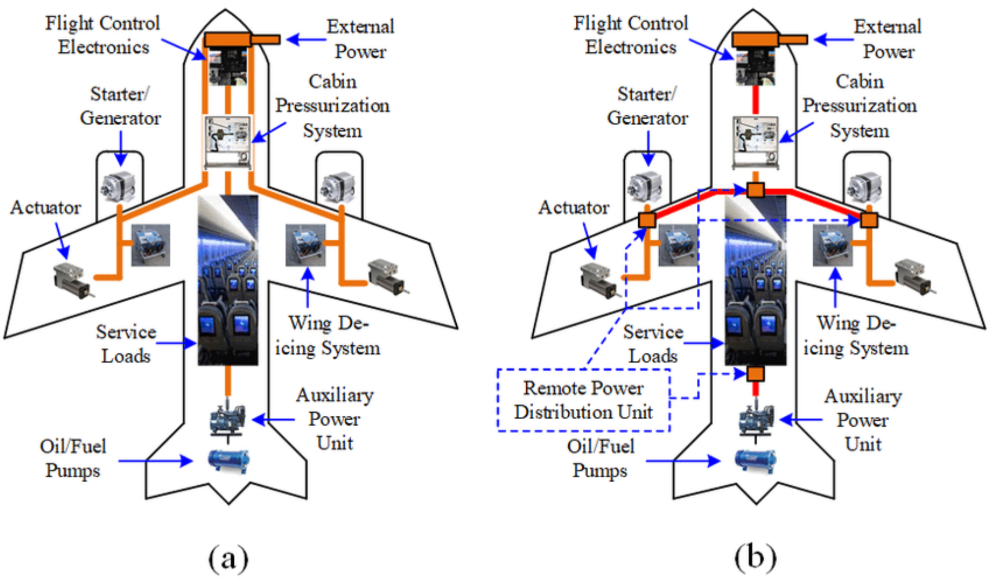


Figure 76 - Typical electrical power flow schematic

(WEDDLE, 1976)

One of the goals in designing and developing this toolset is to make it available and user-friendly the understanding the A320 electrical system.

The MATLAB/Simulink was chosen because of its availability and its capability. It has a wide user base that spans students to professional engineers. It allows the creation of graphical overlays, warnings, and help files for each component model, which are intended to help guide the user in making a model and running a successful simulation. Indeed, this program allows me to simulate different conditions of this system and also for future students related to the aviation engineering.

4.1 Base model

As mentioned before, the base model that I will be working on is the MATLAB file named 'power_aircraft_distribution' an already existing file for a basic electrical system. This file will be tried to be adapted into an Airbus A320 electrical system.

The following figure shows the Simulink of this file:

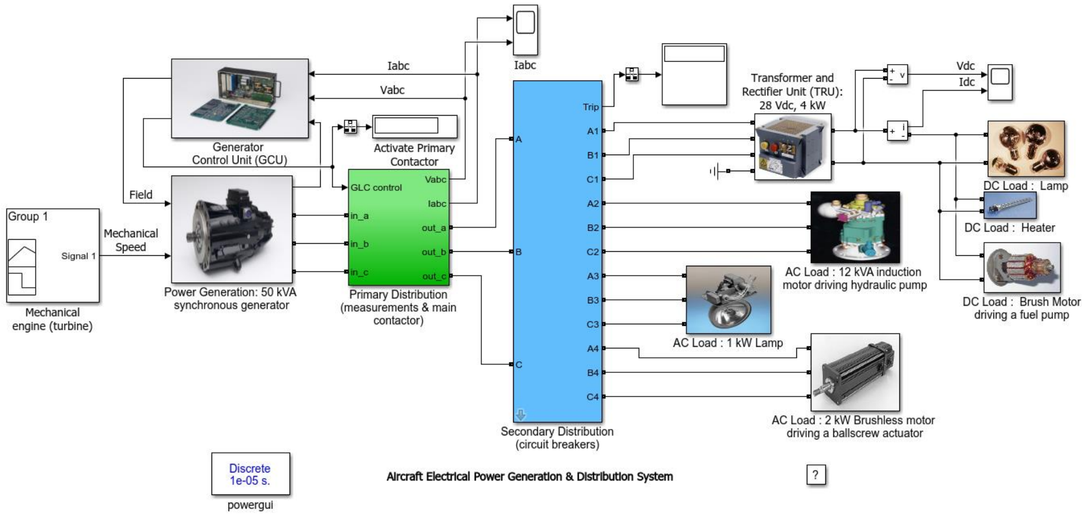


Figure 77 - Power_aircraft_distribution file on MATLAB

This example shows an aircraft electrical power generation and distribution system. The AC power frequency is variable and depends of the engine speed.

This system is being composed by 6 main sections:

- The first section represents the generator mechanical drive and is modelled by a simple signal builder, which provides the mechanical speed of the engine shaft.

- The second section represents the power AC generator. It is composed of a modified version of the simplified synchronous machine. The mechanical input of the modified machine of 50 kW is the engine speed. The Generator Control Unit regulates the voltage of the generator to 200 volts line to line.

- The third section represents the Primary Distribution system. It is composed of three current and voltage sensors. There is also a 3-phase contactor controlled by the Generator Control Unit. Finally, a parasitic resistive load is required to avoid numerical oscillations.

- The fourth section represents the secondary Power Distribution system. It is represented by 4 circuit breakers with adjustable current trip.

- The fifth section represents the AC loads. There is a 4 kW Transformer and Rectifier Unit (which supplies 28 Vdc), a 12-kW induction machine (motor driving a pump), a 1 kW resistive load (lamps) and a 3 hp simplified (using an average value inverter) brushless DC drive (motor driving a ball screw actuator).

- Finally, the last section represents the DC loads. There are two resistive loads (heater and lamp) and a 300 W DC brush motor (motor driving a fuel pump).

4.1.1 Components of the base model

All components for this base model are important, however, some of them depend from another. In this case I will manage to explain from the prioritized until the last.

Not including the scopes, displays, block parameters and main transitions in the main layout, I have divided each segment in different parts.

4.1.1.1 Mechanical engine

This first block, is as simple as a signal builder. It allows to directly inject the speed inserting a value into the plot given.

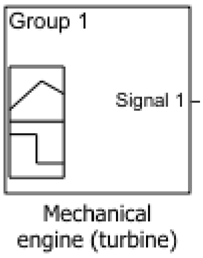


Figure 78 - Mechanical engine turbine block in MATLAB

This block releases a mechanical speed into the next block, which is the power generation.

4.1.1.2 Power generation

The following block is the power generation, exactly a 50 kVA synchronous generator which is being fed with mechanical speed and field into the primary distribution block.

Figure 79 - Power generation block in MATLAB

This block is composed under the mask with a Simplified Synchronous Machine SI Units (SSM). This subsystem is being composed by:

- Field voltage.
- Mechanical speed.
- SSM.
- Permanent magnet generator (PMG).
- Rate transition.
- Scope.

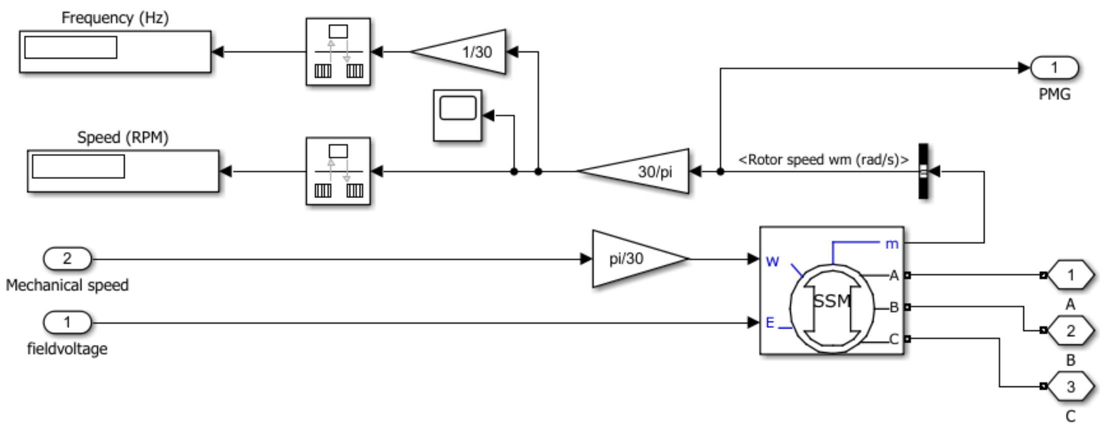


Figure 80 - Under the mask of the power generation

This block has a field, which comes from the Generator Control Unit (GCU).

4.1.1.3 Generator Control Unit

The generator control unit (GCU) is more commonly found on turbine power aircraft. The most basic generator control units perform a number of functions related to the regulation, sensing, and protection of the DC generation system. In this case, this block gives the field into the power generation block and receives the current and voltage.

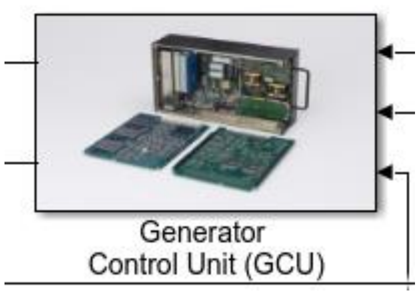


Figure 81 - GCU block in MATLAB

This subsystem is being composed by:

- Block parameter: excitation system.
- Released field voltage.
- Released Global Load Control (GLC).
- Relay.
- PMG input.
- Current sensing input.
- Voltage sensing input.

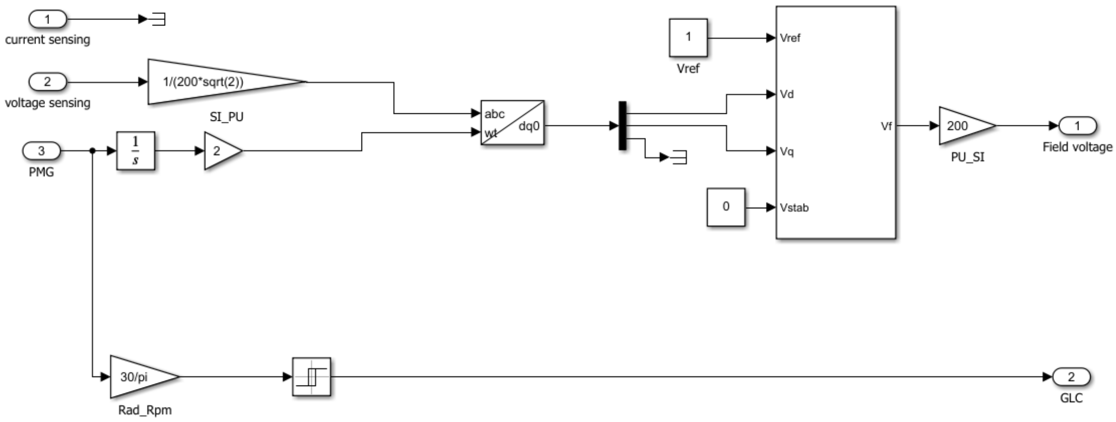


Figure 82 - Under the mask of the GCU

This block and the previous one is connected into the primary distribution system.

4.1.1.4 Primary distribution

The distribution systems used in modern aircraft create a complexity that impacts power system design, physical layout of components, wire routing, and wire selection. In this case, the primary distribution block receives the GLC, 3 Physical Modelling Connection (PMC) input ports, the current and voltage output and finally the PMC output ports.

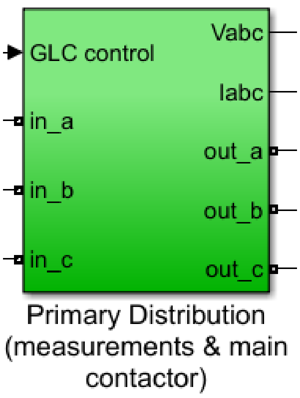


Figure 83 - Primary distribution block in MATLAB

This subsystem is being composed by:

- 3 PMC input ports.
- 3 PMC output ports.
- Parasitic resistive load.
- GLC control.
- Voltage block parameter.
- Current volt parameter.
- POR and CTA block parameter.

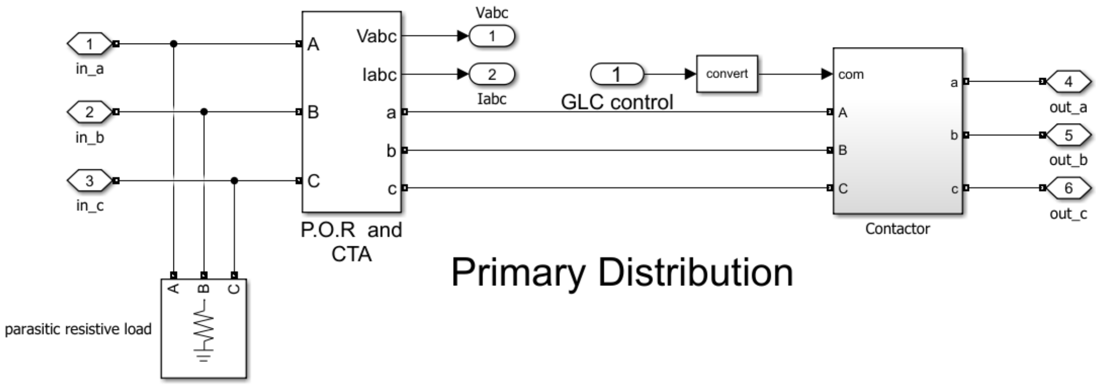


Figure 84 - Under the mask of the primary distribution

Continuing with this block, it has several outputs going into the secondary distribution block, which are related to the circuit brakers.

4.1.1.5 Secondary distribution

Same as the previous block, the distribution systems used in modern aircraft create a complexity that impacts power system design, physical layout of components, wire routing, and wire selection. However, in this situation we receive the inputs related to the PMCs and 13 outputs directly into the aircraft necessities, such as, the AC loads, DC loads, and the Transformer and Rectifier Unit (TRU).

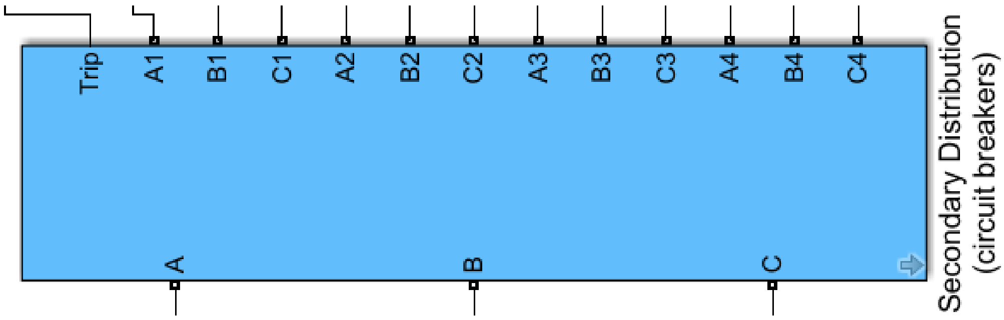
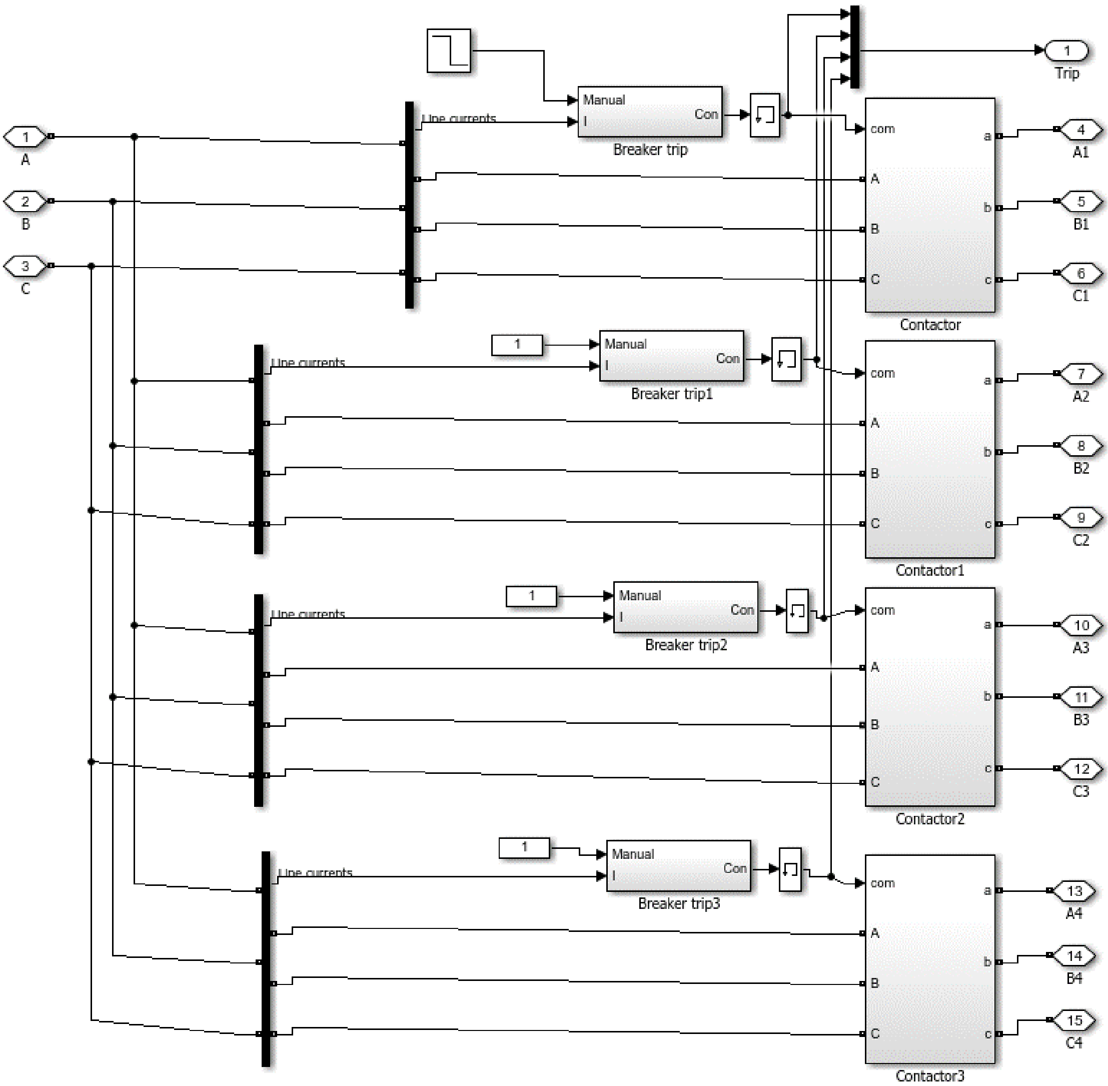


Figure 85 - Secondary distribution block in MATLAB

This is the main and most detailed block in this file. We can observe the following components:

- 3 PMC input ports.
- 12 PMC output ports.
- 1 constant trip output.
- Line currents.
- 4 breaker trips.
- 4 contactors
- Mux.
- 4 memory blocks.
- 1 step block.
- 3 constant value parameters.
- 3 Mux measure systems.



Secondary Distribution

Figure 86 - Under the mask of the secondary distribution

As seen in Figure 79, all blocks have their function. However, the breaker trips and contactor are quite more specific.

The breaker trip is imitating the function of a circuit braker in the aircraft. The following figure shows the subsystem it has:

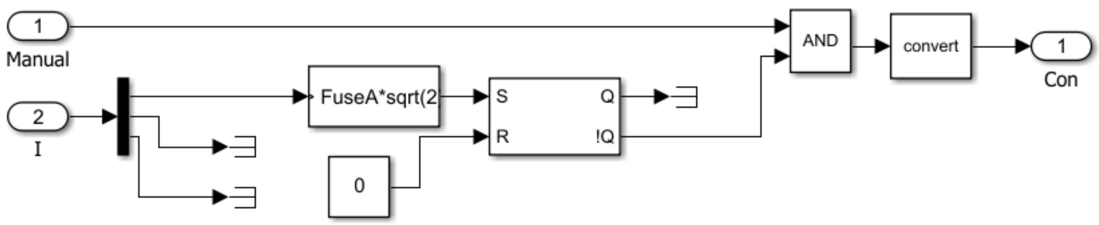


Figure 87 - Subsystem of the breaker trip block in MATLAB

On the other side, we have the contactors, which function is to specialize a type of relay used for switching an electrical circuit on or off. They are most commonly used with electric motors and lighting applications, such as here.

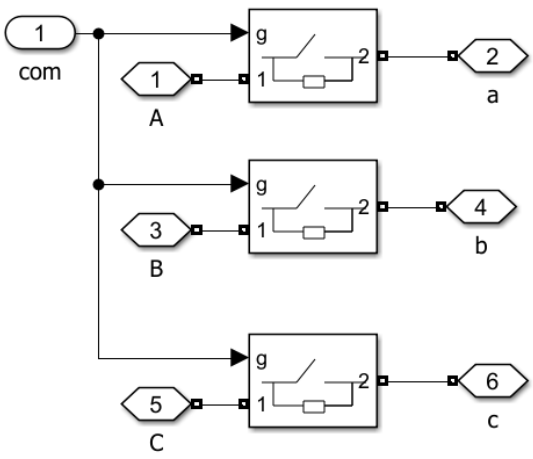


Figure 88 - Subsystem of the contactor block in MATLAB

After both distribution systems, we can divide in three parts how it is being distributed:

- AC loads.
- DC loads.
- TRU.

4.1.1.6 AC loads

AC loads are devices which receives alternating-current (AC) electrical power from a source in an electrical system. A programmable AC load bank is commonly integrated into circuits for testing and measurement of current, voltage and frequency.

In this situation, this MATLAB file shows 3 AC load components:

- 12 kVA induction motor driving hydraulic pump.
- 1 kW Lamp.
- 2 kW brushless motor driving a ball screw actuator.

Beginning with the **12 kVA induction motor driving hydraulic pump**. Knowing how to right-size an electric motor for your hydraulic pump can help reduce energy consumption and increase operational efficiency.

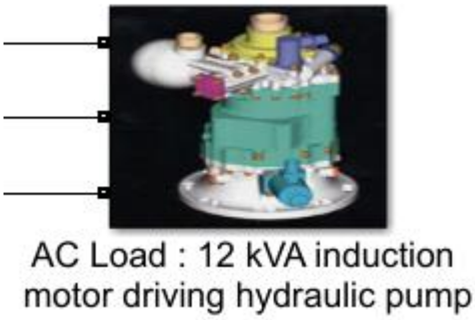


Figure 89 - 12 kVA induction motor driving hydraulic pump block in MATLAB

This block is being composed by:

- AC induction motor
- Mechanical power block parameter.
- AC inputs.
- Scope.
- Bus selector.
    - Rotor speed (wm).
    - Stator current (A).
    - Electromagnetic torque (Nm).
- Product block.
- Rate transition.
- Display block.

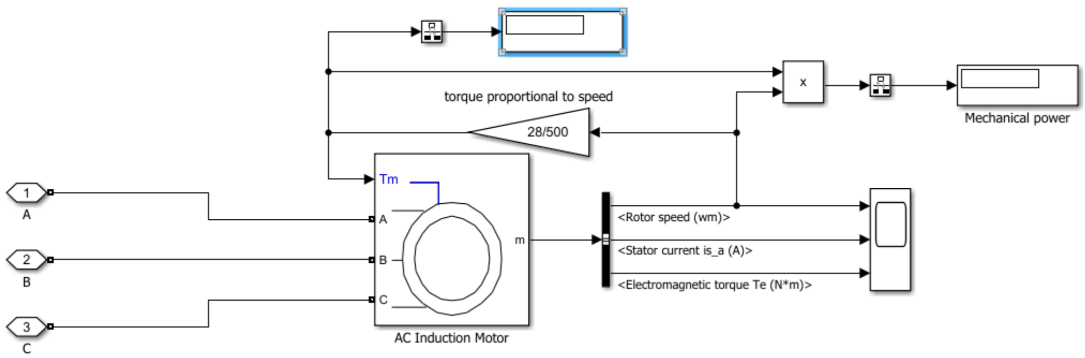


Figure 90 - Under the mask of the AC load: 12 kVA induction motor driving hydraulic pump

Then we have the **1 kW lamp,** which function is to illuminate**.**

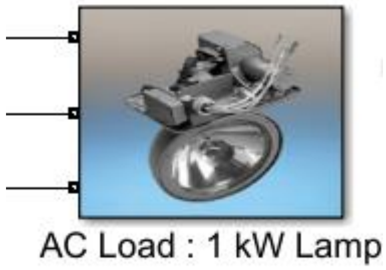


Figure 91 - 1 kW lamp block in MATLAB

This block is being composed by:

- 3 PMC input ports.
- 1 1000W lamp.

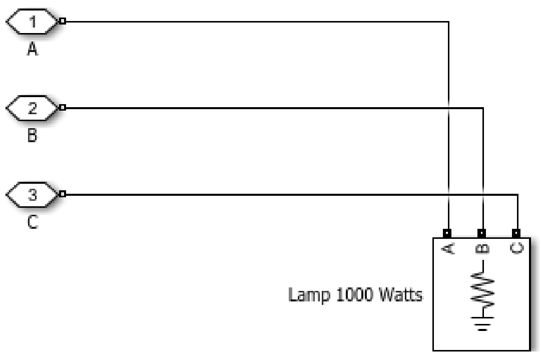


Figure 92 - Under the mask of the AC load: 1 kW lamp

Finally, we have the **2kW brushless motor driving a ball screw actuator.** This Ball Screw Actuator uses a high precision nut with recirculating ball bearings that rotate around a ground screw thread**.**

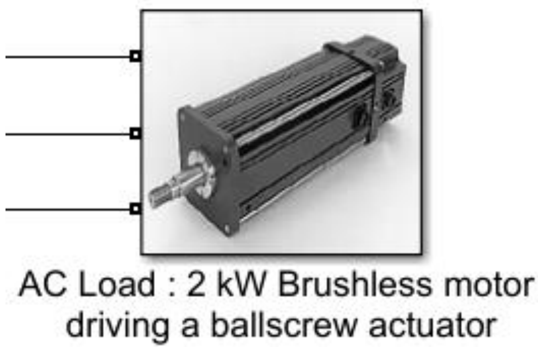


Figure 93 - 2kW brushless motor driving a ball screw actuator block in MATLAB

This block is being composed by:

- PM synchronous motor drive.
- Line inductor.
- 3 PMC input ports.
- Scope.
- Demux.
  - Stator current.
  - Rotor speed.
  - DC bus voltage.
  - Electromagnetic torque.

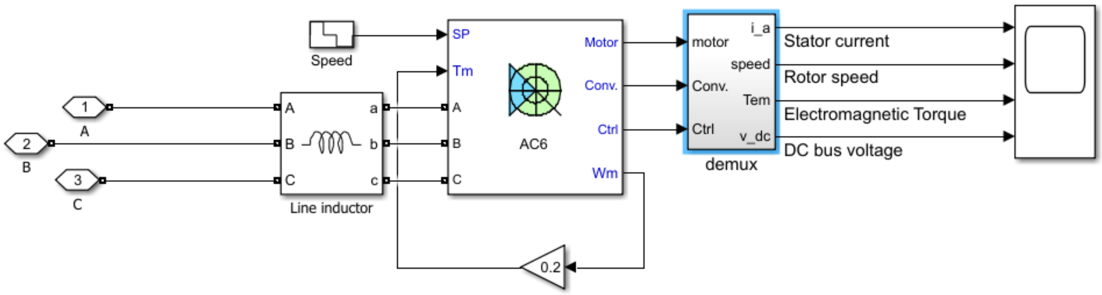


Figure 94 - Under the mask of the AC load: 2kW brushless motor driving a ball screw actuator

In Figure 86, we can observe that there is a demux parameter block which outputs the stator current, rotor speed, DC bus voltage and electromagnetic torque in order to plot it in the scope. Demultiplexing (DEMUX) is the reverse of the multiplexing (MUX) process: it combines multiple unrelated analog or digital signal streams into one signal over a single shared medium, such as a single conductor of copper wire or fibre optic cable.

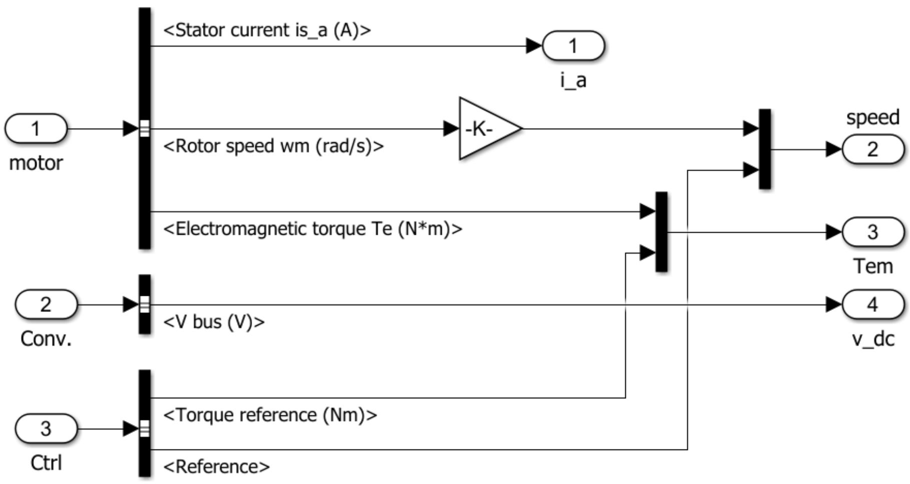


Figure 95 - Subsystem of the demux block parameter in MATLAB

4.1.1.7 DC loads

It is the current that is generated by energy generators such as solar panels and batteries. Loads that require DC Power are called DC loads.

In this situation, this MATLAB file shows 3 AC load components:

- Lamp.
- Heater.
- Brush motor driving a fuel pump.

At first, we have the **lamp,** with the same function as the previous lamp in the AC load.

Figure 96 - Lamp block in MATLAB

This lamp is simply formed by 1 series RLC branch and 2 PMC ports.

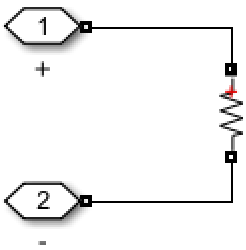


Figure 97 - Under the mask of the DC load: lamp

Same happens with the **heater,** it shares the same under mask as the lamp. However, its function is supplying heat, for example a radiator or a convector.

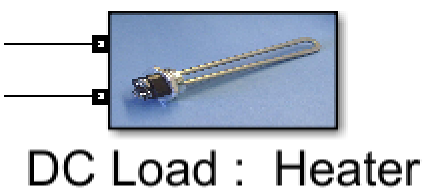


Figure 98 - Heater block in MATLAB

Finally, we have the **brush motor driving a fuel pump.** The brushes charge the commutator/armature inversely in polarity to the ring of magnets, which causes the armature to rotate. Thereby turning the motor shaft and providing propulsion to that which the motor is driving.

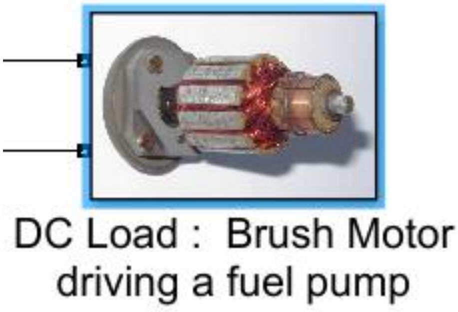


Figure 99 - Brush motor driving a fuel pump block in MATLAB

This block is being composed by:

- DC machine.
- Bus selector.
    - Speed (rad/s).
    - Armature current (A).
    - Electrical torque (Nm).
- Scope.
- PMC input ports.
- Gain.

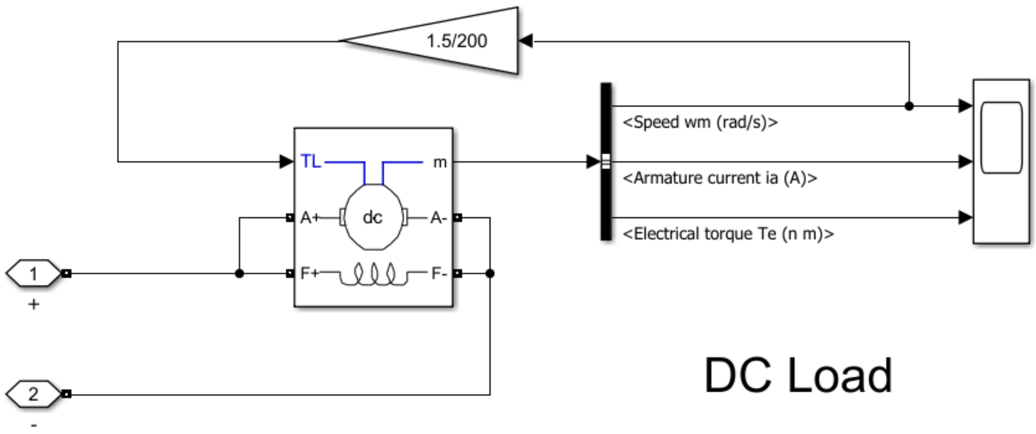


Figure 100 - Under the mask of the DC load: brush motor driving a fuel pump

4.1.1.8 Transformer and rectifier Unit

A Transformer Rectifier Unit (TRU) combines the functions of a Transformer and a Rectifier into one unit. In aircraft applications, the TRU converts the 120V AC power generated by the engine or APU generators or provided by a Ground Power Unit (GPU) to 28V DC power for use by various electrical components.

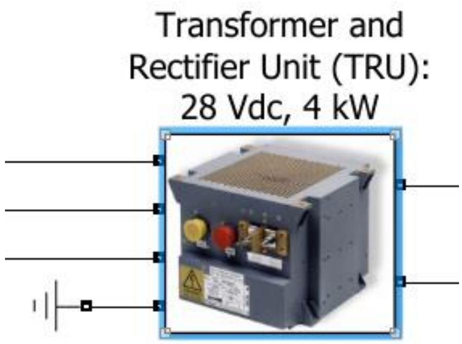


Figure 101 - TRU block in MATLAB

This block is being composed by:

- 6 PMC ports.
- Three-phase transformer.
- 2 universal bridges.
- Ground.
- RLC branch.

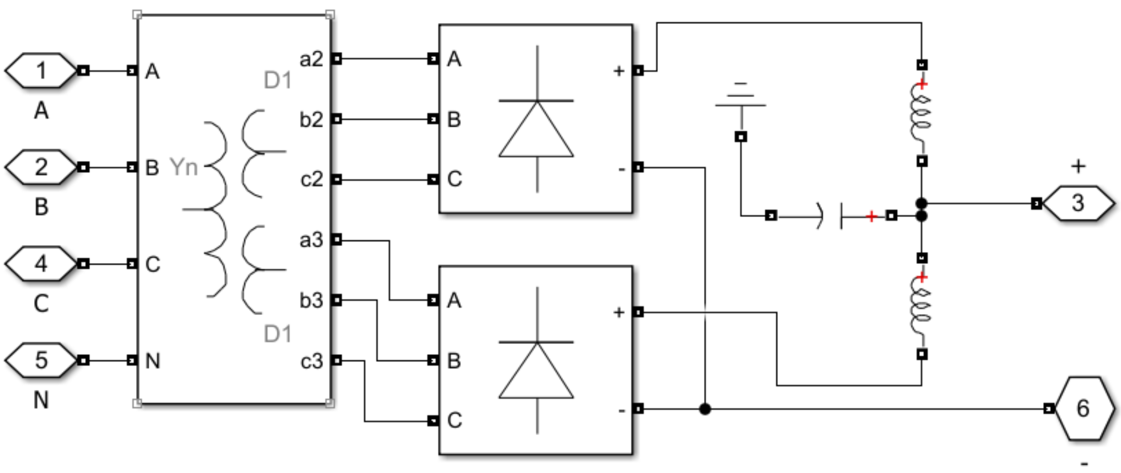


Figure 102 - Under the mask of the TRU in MATLAB

4.2 Airbus A320 adaptation model

After reviewing the base model of the electrical system of an aircraft in MATLAB, now is time to recreate or develop a similar model for the Airbus A320 base on the following figure of the electrical system schematic.

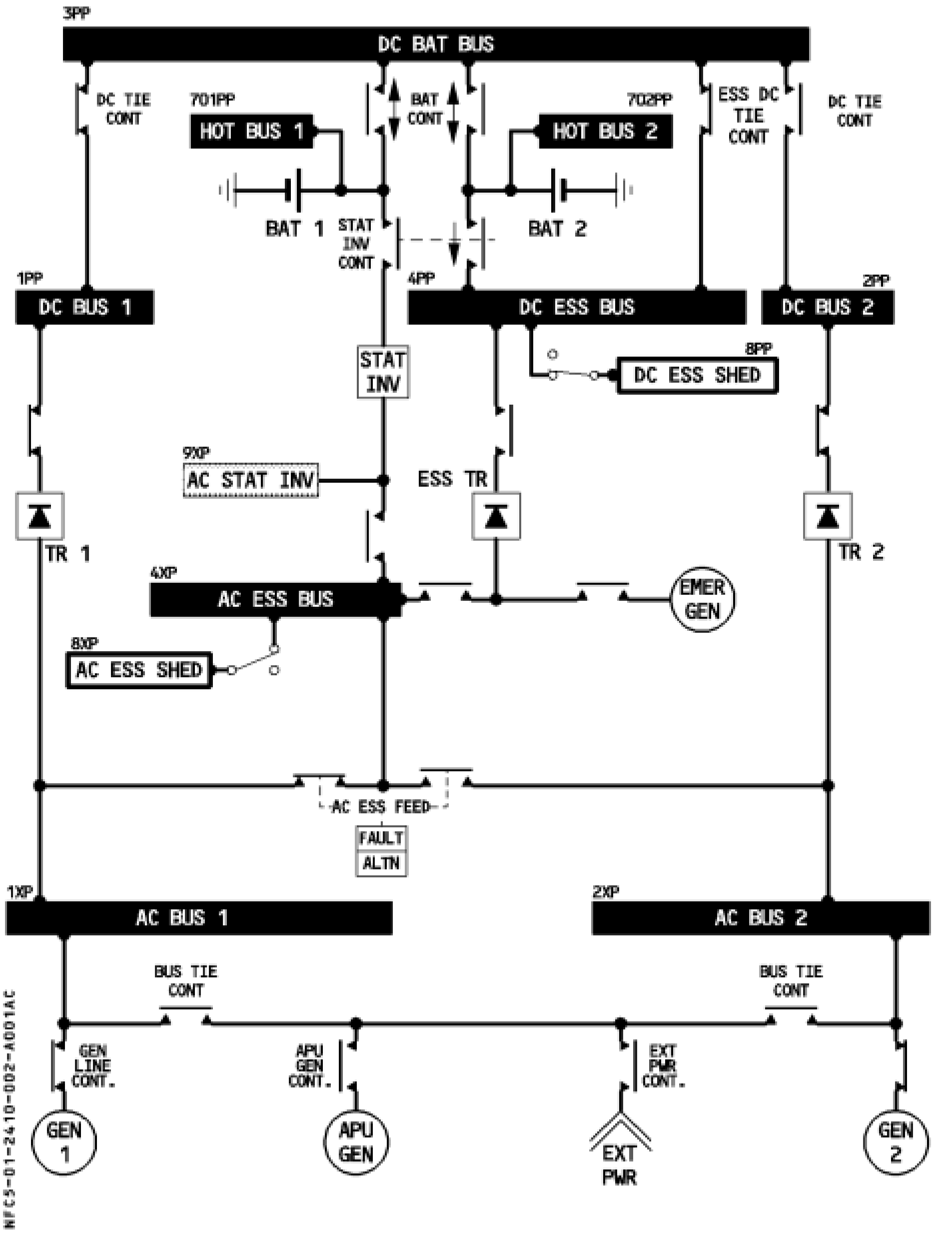


Figure 103 - Airbus A320 electrical system schematic

(Airbus Training, 2016)

The creation of this model will be very strenuous and that is because of the complex electrical system an Airbus A320 has.

The main objective of this part, not including the creation of the model, is to simulate in several conditions, such as the normal ones or abnormal, for example different faults the aircraft can have.

4.2.1 Mechanical engine A320

Going back to how I have started, the first block was the mechanical engine, the basis for the aircraft to run.

At first, I have decided to use a **turbofan engine system**, available in the aerospace blockset in MATLAB's library. However, this block was not really useful for me because I could not find any relation between thrust and fuel flow with the generators speed and this is why I have decided to use a signal builder block.

This first part shows how the turbofan could be implemented.

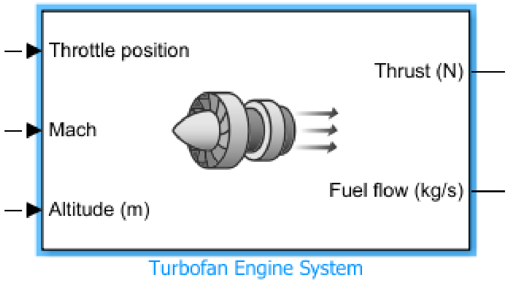


Figure 104 - Turbofan engine system block in MATLAB

This block gives me the opportunity to introduce several values that are crucial for the engine to work.

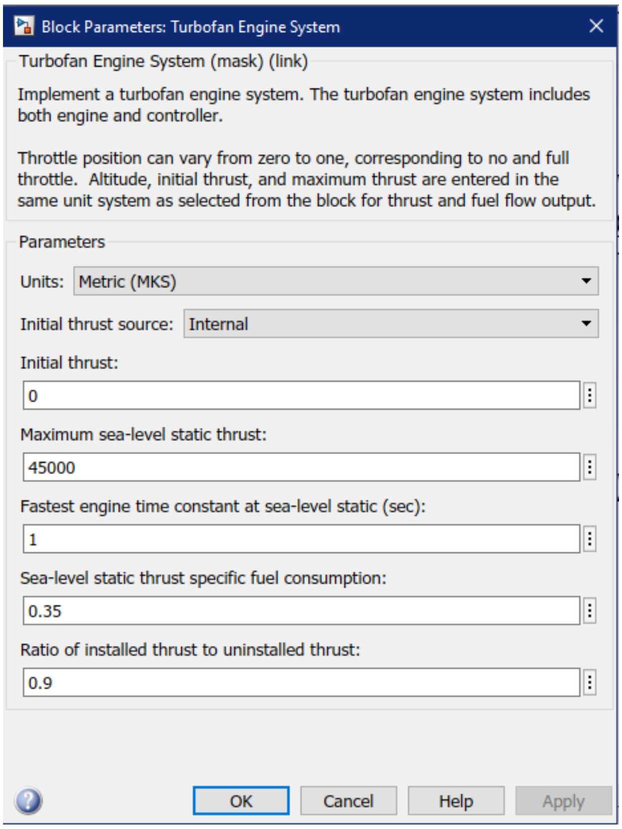


Figure 105 - Turbofan engine system parameters in MATLAB

Then we have the 3 inputs to introduce, the initial thrust which will be done in two different positions, in this case ON and OFF. Then the altitude (sea-level) in meters and finally the Mach speed of the aircraft.

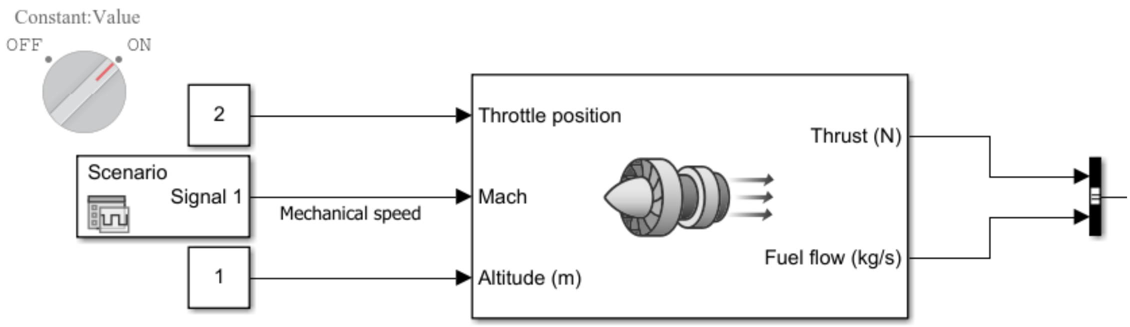


Figure 106 – Mechanical engine block in MATLAB

The inputs to the turbofan engine system are:

- Throttle position
- Mach
- Altitude (m)

The outputs of the turbofan engine system are:

- Thrust (N)
- Fuel flow (kg/s)

As mentioned before, the two constant blocks are just simple values, however, the scenario of Mach speed is a graph that allows me to change speed at any time. The following figure shows how it is done:

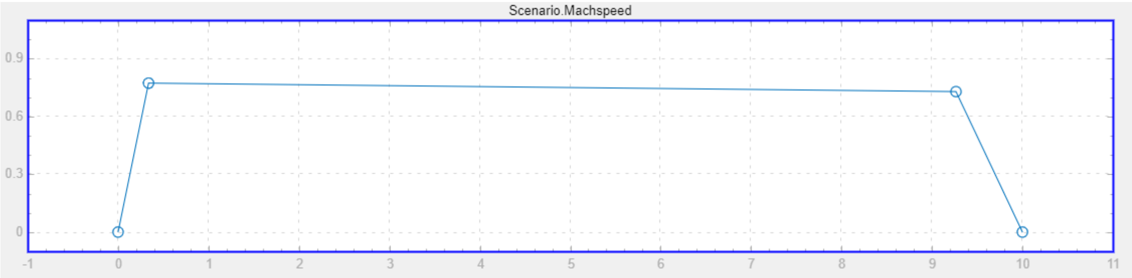


Figure 107 - Mach speed scenario in MATLAB

This speed can be changed, according to the flight speed, in this case was considered as constant speed during cruise. It is important to note that the maximum speed of the Airbus A320 is 0.78 Mach.

Despite all that information about the turbofan, I finally used the signal builder block. One per generator (GEN 1 & GEN2) and another one for the APU.

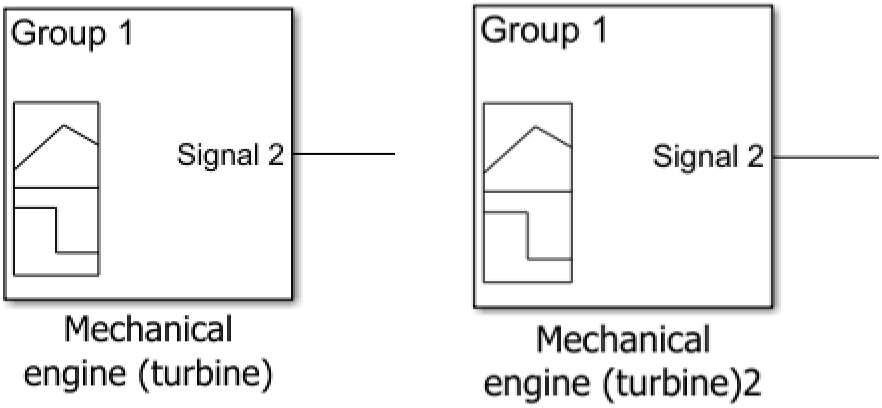


Figure 108 - Two signal builders for GEN 1 and GEN2

And another one for the APU:

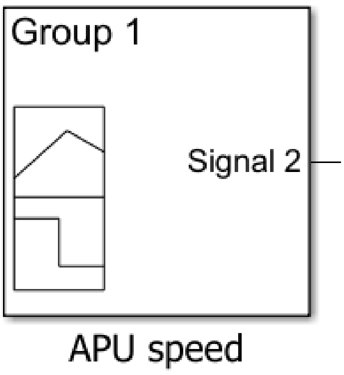


Figure 109 - APU signal builder

Later on in the simulations, the actual signal given for each generator is explained.

4.2.2 Auxiliary Power Unit A320

An auxiliary power unit (APU) is a device on a vehicle that provides energy for functions other than propulsion, in this case is the following block after the engine, however, it is in parallel with the power generator (GEN1&GEN2) that will be mentioned later on.

The following MATLAB block stands for the APU.

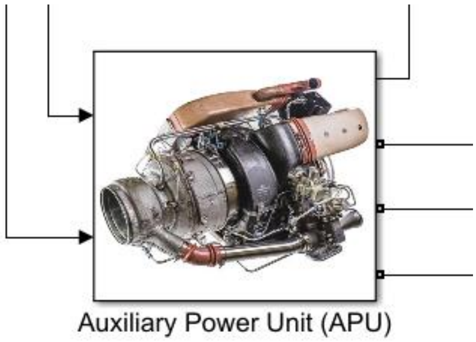


Figure 110 - Auxiliary Power Unit block in MATLAB

The inputs for the APU are:

- Mechanical speed
- Field

The outputs for the APU are:

- 3 PMC ports
- Control unit

An important addition for this block, that would actually help improving the model is by adding a constant speed driver, in this case, adding a constant value speed of 24000rpm into a switch, this Switch block propagates one of two inputs to its output depending on the value of a third input, called the control input. If the signal on the control (second) input is greater than or equal to the Threshold parameter, the block propagates the first input; otherwise, it propagates the third input.

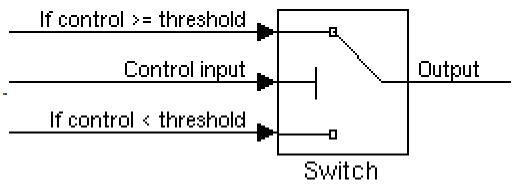


Figure 111 - Switch block in MATLAB

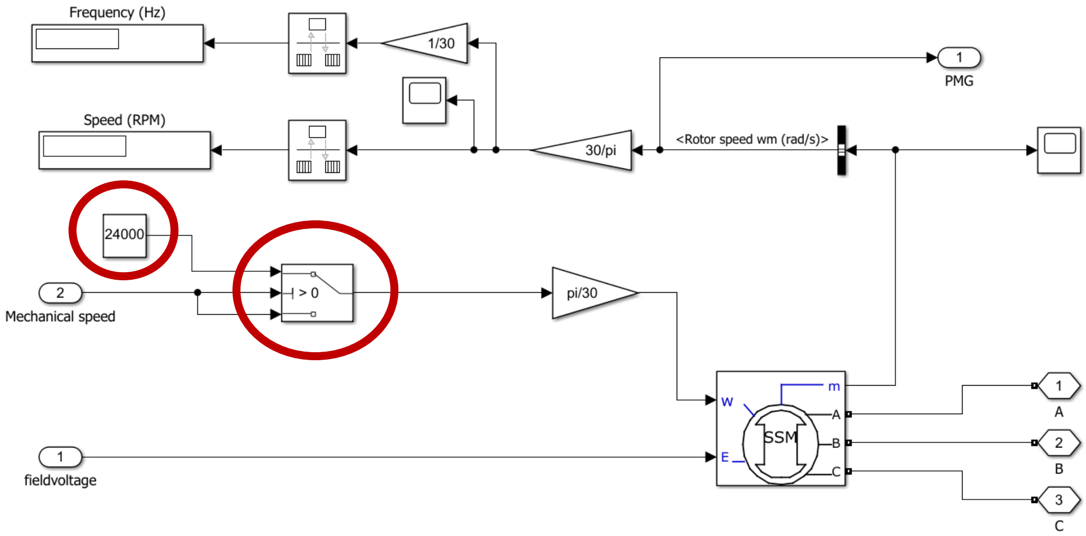


Figure 112 - Under the mask of the APU block in MATLAB

The APU generator is not interchangeable with the Integrated Drive Generators (IDGs). It is driven at a constant speed by the APU and can be connected to the electrical network in flight in case of any generator failure. It can supply the entire electrical network if no other power sources are available.

4.2.3 Power generation A320

The Airbus A320 has two three-phase AC generators, which actually works similar to the APU, as being a generating system, the MATLAB under-mask will be the same. However, these generators are directly integrated into the engines through a driver.

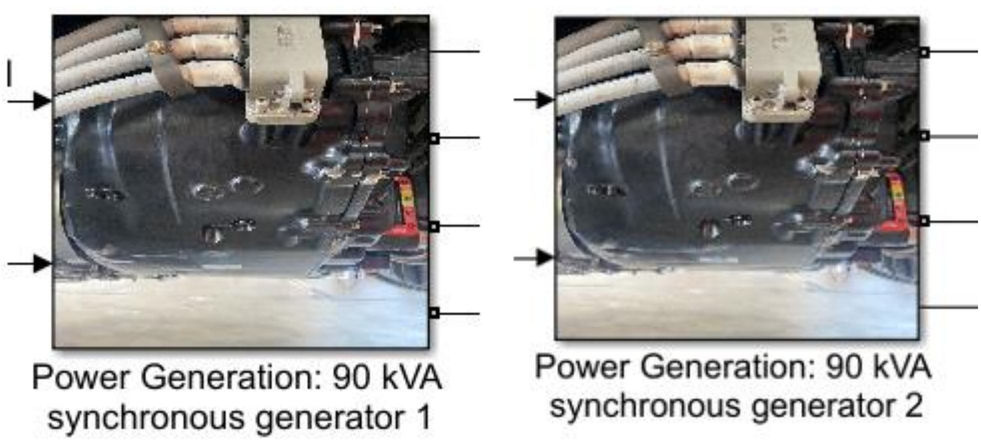


Figure 113 - Power generation block in MATLAB

The inputs for the power generation are:

- Mechanical speed
- Field

The outputs for the APU are:

- 3 PMC ports
- Control unit

As in the previous part, another important block that would actually help improving the model is by adding a constant speed driver, in this case, adding a constant value speed of 24000rpm into a switch, this Switch block propagates one of two inputs to its output depending on the value of a third input, called the control input. If the signal on the control (second) input is greater than or equal to the Threshold parameter, the block propagates the first input; otherwise, it propagates the third input.

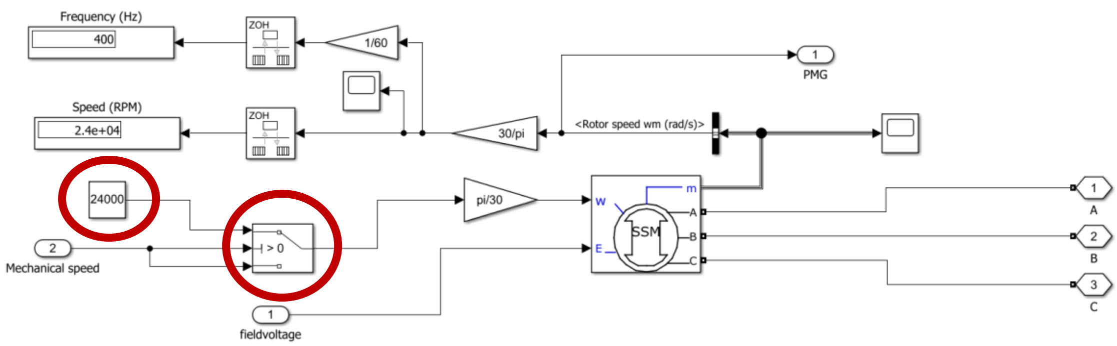


Figure 114 - Under the mask of the generator system in MATLAB

4.2.4 Generator Control Unit A320

The generator control unit (GCU) is more commonly found on turbine power aircraft. The most basic generator control units perform a number of functions related to the regulation, sensing, and protection of the DC generation system. Voltage Regulation. The most basic of the GCU functions is that of voltage regulation.

In this situation, in the Airbus A320 the GCU is supplied by the Permanent Magnet Generator (PMG). The GCU is also supplied by the AC network. The GCU has three different functions. These functions are:

- Voltage regulation
- Control and protection
- System test and self-monitoring

The following figure shows the MATLAB block used.

The inputs for the GCU are:

- Iabc
- Vabc

- PMC port from Power Generation
- PMC port from APU

The outputs for the GCU are:

- Field
- GLC
- Scope
- Rate transition

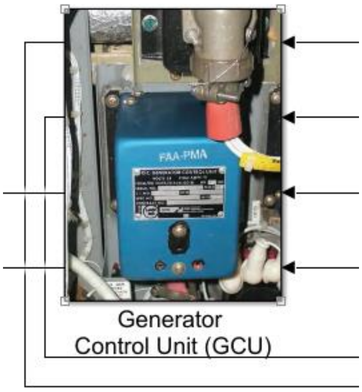


Figure 115 - Generator Control Unit block in MATLAB

For this block, I have implemented the APU generator control, as shown in Figure 122, which includes the Gain block which multiplies the input by a constant value, in this situation $30/\pi$ and then a Relay block that switches between two specified values, the values are below the 24000rpm.

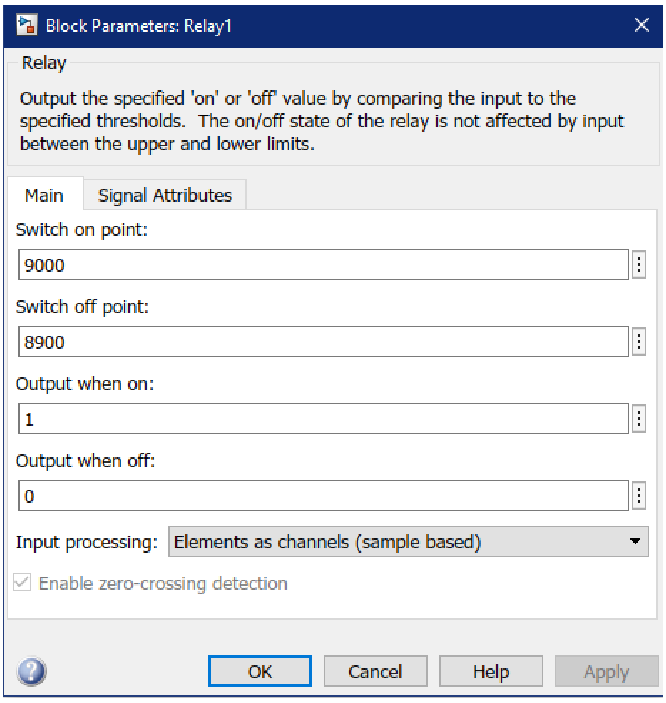


Figure 116 - Relay block values in MATLAB

On the other side, the APU in-port releases the integrator and the gain block in other to do the Park transformation to transform a three-phase (abc) signal into a dq0 rotating reference frame. The angular position of the rotating frame is given by the input wt, in rad.

The dq0 to abc block uses an inverse Park transformation to transform a dq0 rotating reference frame to a three-phase (abc) signal. The angular position of the rotating frame is given by the input wt, in rad. When the rotating frame alignment at wt=0 is 90 degrees behind the phase A axis, a positive-sequence signal with Mag=1 and Phase=0 degrees yield the following dq values: d=1, q=0.

Following the next equations:

$$Vd = \frac{2}{3}\left(Va \cdot sin \cdot (\omega t) + Vb \cdot sin \cdot \left(\omega t - \frac{2\pi}{3}\right) + Vc \cdot sin\left(\omega t + \frac{2\pi}{3}\right) \right. \quad (23)$$

$$Vq = \frac{2}{3}\left(Va \cdot cos \cdot (\omega t) + Vb \cdot cos \cdot \left(\omega t - \frac{2\pi}{3}\right) + Vc \cdot cos\left(\omega t + \frac{2\pi}{3}\right) \right. \quad (24)$$

$$Vo = \frac{1}{3}\left(Va + Vb + Vc\right) \quad (25)$$

$$Va = Vd \cdot sin \cdot (\omega t) + Vq \cdot cos \cdot (\omega t) + V0 \quad (26)$$

$$Vb = Vd \cdot sin \cdot \left(\omega t - \frac{2\pi}{3}\right) + Vq \cdot cos \cdot \left(\omega t - \frac{2\pi}{3}\right) + V0 \quad (27)$$

$$Vc = Vd \cdot sin \cdot \left(\omega t + \frac{2\pi}{3}\right) + Vq \cdot cos \cdot \left(\omega t + \frac{2\pi}{3}\right) + V0 \quad (28)$$

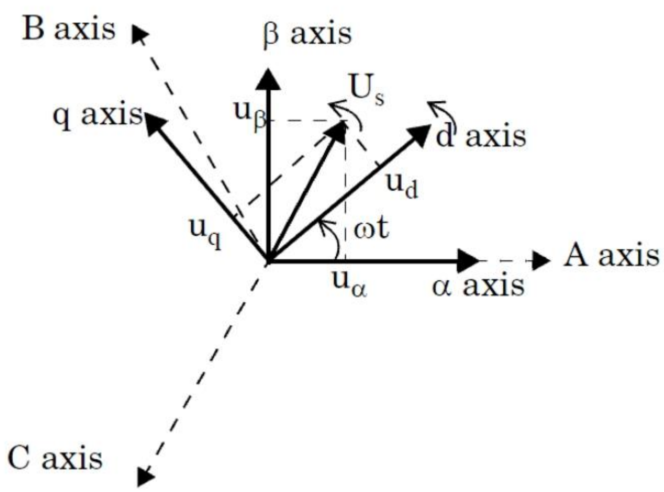


Figure 117 - Axis distribution

The block supports the two conventions used for the Park transformation:

- When the rotating frame is aligned with the phase A axis at t = 0, that is, at t = 0, the d-axis is aligned with the a-axis. This type of Park transformation is also known as the cosine-based Park transformation.
- When the rotating frame is aligned 90 degrees behind the phase A axis, that is, at t = 0, the q-axis is aligned with the a-axis. This type of Park transformation is also known as the sine-based Park transformation. Specialized Power Systems models with three-phase synchronous and asynchronous machines.

After that, adding an excitation system in which, Vref (constant), Vd, Vq and Vstab (constant) are the inputs and outputting the Vf into a field voltage.

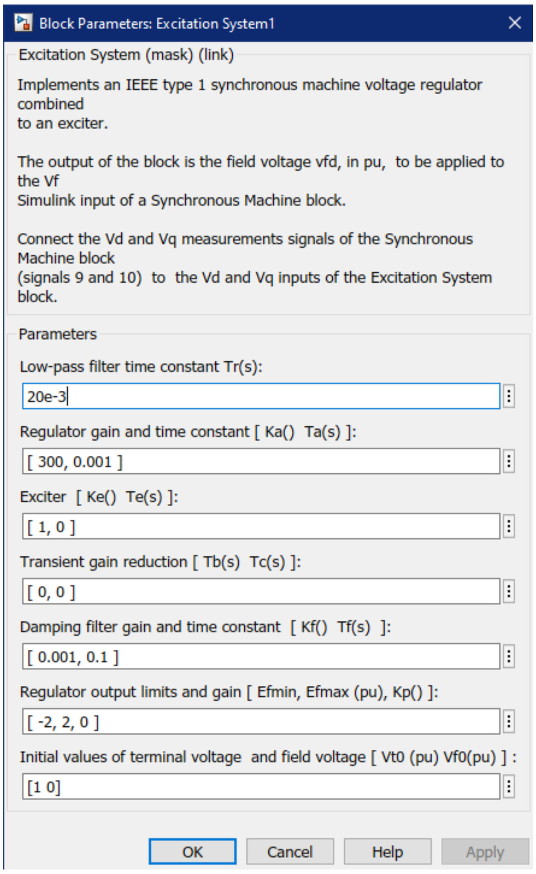


Figure 118 - Excitation system parameters in MATLAB

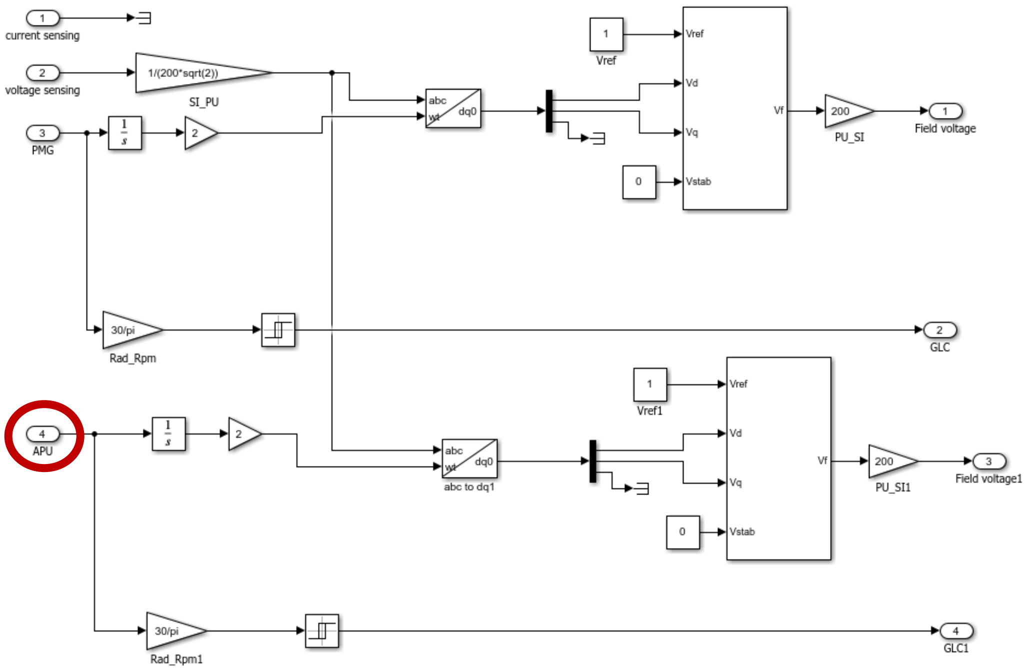


Figure 119 - Under the mask of the GCU block in MATLAB

4.2.5 Primary distribution A320

The distribution systems used in modern aircraft create a complexity that impacts power system design, physical layout of components, wire routing, and wire selection. However, in this situation it is composed of three current and voltage sensors.

The inputs for the GCU are:

- 2 GLC control.
- 6 PMC ports.

The outputs for the GCU are:

- Vabc
- Iabc
- 6 PMC ports

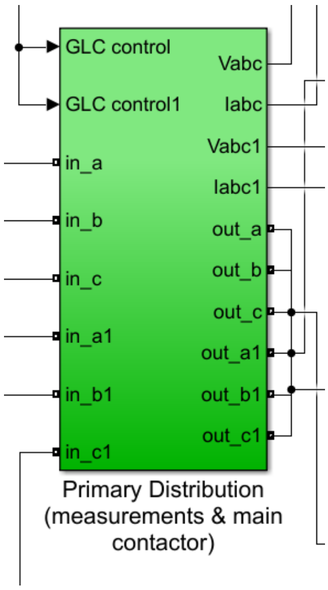


Figure 120 - Primary distribution block in MATLAB

There is also a 3-phase contactor controlled by the Generator Control Unit. Finally, a parasitic resistive load is required to avoid numerical oscillations.

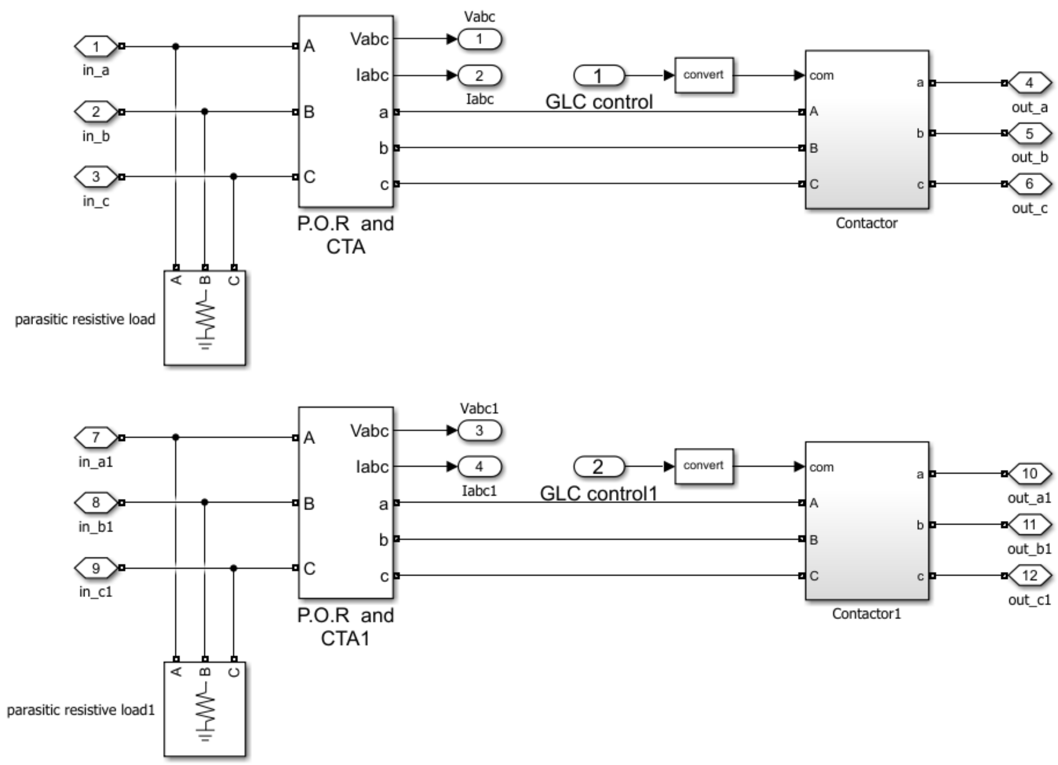


Figure 121 - Under the mask of the primary distribution in MATLAB

4.2.6 Secondary distribution A320

Same as in the primary distribution, the secondary distribution systems used in modern aircraft create a complexity that impacts power system design, physical layout of components, wire routing, and wire selection. However, in this situation we still have the inputs related to the PMCs and 13 (15) outputs directly into the aircraft necessities counting TRU's, such as, the AC loads, DC loads, and the Transformer and Rectifier Unit (TRU).

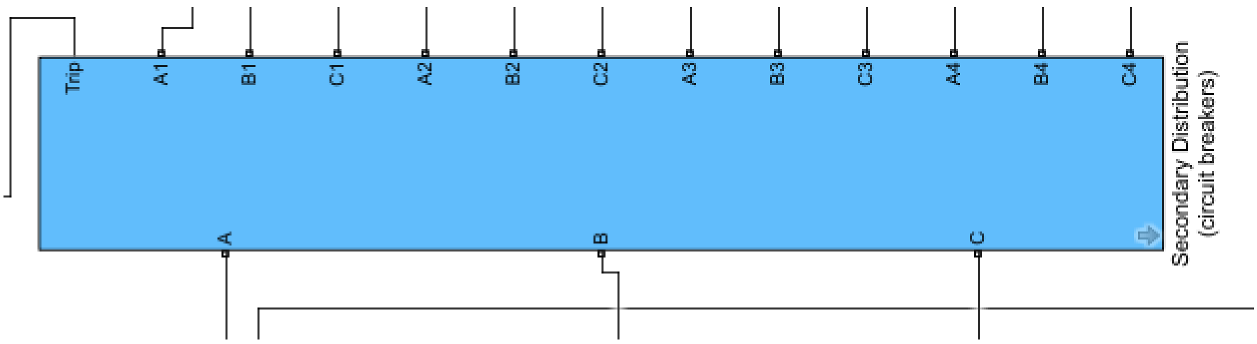


Figure 122 - Secondary distribution block in MATLAB

The inputs for the GCU are:

- 3 phases (A, B and C).

The outputs for the GCU are:

- 13 PMC ports.
- 1 trip output.

Despite that, one important modification was done, which actually will help me simulate different situation in different times. What I have added is an operational block, exactly two relational operator and a logical operator each of this with a constant given which is the time set and all of it connected to a ramp block giving its slope. So, the idea is as the following figure:

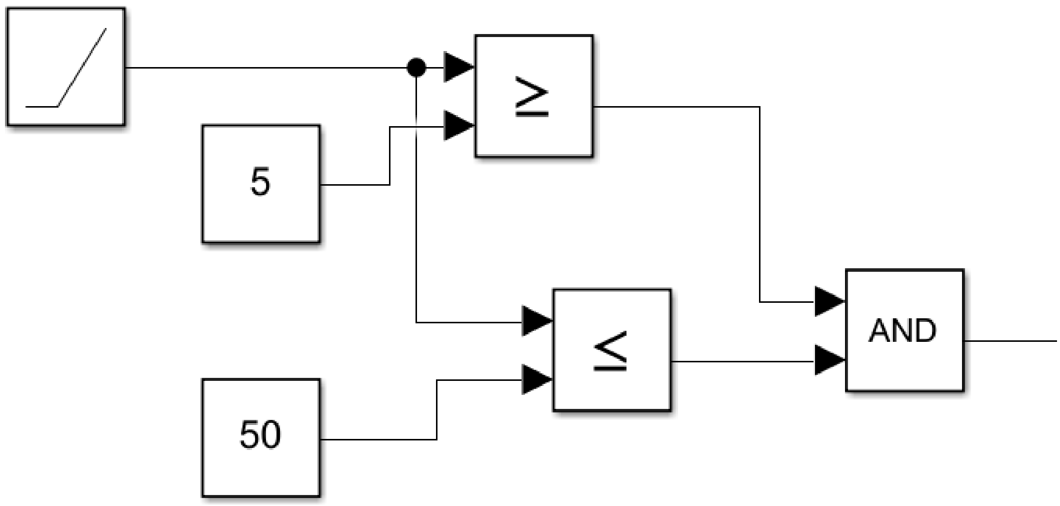


Figure 123 - Operational blocks in MATLAB

The main objective is simple, two constants based on the times I want to simulate are connected to a relational operator which applies the selected relational operator to the inputs and outputs the result, the top input corresponds to the first operand. Then the logical operators, for instance a single input, operators are applied across the input vector. For multiple inputs, operators are applied across the inputs giving action into the breaker trip.

In addition, this operation allows me to simulate different failures during flight, just by giving the constant an exact value.

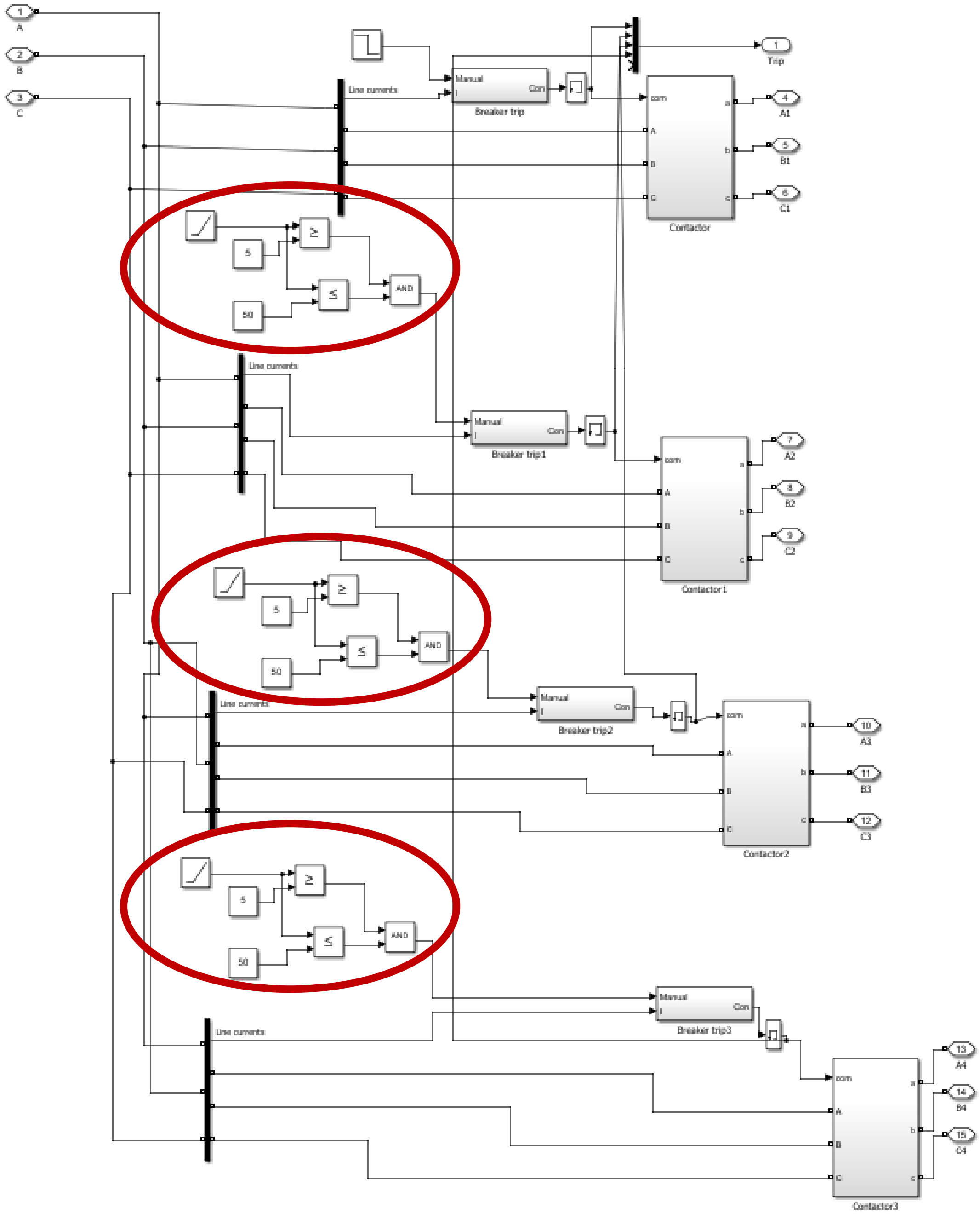


Figure 124 - Under the mask of the secondary distribution block in MATLAB

4.2.6.1 AC Loads A320

The AC electrical power is provided by two engine-driven generation systems. Each system includes an integrated drive generator (IDG) and a generator control unit (GCU). An auxiliary power unit (APU) generator is also available as a back AC power source to replace either or both IDGs.

Coming from the secondary distribution as output ports, I have decided to add the following AC loads:

- 12 kVA induction motor driving hydraulic pump.
- 2kW brushless motor driving a ball-screw actuator.
- Lights
    - Cabin equipment
    - Beacon 35J / Pulse rotation 20-200ms.
    - Logo light 115 V_{rms} / 350mA_{rms}.
    - Taxi light 115 V_{rms} / 600mA_{rms}.
    - Runway light V_{rms} / 350mA_{rms}.

In my opinion, this were the basic lights for the aircraft to take into account, however many other could be included.

The following figure shows how the light are distributed in MATLAB:

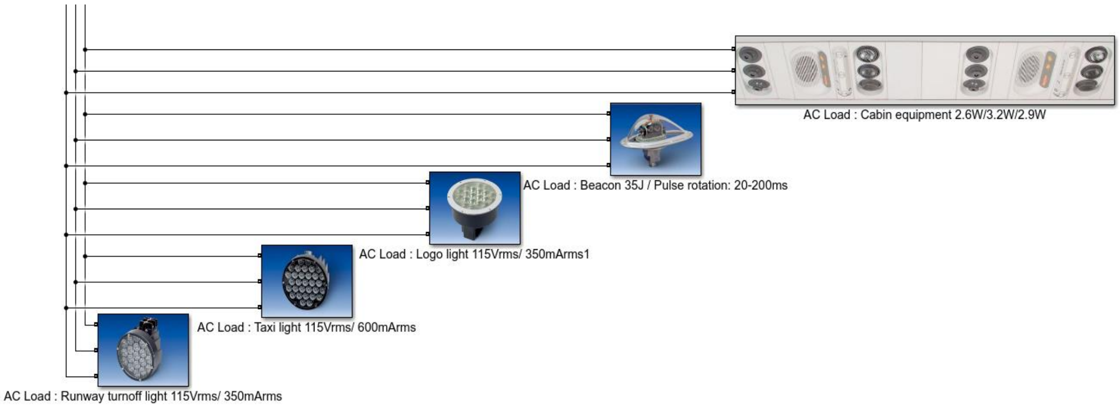


Figure 125 - AC loads: lights in MATLAB

Each of these lights are composed by 3 PMC ports and a three-phase series RLC load, each with its equivalent values.

Starting with the **cabin equipment**, divided into three sections, the single aisle passenger supply, the LED reading light and air outlet panels.

Figure 126 - Cabin equipment blocks in MALTAB

The inputs for the cabin equipment are:

- 3 PMC ports.

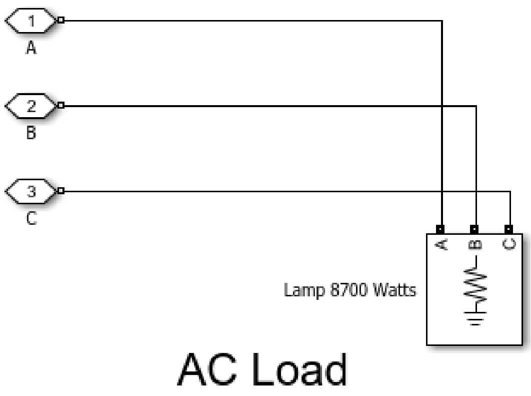


Figure 127 - Under the mask of the cabin equipment block in MATLAB

Then we have the **beacon light** with an energy per flash of 35 J max and a pulse duration between 20ms – 200ms. It is installed on top of the fuselage and one at the bottom of the A320 family aircraft. The aero-dynamic shape of the highly resistant glass cover reduces the drag load significantly in comparison to other designs.

Figure 128 - Beacon light block in MATLAB

The inputs for the cabin equipment are:

- 3 PMC ports.

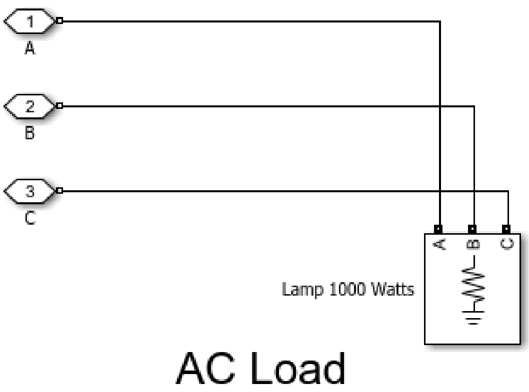


Figure 129 - Under the mask of the beacon light in MATLAB

An important and interesting aspect of the beacon is that it is synchronized with the wing strobe light and tail strobe light.

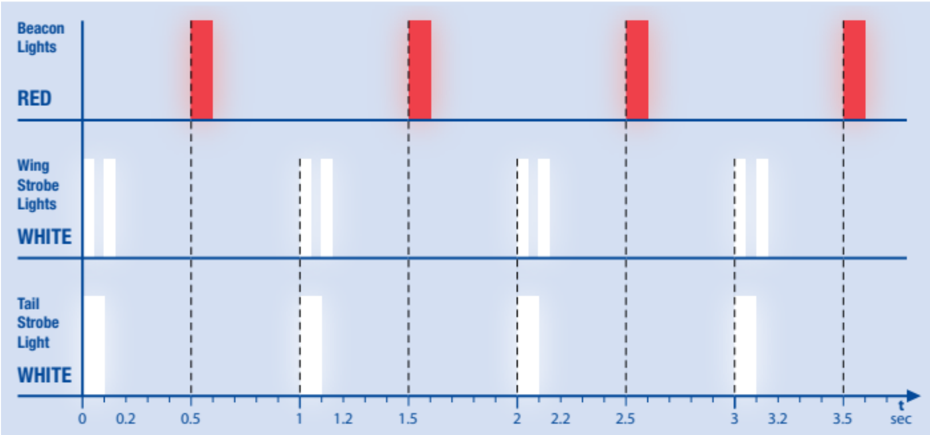


Figure 130 - Flashing sequences and synchronization

After the beacon we have the **logo light** with 115V_{rms} and 350 mA_{rms}. Same as in the other situations, is composed by the 3 PMC ports and a three-phase series RLC load.

Figure 131 - Logo light block in MATLAB

The inputs for the cabin equipment are:

- 3 PMC ports.

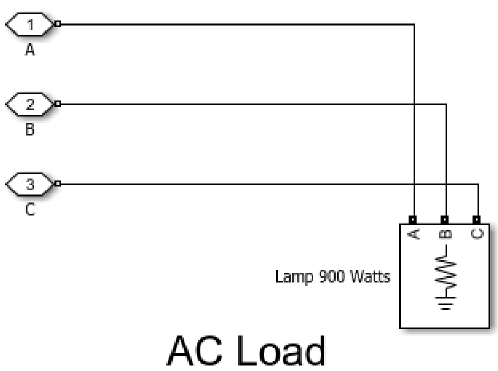


Figure 132 - Under the mask of the logo light in MATLAB

Continuing with the **taxi light** with 115V_{rms} and 600 mA_{rms}. is integrated into the aircraft's nose landing gear (NLG) and provides optimal light to illuminate taxi ways, runway turnoff locations and ground obstructions that may cause hazard to the aircraft.

Figure 133 - Taxi light block in MATLAB

The inputs for the cabin equipment are:

3 PMC ports.

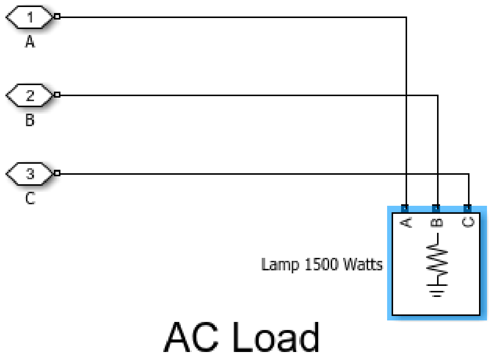


Figure 134 - Under the mask of the taxi light in MATLAB

Finally, we have the runway turnoff light with 115V_{rms} and 3500 mA_{rms}. They are integrated into the aircraft's nose landing gear (NLG) and provide optimal light to illuminate the runway turnoff location.

Figure 135 - Runway turnoff light in MATLAB

The inputs for the cabin equipment are:

3 PMC ports.

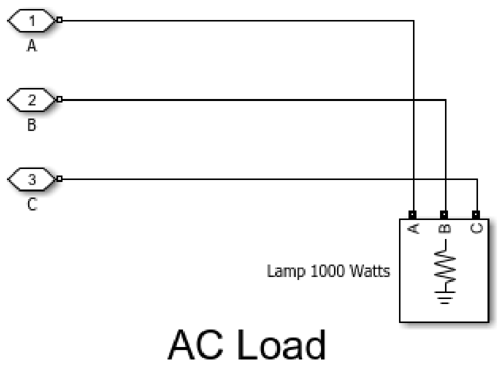


Figure 136 - Under the mask of the runway turnoff light in MATLAB

4.2.6.2 DC Loads A320

In the Airbus A320 we have several DC loads, such as the heater, lamps, brush motor and batteries and all connected to two Transformers Rectifier Unit (TRU).

Starting with both TRU's, the following figures shows the block used:

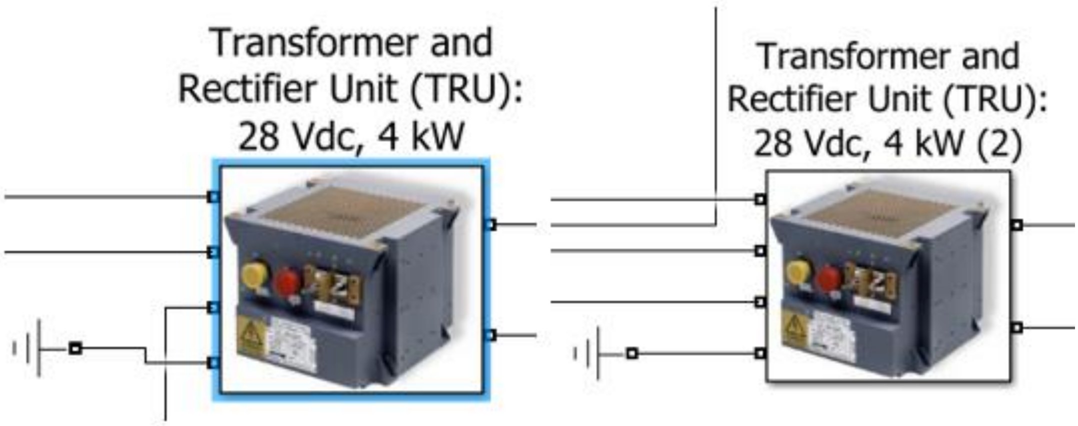


Figure 137 - Both TRU's block in MATLAB

One of these blocks is being composed by:

- 6 PMC ports
- Three-phase transformer.
- 2 universal bridges.
- Ground.
- RLC branch.

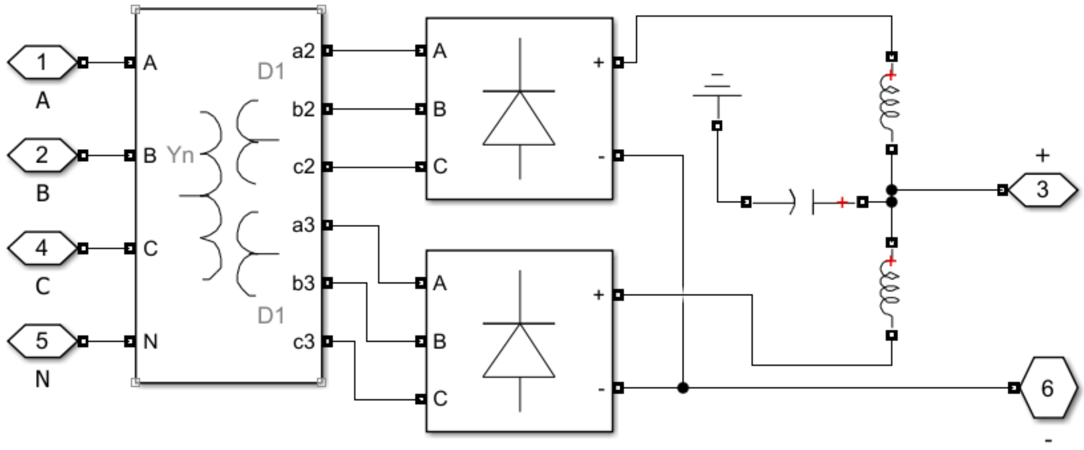


Figure 138 - Under the mask of the TRU block in MATLAB

Then, after the TRU's connection we have the DC loads and the two batteries. The only additions for this part were those two batteries In my opinion leaving the lamp, heater and brush motor is important.

Starting with the DC loads, we have the lamp, with its objective of illuminating any specific area.

Figure 139 - Lamp block in MATLAB

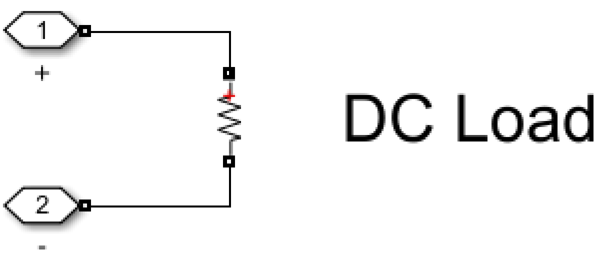


Figure 140 - Under the mask of the lamp block in MATLAB

The inputs for the lamp are:

- 2 PMC ports.

After the lamp we have the heater, it shares the same under mask as the lamp. However, its function is supplying heat.

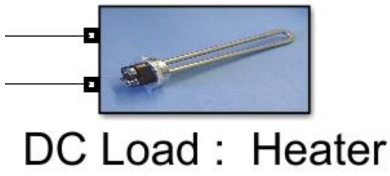


Figure 141 - Heater block in MATLAB

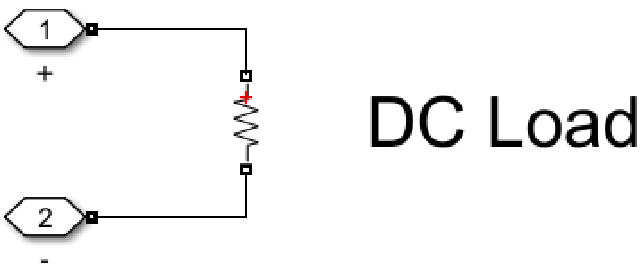


Figure 142 - Under the mask of the heater block in MATLAB

The inputs for the heater are:

- 2 PMC ports.

Continuing with the brush motor driving a fuel pump, which is providing propulsion to that which the motor is driving.

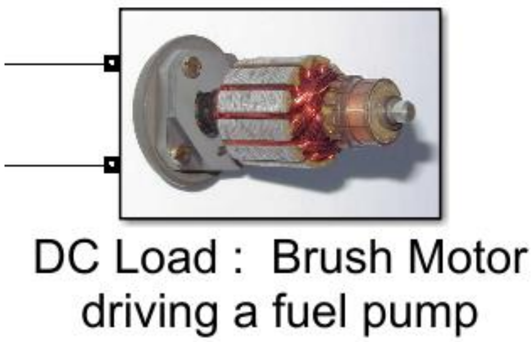


Figure 143 - Brush motor driving a fuel pump block in MATLAB

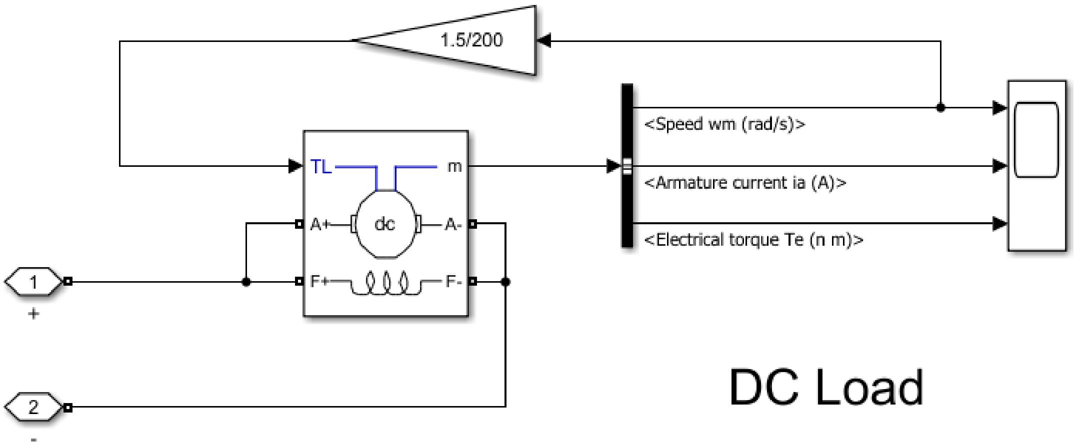


Figure 144 - Under the mask of the brush motor driving a fuel pump block in MATLAB

The inputs for the brush motor are:

- 2 PMC ports.

Then, after those 3 already known block, I have managed to add two batteries based on the real Airbus A320. A nickel-cadmium batteries with 28 V as nominal voltage and 23 Ah rated capacity.

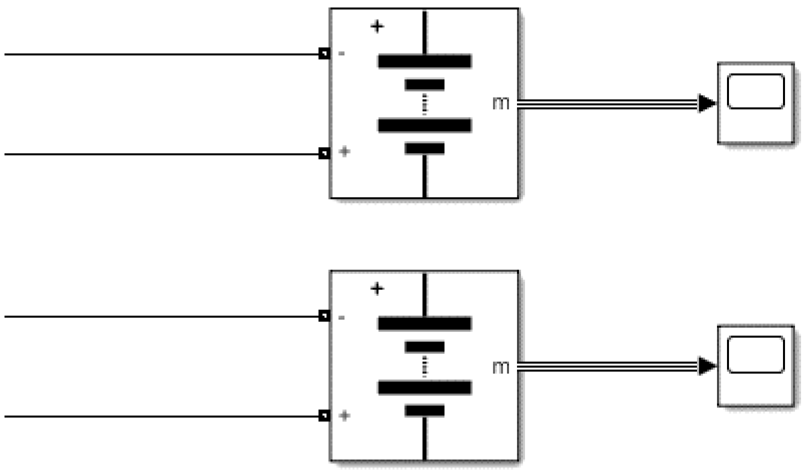


Figure 145 - Batteries blocks in MATLAB

The inputs for the batteries are:

- 4 ports.

The following figure shows the actual values for the batteries.

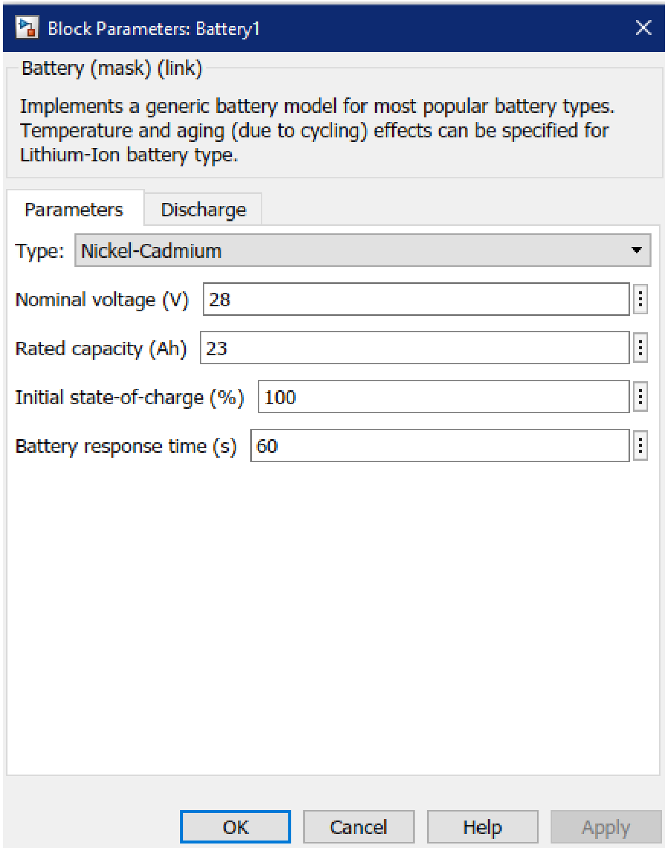


Figure 146 - Batteries parameters

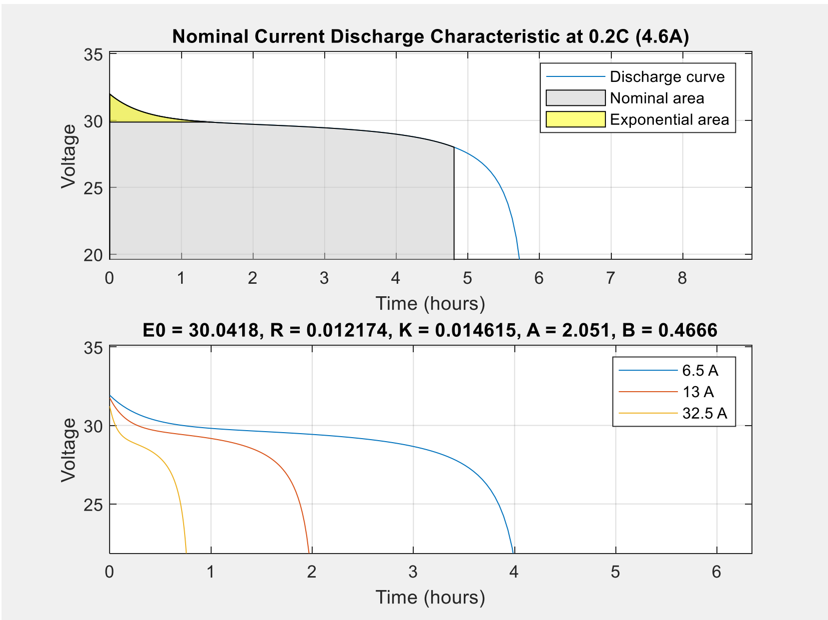


Figure 147 - Battery discharge characteristic

4.3 MATLAB/Simulink schematic result

For the MATLAB/Simulink result of the schematic, the idea was to recreate the following figure of the A320 electrical system schematic to a way that it could be the more similar as possible. However, as I said before, doing a complete A320 electrical system it could take a long time.

As the time is limited for this project, I decided to do it as similar as possible to the real one, with the objective of simulating all main important features.

During the creation of the model, no tags "Goto" and "From" were used to simplify it. However, I have managed to try and do it as simplified and clear as possible.

The following figure shows the actual A320 electrical system and the figure after that one shows my MATLAB model.

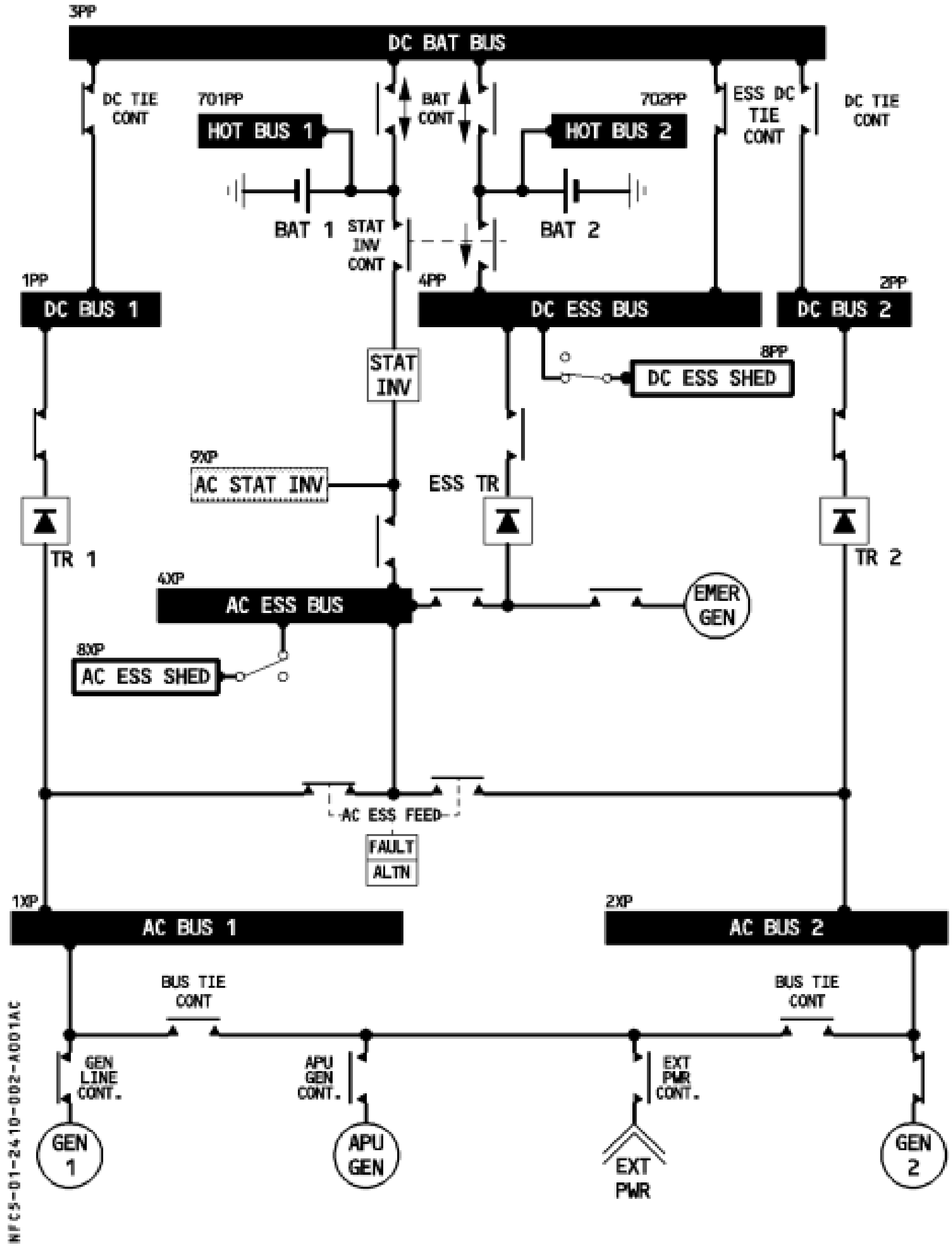


Figure 148 - Airbus A320 electrical system schematic

As the MATLAB model is quite expanded through the screen it is difficult to acknowledge each part so I will divide in several parts in order to see it better.

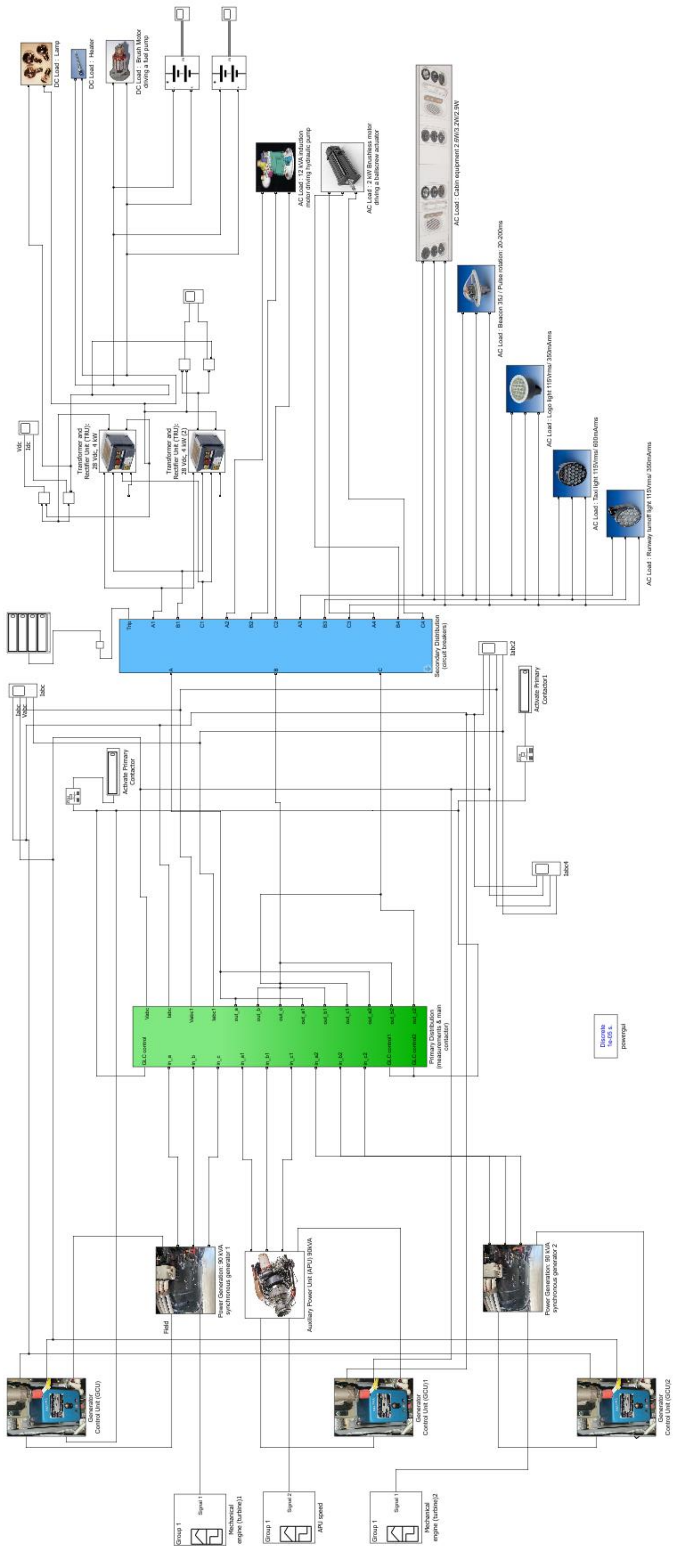


Figure 149 - Airbus A320 final schematic in MATLAB (full)

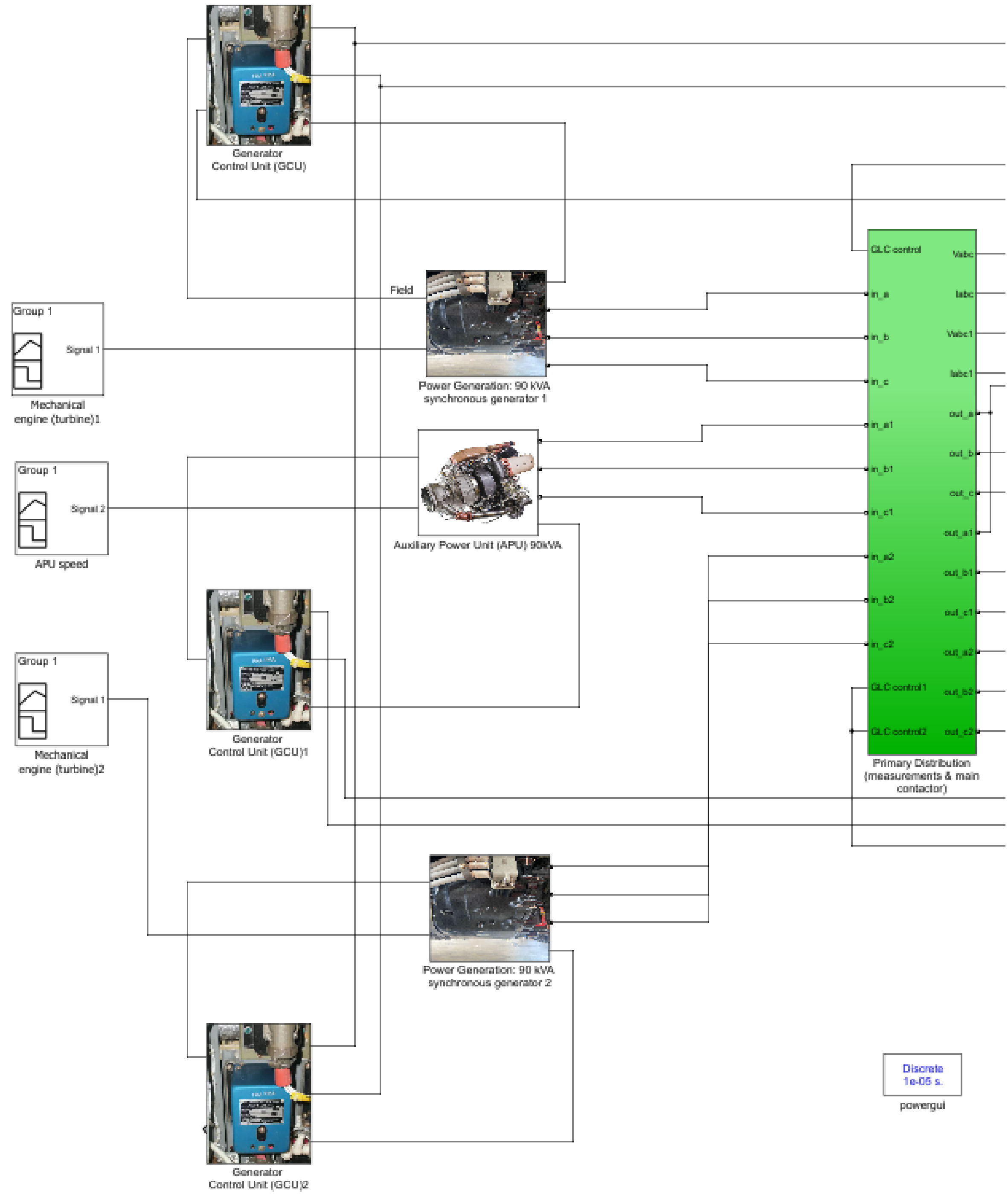


Figure 150 - Airbus A320 final schematic in MATLAB (1/4 parts)

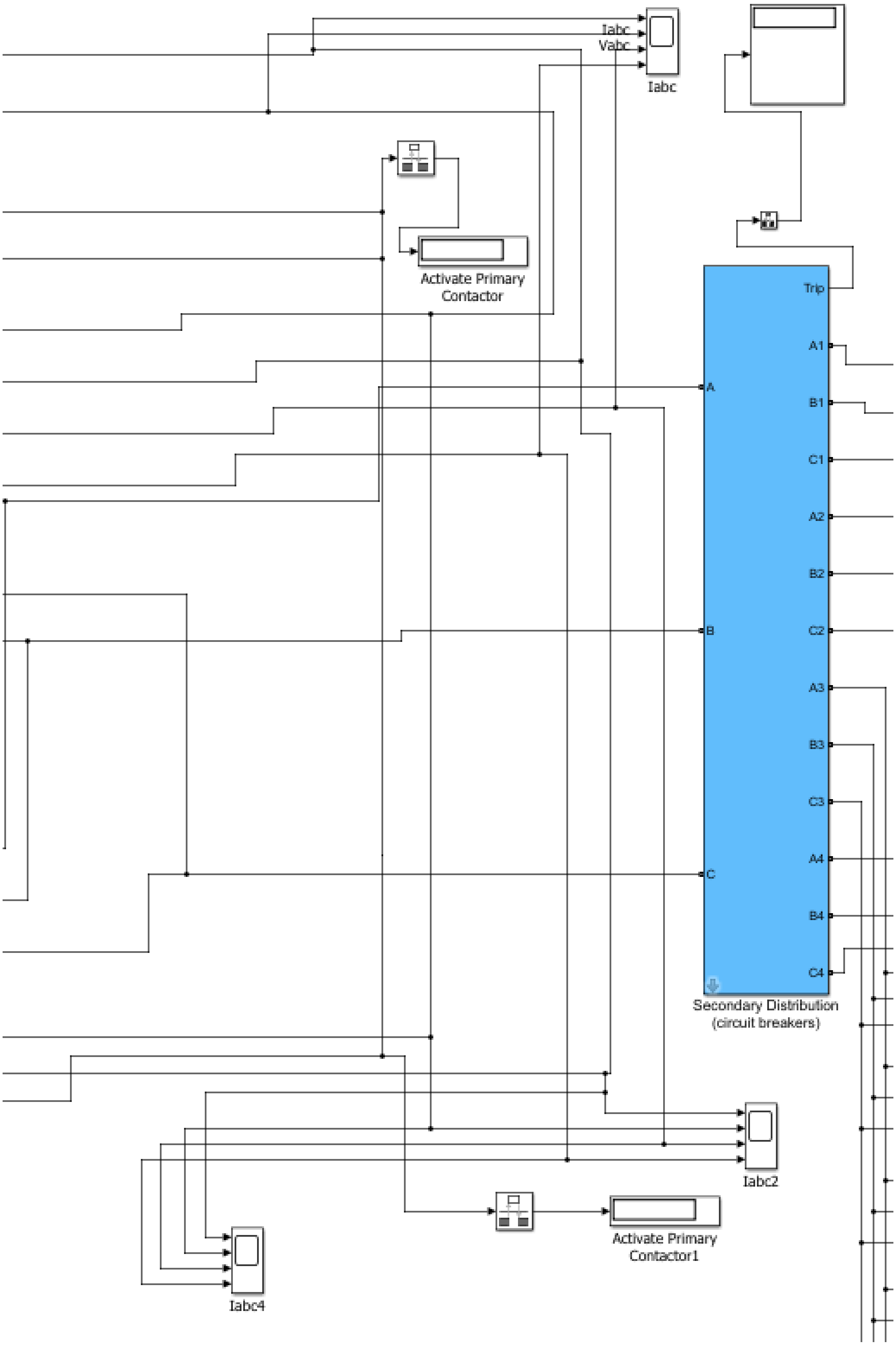


Figure 151 - Airbus A320 final schematic in MATLAB (2/4 parts)

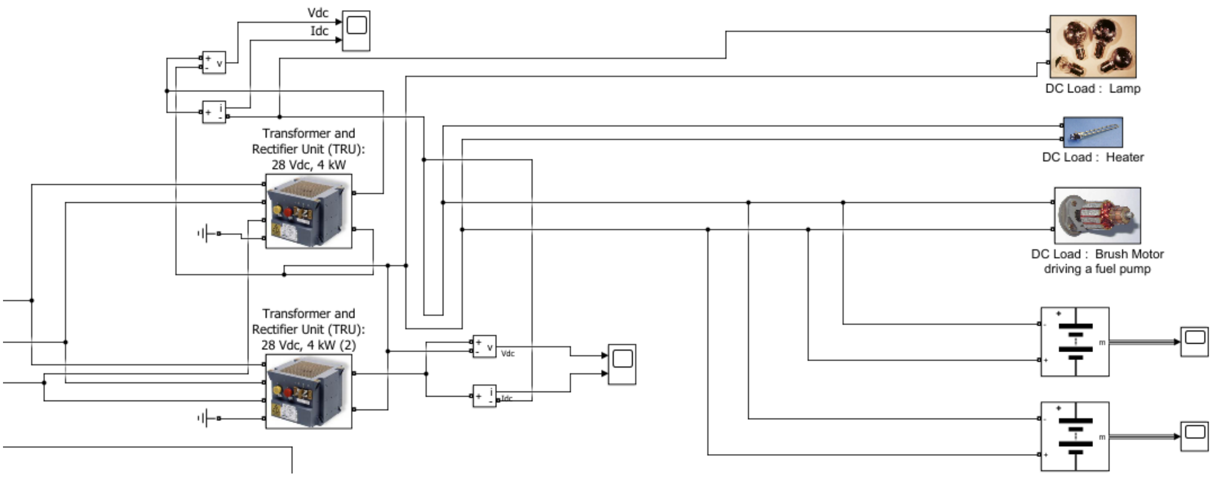


Figure 152 - Airbus A320 final schematic in MATLAB (3/4 parts)

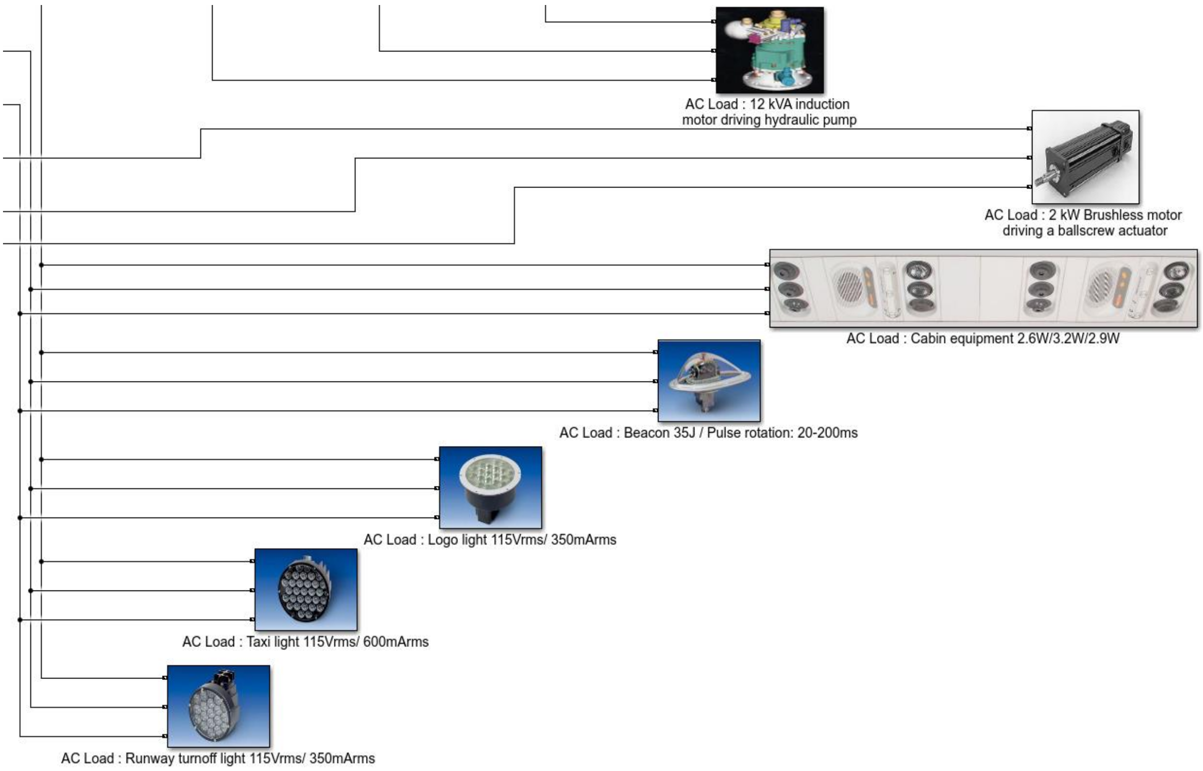


Figure 153 - Airbus A320 final schematic in MATLAB (4/4 parts)

4.4 Simulation results

All previous points described the various component block that this model has, from the basic one to the Airbus A320 model. All block explained before are assembled all together in order to complete the electrical system of the Airbus A320, obviously to some point. Doing a full scale A320 electrical system on MATLAB could take even years to do.

For the simulation I decided to do it in a scale of 60 second simulation. Obviously doing a full-time flight simulation could take even hours to do. The sample profile used to simulate was based on the ELA phases.

1. **Start phase** is from the start up when pushback is done to the start of roll.

2. **Roll phase** begins when the aircraft is leaving the parking stand into the taxiing, to runways and finally the take-off roll. The roll last until the landing gear is not up.

3. **Take-off phase** the moment when the aircraft rises from the surfaces and last altitude of 1500 feet.

4. **Climb** starts above 1500 feet and ending in aircraft cruise level.

5. **Cruise phase** is from the end of climb until the start of descent. This is the longest electrical consumption during the flight, which means it is the highest number consumption, from coffee makers to ovens.

6. **Descent phase** start when aircraft leaves the cruising altitude and ends at 800 feet.

7. **Landing phase** commences at 800 feet when landing gear is down until the touchdown and rollout.

8. **Taxi phase** is from touchdown to the moment when the engines are not running anymore and the aircraft is on stand.

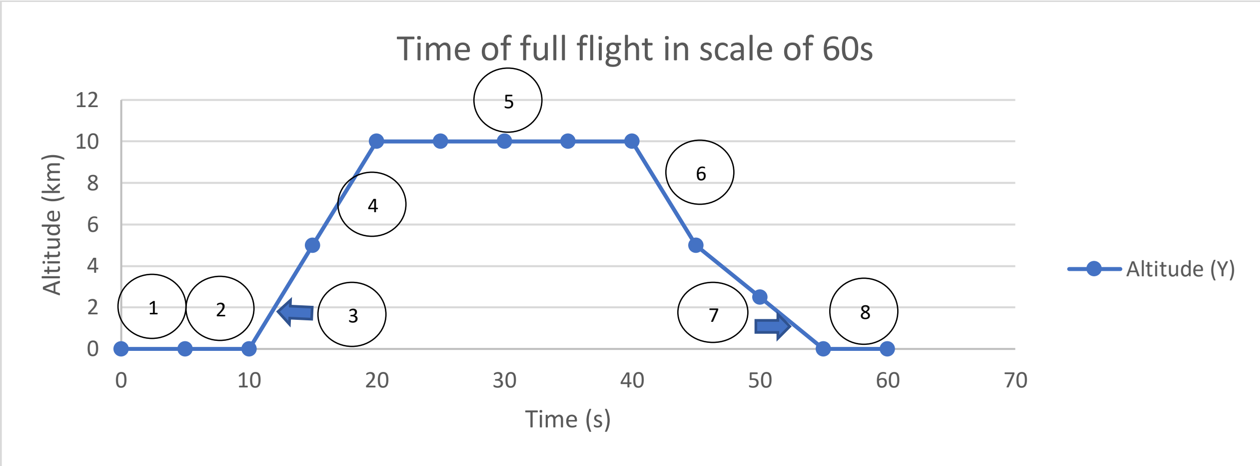


Figure 154 - Altitude graphic during flight

With this same graphic I will determine the speed (rpm) that will be used in the mechanical engine based on actual A320 data during flight. To adjust the speed depending of the flight time or altitude, I have used a Signal Builder block in MATLAB, already explained in point 4.2.1.

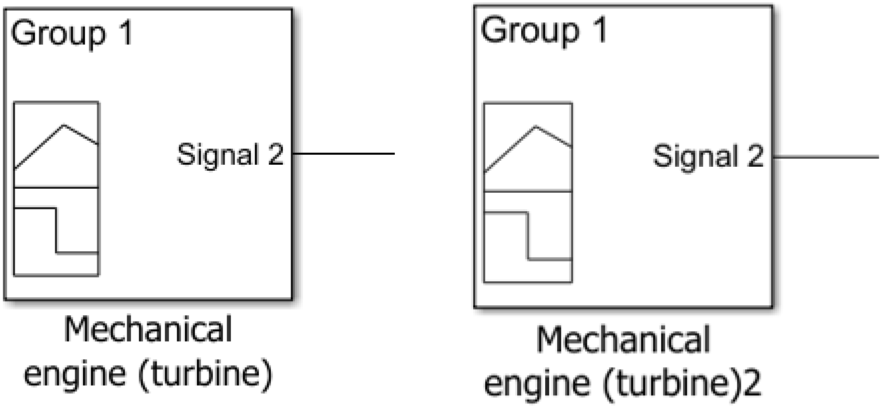


Figure 155 - Two signal builder imitating the mechanical speed

The power sources of the Airbus A320 include two synchronous generators, a secondary generator system called the auxiliary power unit (APU), and a battery. The twin-engine Airbus A320 is capable of supporting 180 kVA (90 kVA from each generator), already explained in the academical part. The APU is composed of a synchronous generator driven by a gas turbine engine.

There are various power distribution buses that route and reroute power through the electrical system for safe operation. Each generator has its own GCU and all of them connected directly to the primary distribution which is directly routed to the secondary distribution into 3 phases (A, B and C).

Then from the secondary distribution each AC and DC load, also including the TRU are connected.

4.4.1 Simple simulations

For this simulation of the Airbus A320, the generators (GEN 1 & GEN 2) and the APU were set to 90 kVA each with the nominal voltage of 115 VAC. Under normal operations, the AC voltage oscillates on 115 VAC and the DC voltage is 28 VDC. Two 23Ah batteries also provided for the DC power with a minimum voltage of 25.5 V.

Despite that, at the beginning we have the two mechanical speed in take for the generators and one for the APU, as shown in Figure 137. However, the following signal shows the actual speed given. All data are real data from an actual Airbus A320.

Starting with the APU speed in take, note that in the Y axis we have rpm as units:

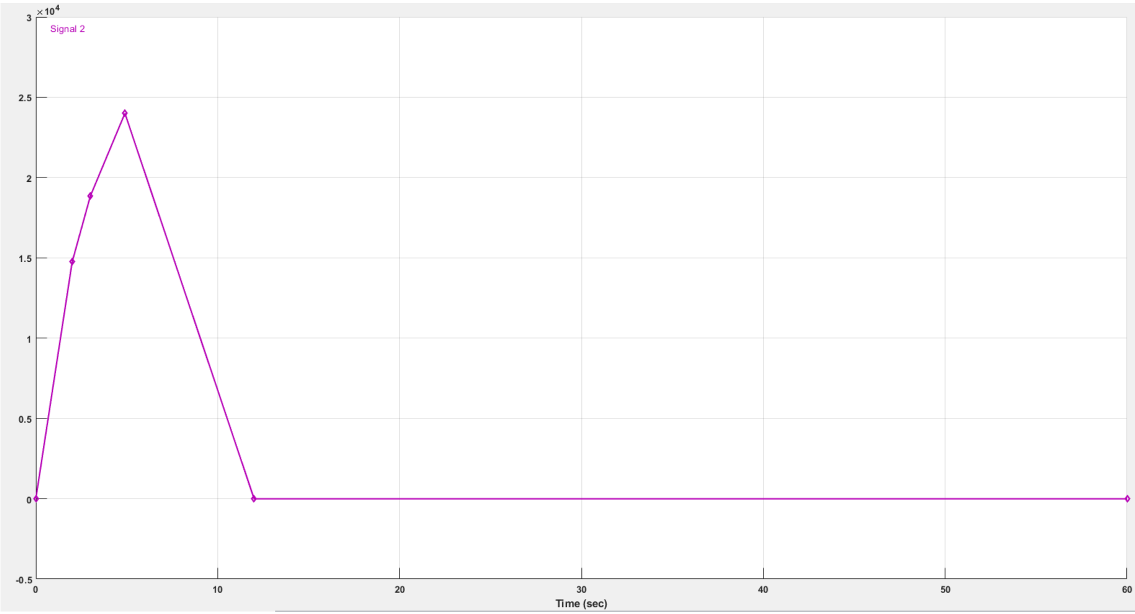


Figure 156 - APU signal builder block

As seen in Figure 138, the APU starts working at a 0-rpm speed and accelerating after reaching its maximum speed of 24000 rpm after 5 second. When 5 second are over, the APU is turned off as the aircraft it is supposed to do the start-up of the engines. When start-up is done APU is off and both generators have an actual speed of 24000 rpm based on a signal builder. Note that in the Y axis we have rpm as units:

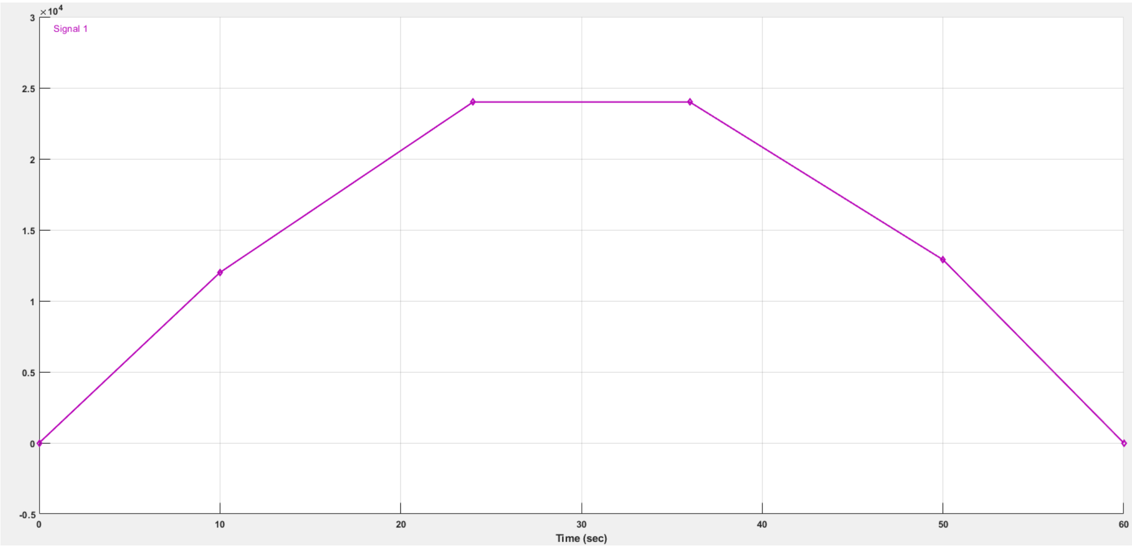


Figure 157 - GEN 1 signal builder plot

Same situation for the second generator, note that in the Y axis we have rpm as units:

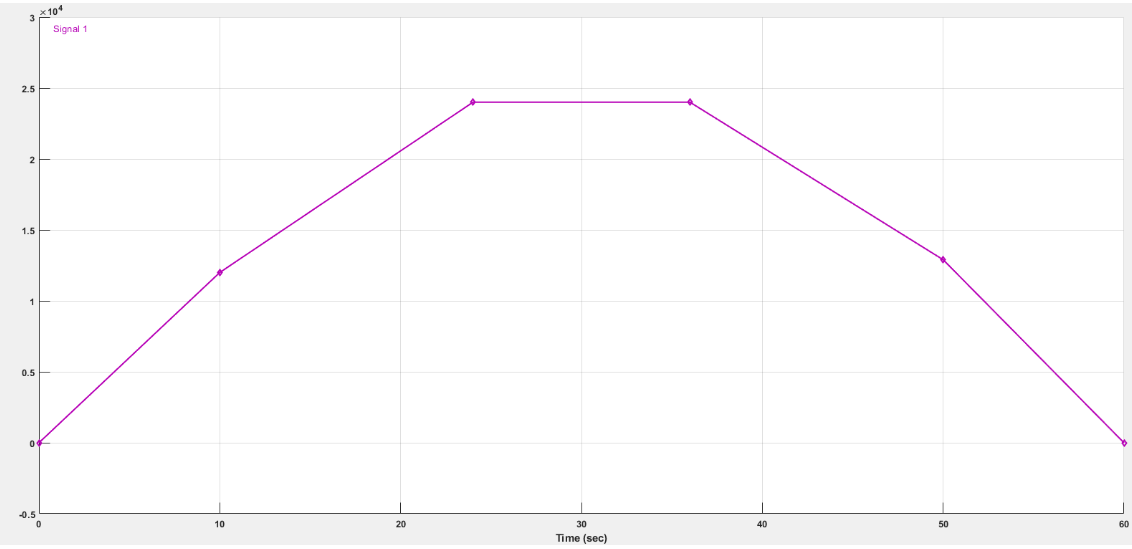


Figure 158 - GEN 2 signal builder plot

After inserting that speed to both generators (GEN1 & GEN2) and the APU, we can obtain the first SCOPE from those mechanical speeds.

Starting from the inside or better said, under the mask of the APU block as shown in the following figure, with the SCOPE we are looking for:

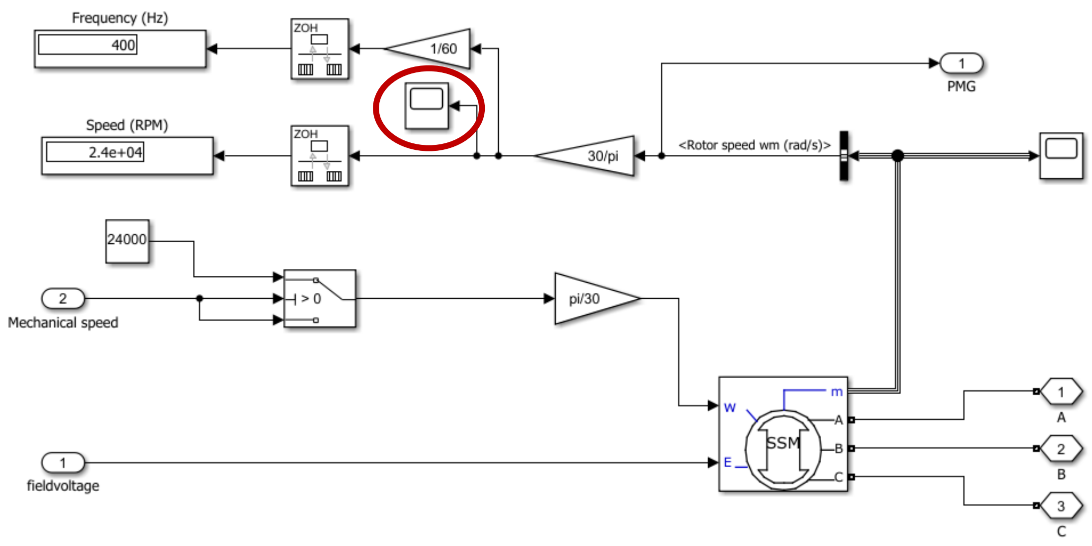


Figure 159 - Under the mask of the APU (SCOPE)

The following figures shows the SCOPE obtained from the speed injected:

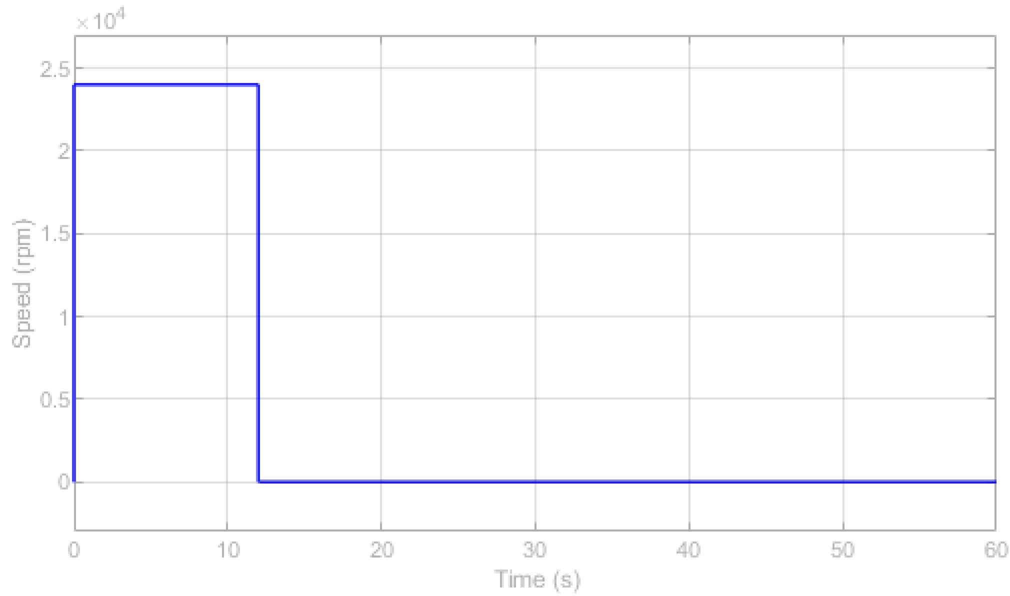


Figure 160 - APU Scope

However, the following two figures will show the speed of each generator, which is equal to 24000 rpm as the A320 manual.

As we observe there is a small retard after the 10th second, which is when the APU speed decreases and both generators start up. I could actually add another phase, which could be the PKN (parking) phase when APU is again connected. However, I found it unnecessary as this is when the flight is already over. But is a simple as adding a scale into the last second of the plot.

It is important to note that the APU functionality changes depending its temperature and altitude, as shown in the following figure:

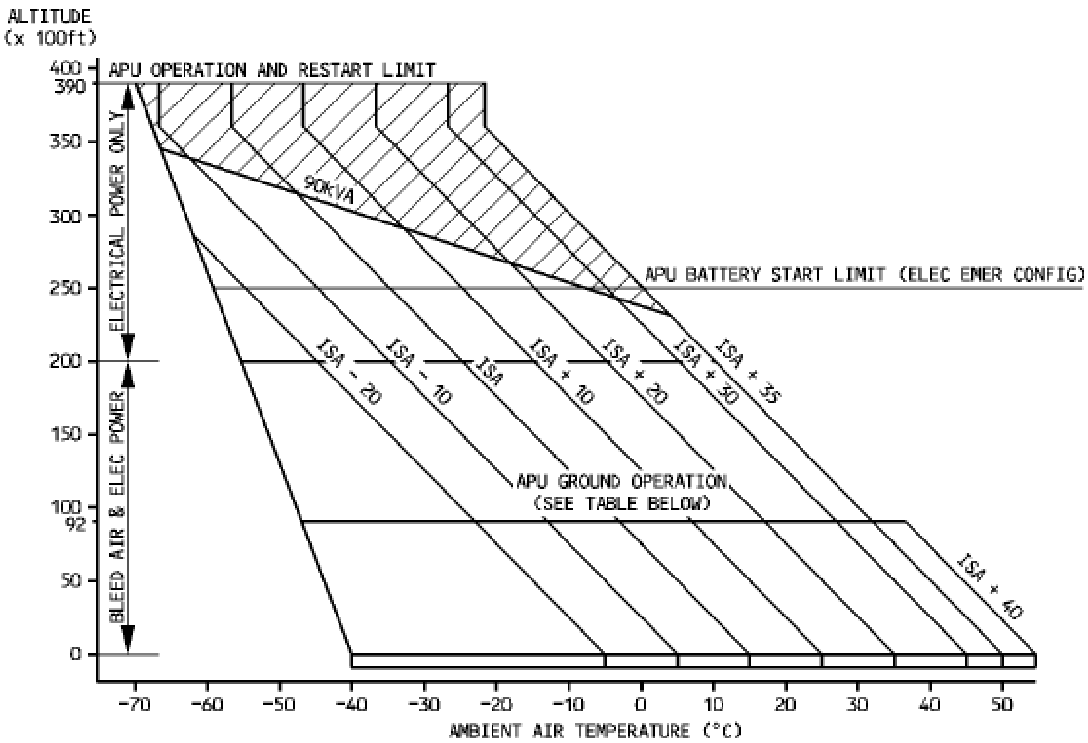


Figure 161 - APU power loses [9]

Now onto the generator simulations, which begin just after APU is off.

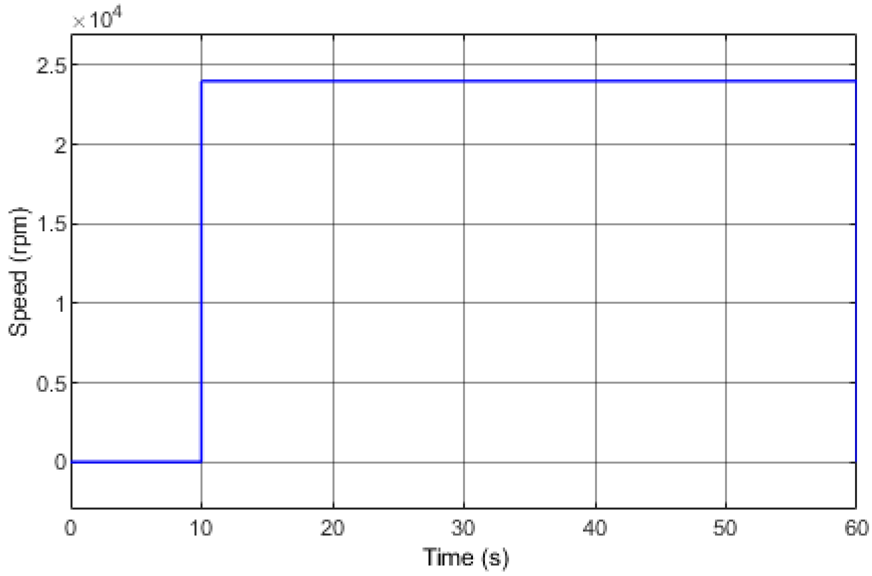


Figure 162 - GEN1 Scope

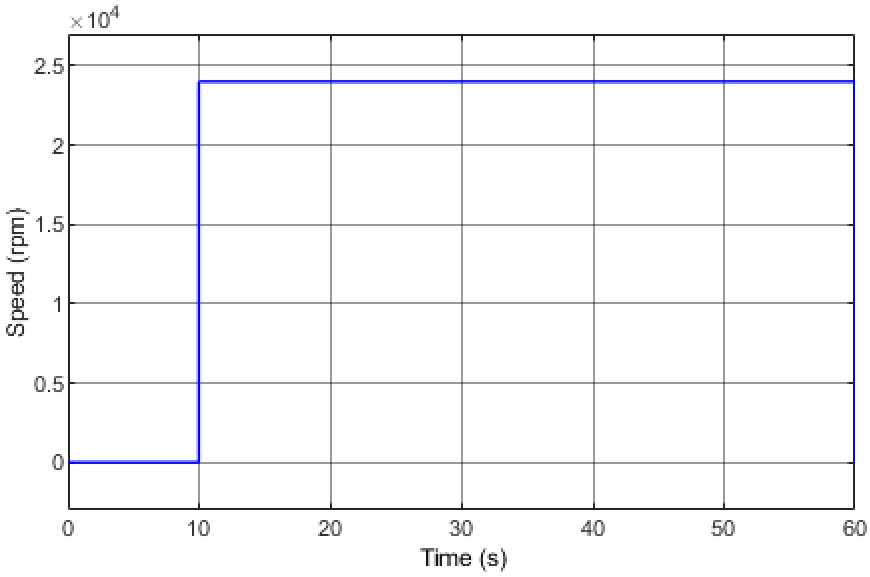


Figure 163 - GEN2 Scope

As seen in Figures 143 and 144, both generators are on after the APU is off. When APU is off it means that the aircraft starts its start-up procedure, which is when the engines are starting.

As this last two figures being the generator simulations in a linear way, there is no appreciation of the two peaks during take-off and the descent transition to approach. Over the 10th – 15th second of flight we could find a voltage and current spike for take-off and between 40th and 45th second of descent. Both of these events are associated with an increase in thrust that increases the engine shaft speed and therefore generator speed. The increase in shaft speed increases the voltage and these voltage spikes can be reduced by changing the parameters of the voltage regulator of the generators or by increasing the size of the generator.

During these simulations, both batteries still maintained the rated 28 VDC approximately.

The various energy flows throughout the electrical system are AC energy, DC energy. All AC and DC power goes to the electrical charges and is converted to heat. All the heat is collected in a sum block and sent to the thermal subsystem for thermal management. These signals do not need to be added and can be sent separately to account for the different locations within the aircraft. For example, some of the heat is passively released through the plane's structure into the environment, and some of the heat is actively treated by the plane's heat exchangers.

During this project, I was searching for exact information of aircraft consumption, the ELA (Electrical Load Analysis), this data was not available in any sort of information I had the opportunity to check. I even went to the Iberia Hangar in LEBL (Barcelona airport) and there was no manual or data about it. However, I have managed to deduce some of those values by checking similar aircraft such as Boeing 737 which is a really similar model to the A320.

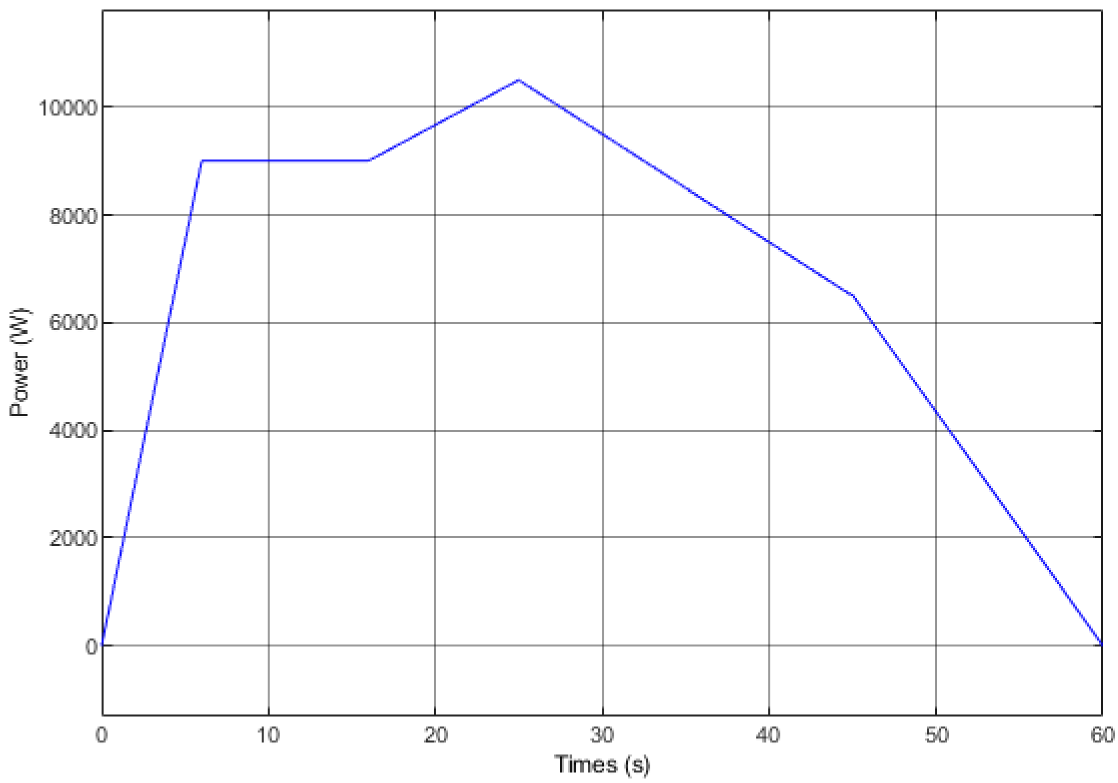


Figure 164 - AC power demand

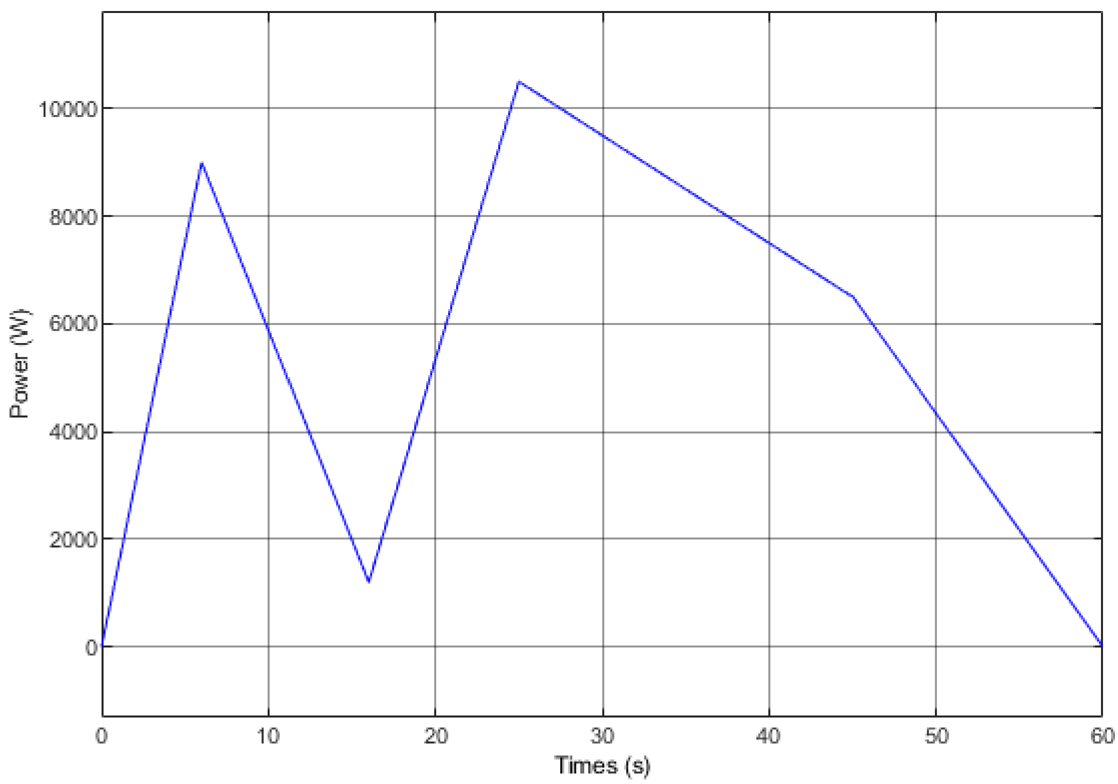


Figure 165 - DC power demand

4.5 Faults

When it comes to airworthiness, there is a distinct connection to flight safety, although it can be somewhat complicated. When a defect is present in the aircraft, it significantly affects airworthiness and can cause the craft to fail to meet the required conditions for safe operation.

I had the opportunity to experience in Iberia's Hangar which are the actual faults for most common commercial aircraft, but in specific the Airbus A320 which will be explained later on.

If left uncorrected defects can cause major accidents. Sometimes, the aircrew themselves are partly to blame in the event of a malfunction due to an improper response. Nowadays accidents are less probable than before, however, they still happen, some of them because of the electrical system failure. Good examples are the Aeroflot flight 909 or the Air Illinois flight 710. The aircraft lost control following an electrical failure and crashed near Voronezh in the Soviet Union and the other the flight crew's mismanagement of electrical generator and distribution problems.

In aviation we can find different faults or failures, the most common are:

- Overload.
- Accidental damage.
- Environmental damage.
- Maintenance errors.
- Deterioration.
- Human factors.
- Wrong control configuration.
- Inadequate maintenance or servicing.
- Legislation changes.
- Hazard regarding fuel and/or fuel system.
- Design and supply.
- Operating the aircraft beyond the certificated limits.

There are many procedures that can help with threats such as degradation, including vibration analysis. Vibration analysis is a process that monitors the levels and patterns of vibration signals within a component, machinery or structure, to detect abnormal vibration events and to evaluate the overall condition of the test object.

The main vibrations generators on the aircraft are the hydraulic pipeline system, the hydraulic pipeline system is an important mechanical and electrical system for aircraft control tasks, such as landing gear, flaps and deceleration plate, aileron, elevator and rudder assistant control, wheel brake and front wheel turning.

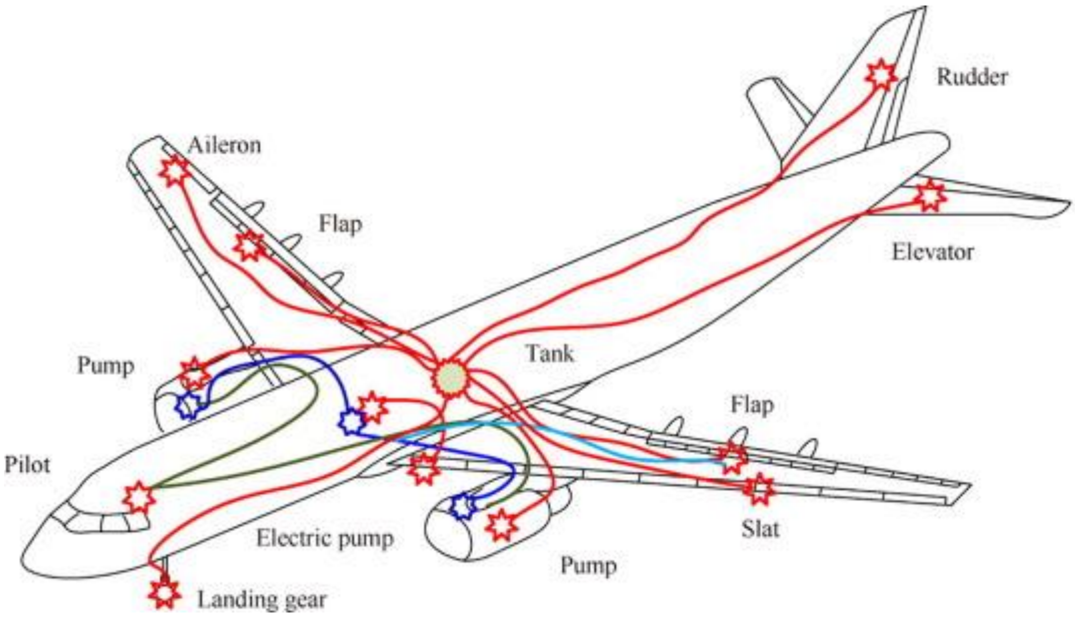


Figure 166 - Hydraulic aircrafts pipeline system [9]

4.5.1 Airbus A320 faults

In the Airbus family different faults can happen. From the previous one commented into even more catastrophic. However, it is considered to be the manufacturer in grand scale with less aircraft failures compared to other.

In general, the most common faults in the Airbus A320, including all systems are:

- Dual FM reset.
- Engine fire on start-up.
- ADR 1 fault.
- Brake release on landing.
- Unreliable airspeed.
- Overspeed.
- Air bleed fault 1+2.
- Air pack fault.
- Exhaust and blower fault.
- Air Pack 1(2) fault.
- APU auto (emer) shutdown.
- Eng 1(2) fuel filter clogged.
- Nav adr 3 fault.
- Cids in maintenance.
- Bleed in maintenance.
- SEC1 fault.
- ELEC/CB/s tripped.
- Transformer rectifier problem.

- F/CTL elac 1 pitch fault.
- HYD RAT fault.
- Anti-Ice L(R) window.
- Brakes hot.
- ELEC-BCL 1(2) fault.
- Smoke detection fault.
- TPIS fault.
- Auto FLT rudder travel limiter system fault.
- Auto FLT FCU 1 fault.
- COM single PTT stuck.
- ELEC GEN 1(2) fault.
- Avionics smoke.
- Igniter fault.
- GPU will not connect.
- All 24 chapters Cb/s
- L/G LGCIU 1 fault.
- Flap runway disagree.
- Air cooling system fault.
- Engine generator parameters not shown.
- Fuel CTR TK pumps off.

From all those faults, several of them are actually related directly to the electrical system of the aircraft, such as:

- APU auto (emer) shutdown.
- Eng 1(2) fuel filter clogged
- F/CTL elac 1 pitch fault
- Anti-Ice L(R) window.
- ELEC GEN 1(2) fault.
- ELEC/CB/s tripped.
- ELEC-BCL 1(2) fault.
- GPU will not connect.
- All 24 chapters Cb/s
- Transformer rectifier problem.
- Engine generator parameters not shown.

I consider that entering into detail for all A320 faults is not as relevant as entering into detail for the electrical ones.

The '**Engine generator parameters not shown'** fault aircraft configuration prior to reset.

LABEL	PANEL	NUMBER
ENG #1	122VU	T26,Z30,AF12
ENG #2	122VU	T27,Y31,AF1

Figure 167 - Circuit breakers to reset

To clear the warning, open associated CB/s for 1 second, then close. Associated GCU or EGIU is at fault, there is a reset button on each GCU (Nose E&E). **Signs TSM24-22-00-810-805 (#1 engine parameter check) and TSM24-22-00-810-807 (#2 engine parameter check)** must go off. Deferral **MEL24-20-01=Engine Driven Generator** is applicable.

For the '**ELEC/CB/s tripped'** there is no specific configuration. Just by resetting the tripped circuit breaker only once, if unsuccessful, do not make second attempt, troubleshoot and fix problem. If no tripped breakers can be located, a green circuit breaker in the identified panel has failed. Remember, green breakers do exist in relay panels 105VU and 106VU located in the E&E bay. The sign **US AMM CHAPTER20-24-20** must be off.

Then we have the '**Transformer Rectifier problem'.** Aircraft on ground for prior configuration reset. First, reset T/R's through MCDU or all three using guarded button on 103VU panel in E&E bay. If unsuccessful, reset associated breaker.

LABEL	PANEL	NUMBER
TR #1	123VU	AB10
TR #2	123VU	AB4
TR #3	106VU	TR3

Figure 168 - Circuit breakers to reset (2)

If ESS TR3 is in operation with TR1 & TR2 serviceable, release the AC ESS FEED pushbutton on the 35VU, then push the AC ESS FEED pushbutton. ESS TR3 will return to standby. Sign that must be off are: **TSM24-30-00-810-801 (#1 TR test) and TSM24-30-00-810-802 (#2 TR test).** For applicable deferral **MEL24-30-01=Transformer/Rectifier Units (TR).**

Continuing with **'ELEC-BCL 1(2) fault',** prior configuration aircraft on ground.

LABEL	PANEL	NUMBER
BAT/REF/BCL #1 & BAT/BUS/REF/BCL1		
BAT/REFBCL #2 & BAT/BUS/REF/BCL2		

Figure 169 - Circuit breakers to reset (3)

Reset by using associated battery pushbutton in overhead. If no help, open associated breakers for 1 second, then close. All circuit breakers are located on the 105VU in the E&E panel. Sign **AMM24-38-00-710-001** must be off.

Then, the ground power won't connect, no AVAIL LIGHT in pushbutton or also known as **'GPU will not connect'**. The aircraft stays on ground, engines stopped, APU stopped, ground power connected.

LABEL	PANEL	NUMBER
GPCU	122VU	Y24

Figure 170 - Circuit breakers to reset (4)

Sign **AMM24-41-00-740-002** must be off and applicable deferrals are: **MEL24-41-01=External Power Control, MEL24-41-02=" Not in use" or "AVIL" light inop and MEL24-41-03=EXT PWR PB Switch.**

Finally, there is a full chapter list for all circuit breaker location that important to note, they are in order of designation | location | panel:

- |COM/VHF/1 | G09 | 49VU
- |ELEC/GALLEY/CNTOR | S28 | 122VU
- |ELEC/HOT BUS/701PP SPLY | D01 | 105VU
- |ELEC/HOT BUS/702PP SPLY | D02 | 105VU
- |ELEC/BAT BUS/REF/BCL1 | G01 | 105VU
- |ELEC/BAT BUS/REF/BCL2 | J02 | 105VU
- |ELEC/BAT REF/BCL1 | F01 | 105VU
- |ELEC/BAT REF/BCL2 | F02 | 105VU
- |ELEC/HOT BUS/701PP SPLY | E01 | 105VU
- |ELEC/HOT BUS/702PP SPLY | E02 | 105VU
- |ELEC/CNTOR/ESS/DC BUS/TIE | W26 | 122VU
- |ELEC/TR1/FAULT/DC BUS TIE/CONFIG | W29 | 122VU
- |ELEC/TR2/FAULT/DC BUS TIE/CONFIG | W30 | 122VU
- |ELEC/CNTOR/DC/BUS/TIE1 | W25 | 122VU
- |ELEC/CNTOR/DC BUS/TIE 1/FAULT | U24 | 122VU

- |AC ESS/BUS/EMER/CNTOR/SPLY | C08 | 106VU
- |ELEC/DC BUS/TIE2//APU/START | W31 | 122VU
- |ESS TR/SPLY | C01 | 106VU
- |ESS TR/CNTOR/CTL | C02 | 106VU
- |EMER/SHED/CNTOR/SPLY | C07 | 106VU
- |ELEC/DC/SVCE/BUS | X24 | 122VU
- |ELEC/DC SHED BUS/CNTR | U26 | 122VU
- |ELEC/REFLNG/ON/BAT | U28 | 122VU
- |ELEC/REFLNG/NORM | S27 | 122VU
- |ELEC/RFL/SPLY/LOGIC | U29 | 122VU
- |ELEC/TR1/MONG | X25 | 122VU
- |ELEC/TR2/MONG | X26 | 122VU
- |ELEC/DC SVCE/BUS/ON TR2 | U30 | 122VU
- |ELEC/GALY & CAB/CTL | S26 | 122VU
- |ELEC/GALY & CAB/GND/FLT/LOGIC | S24 | 122VU
- |ELEC/GALY & CAB/FAULT/LT CTL | S25 | 122VU
- |ELEC/STAT INV/BUS 901XP/SPLY | H02 | 105VU
- |ELEC/STAT INV/CNTOR/CTL | G02 | 105VU
- |AC ESS/BUS NORM/CNTOR/CTL | B03 | 106VU
- |AC ESS BUS/STBY/CNTOR/CTL | B08 | 106VU
- |AC ESS BUS/EMER/CNTOR/CTL | B07 | 106VU
- |CSM/G /EV/MAN/SPLY | B04 | 106VU
- |ELEC/CSM/G /EV AUTO/SPLY | C01 | 105VU
- |ELEC/EMER GEN AUTO/2 | Z26 | 122VU
- |AC ESS BUS/EMER/STBY/CNTOR/SPLY | C06 | 106VU
- |ELEC/EMER GEN AUTO/1 | Z25 | 122VU
- |ELEC/EXT PWR/LT CLT/AVAIL | X31 | 122VU
- |ELEC/EXT PWR/LT CLT/NOT IN/USE | X30 | 122VU
- |ELEC/GPCU | Y24 | 122VU
- |ELEC/EXT PWR/CTL | X29 | 122VU
- |ELEC/EXT PWR/COCKPIT/AVAIL/LT | X28 | 122VU
- |ELEC/LT/CTL | H10 | 49VU
- |AC/SHED/ESS BUS/CNTOR/CTL | C04 | 106VU
- |AC ESS BUS/MONG/SPLY | C05 | 106VU
- |26VAC/ESS BUS/SPLY | B06 | 106VU
- |ELEC/AC BUS/8XP/MONG | H11 | 49VU
- |ELEC/AC/BUS1/CTL | V25 | 122

5. Discussion and conclusions

A specific model of different components has been created in order to understand and simulate an Airbus A320 electrical system, however this MATLAB is still far from the exact model in a 1:1 scale.

My first conclusion for this thesis is figuring out how difficult it was for me to find information regarding the electrical system of any aircraft as base in the theoretical part and also regarding the practical part based on the Airbus A320.

In addition, I must say I still had several advantages as I already said during this work, I am an employee for Iberia at Barcelona's airport and this gave me the opportunity to be closer to any other information anyone could get.

In second place, a sample electrical system model of an Airbus A320 was modelled and simulated with similar components as the real one taking into account the MATLAB library is limited. All this electrical system included the generation and distribution systems. Unfortunately, the aircraft faults simulation, such as generator's fault, could not be done because lack of several information and time due to dead-line. However maybe in further studies this project could be continued with more detail, in which I would be extremely excited on doing it.

The development of this model in MATLAB is an ongoing process to makes it accurate, easy and fast to daily usage. Obviously, everything could be improved, for example by adding exact wires length as in a real A320 is used. However, as I already mentioned before, this is a matter of information and time.

Finally, as being part of this project, the usage of this toolset permits me to improve my knowledge in several fields, such as in electrical and aviation. Hopefully once I could come back to this and try to improve it even more with new technologies.

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List of acronyms for the Airbus A320

A - Amber

A - Alternate

A/C - Aircraft

A/D - Analog/Digital

A/DC - Analog-to-Digital Converter

A/R - Audio Reproducer

A/SKID - Anti-Skid

A/THR - Autothrust

A/XFMR - Autotransformer

ABCU - Alternate Braking Control Unit

AC - Alternating Current

ACARS-Aircraft Communication Addressing and Reporting System

ACC - Active Clearance Control

ACCEL - Acceleration/Accelerate

ACCLRM - Accelerometer

ACCU - ACCUMULATOR

ACMM - Abbreviated Component Maintenance Manual

ACMS - Aircraft Condition Monitoring System

ACP - Area Call Panel

ACP - Audio Control Panel

ACQN - Acquisition

ACSC - Air Conditioning System Controller

ACT - Active

ACTR - Actuator

ADC - Air Data Computer

ADF - Automatic Direction Finder

ADIRS - Air Data/Inertial Reference System

ADIRU - Air Data/Inertial Reference Unit

ADM - Air Data Module

ADR - Air Data Reference

ADS - Air Data System

ADV - Advisory

AEVC - Avionics Equipment Ventilation Computer

AF - Audio Frequency

AFS - Automatic Flight System

AGB - Accessory Gearbox

AGC - Automatic Gain Control

AGL - Above Ground Level

AGW - Actual Gross Weight

AIL - Aileron

AIM - Aircraft Integrated Maintenance

AIP - Attendant Indication Panel

ALIGN - ALIGNMENT

ALT - Altitude

ALTM - Altimeter

ALTN - Alternate, Alternative

AM - Amplitude Modulation

AMM - Aircraft Maintenance Manual

AMU - Audio Management Unit

ANI - Analog Input

ANN - Annunciator

ANN LT - Annunciator Light

ANO - Analog Output

ANT - Antenna

AOA - Angle-of-Attack

AP - Autopilot

AP/FD - Autopilot/Flight Director

APPR - Approach

APPU - Asymmetry Position Pick Off Unit

APU - Auxiliary Power Unit

ARINC - Aeronautical Radio Incorporated

ARPT - Airport

ASCII - American Standard Code for Information Interchange

ASI - Airspeed Indicator

ASIC - Application Specific Integrated Circuits

ASM - Aircraft Schematics Manual

ASP - Audio Selector Panel

ASSY - Assembly

ATA - Air Transport Association of America

ATC - Air Traffic Control

ATE - Automatic Test Equipment

ATLAS - Abbreviated Test Language for All Systems

ATS - Autothrottle System

ATSU - Air Traffic Service Unit

ATT - Attitude

ATTND - Attendant

AUTO - Automatic

AUX- Auxiliary

AVAIL - Available

AVNCS - Avionics

AWM - Aircraft Wiring Manual

AWY - Airway

AZ - Azimuth

B - Blue

BARO - Barometric

BAT - Battery

BCD - Binary Coded Decimal

BCL - Battery Charge Limiter

BFO - Beat Frequency Oscillator

BGM - Boarding Music

BITE - Built-in Test Equipment

BMC - Bleed Monitoring Computer

BNR - BINARY

BOT - Begin of Tape

BP - Bottom Plug

BRG - Bearing

BRK - Brake

BRKR - Breaker

BRKT - Bracket

BRT - Bright, Brightness

BSCS - Braking and Steering Control System

BSCU - Braking/Steering Control Unit

BTC - Bus Tie Contactor

BTMU - Brake Temperature Monitoring Unit

BTN - Button

BTR - Bus Tie Relay

BU - Battery Unit

BUS - Busbar

BYDU - Back-Up Yaw Damper Unit

C - Close

C - Celsius, Centigrade

C/B - Circuit Breaker

C/L - Check List

CAB - Cabin

CAM - Cabin Assignment Module

CAPT - Captain

CAS - Calibrated Air Speed

CAUT - Caution

CAUT LT - Caution Light

CBMS - Circuit Breaker Monitoring System

CBMU - Circuit Breaker Monitoring Unit

CCS - Cabin Communications System

CCW - Counter Clockwise

CDP - Compressor Discharge Pressure

CDU - Control and Display Unit

CFDIU - Centralized Fault Display Interface Unit

CFDS - Centralized Fault Display System

CFMI - CFM International

CFRP - Carbon Fiber Reinforced Plastic

CG - Center of Gravity

CGCS - Center of Gravity Control System

CHAN - Channel

CHG - Change

CIDS - Cabin Intercommunication Data System

CK - Check

CKPT - Cockpit

CKT - Circuit

CL - Center Line

CLB - Climb

CLG - Centerline Landing Gear

CLOG - Clogging

CLR - Clear

CMC - Central Maintenance Computer

CMD - Command

CMM - Component Maintenance Manual

CMS - Central Maintenance System

CNTOR - Contactor

CO - Company

COM - Communication

COMPT - Compartment

COMPTR - Comparator

COND - Conditioned, Conditioning

CONFIG - Configuration

CONT - Controller

CONV - Converter

COOL - Cooling, Cooler

COS - Cosine

CPC - Cabin Pressure Controller

CPLR - Coupler

CPMS - Cabin and Passenger Management System

CPMU - Cabin Passenger Management Unit

CPRSR - Compressor

CPU - Central Processing Unit

CRC - Continuous Repetitive Chime

CRG - Cargo

CRS - Course

CRT - Cathode Ray Tube

CRZ - Cruise

CSD - Constant Speed Drive

CSM/G - Constant Speed Motor/Generator

CSTR - Constraint

CSU - Command Sensor Unit

CT - Current Transformer

CTL - Central

CTL - Control

CTR - Center

CU - Control Unit

CUDU - Current Unbalance Detection Unit

CUR - Current

CVR - Cockpit Voice Recorder

CVT - Center Vent Tube

CW - Clockwise

D/D - Engine Out Drift Down Point

D/O - Description and Operation

DA - Drift Angle

DAC - Digital to Analog Converter

DAR - Digital ACMS Recorder

DC - Direct Current

DDRMI - Digital Distance and Radio Magnetic Indicator

DEC - Declination

DECEL - Decelerate

DECR - Decrease

DEF - Definition

DELTA P - Differential Pressure

DES - Descent

DEST - Destination

DET - Detection, Detector

DEU - Decoder/Encoder Unit

DEV - Deviation

DFDR - Digital Flight Data Recorder

DFDRS - Digital Flight Data Recording System

DGI - Digital Input

DGO - Digital Output

DH - Decision Height

DIA - Diameter

DIFF - Differential

DIM - Dimming, Dimension

DIR - Direction, Direct, Director

DISC - Disconnect, Disconnected

DIST - Distance

DMA - Direct Memory Access

DMC - Display Management Computer

DME - Distance Measuring Equipment

DMU - Data Management Unit

DN - Down

DNLK - Downlock

DPDT - Double Pole/Double Throw

DPI - Differential Pressure Indicator

DR - Dead Reckoning

DRVR - Driver

DSCRT - Discrete

DSDL - Dedicated Serial Data Link

DSI - Discrete Input

DSO - Discrete Output

DSPL - Display

DTG - Distance to Go

DTMF - Dual Tone Multiple Frequency

DU - Display Unit

E - East

ECAM - Electronic Centralized Aircraft Monitoring

ECB - Electronic Control Box (APU)

ECM - Engine Condition Monitoring

ECMU - Electrical Contactor Management Unit

ECON - Economy

ECP - Ecam Control Panel

ECS - Environmental Control System

ECU - Electronic Control Unit

EEC - Electronic Engine Control

EEPROM -Electrically Eraseable Programmable Read Only Memory

EFCS - Electrical Flight Control System

EFF - Effective, Effectivity

EFIS - Electronic Flight Instrument System

EGIU - Electrical Generation Interface Unit

EGT - Exhaust Gas Temperature

EIS - Electronic Instrument System

EIU - Engine Interface Unit

EIVMU - Engine Interface and Vibration Monitoring Unit

ELEC - Electric, Electrical, Electricity

ELEV - Elevation, Elevator

EMER - Emergency

EMI - Electromagnetic Interference

EMM - Enhanced Maintaining and Manufacturing

END - Endurance

ENG - Engine

EO - Engine Out

EOSID - Engine Out Standard Instrument Departure

EOT - End of Tape

EPC - External Power Contactor

EPGS - Electrical Power Generation System

EPR - Engine Pressure Ratio

EPROM - Erasable Programmable Read Only Memory

EPSU - Emergency Power Supply Unit

EQPT - Equipment

ESS - Essential

EST - Estimated

ETA - Estimated Time of Arrival

ETE - Estimated Time en Route

ETP - Equal Time Point

EVAC - Evacuation

EWD - Engine/Warning Display

EXC - Excitation, Excite

EXCESS - Excessive

EXT - Exterior, External

F - Fahrenheit

F-PLN - Flight Plan

F/O - First Officer

FAC - Flight Augmentation Computer

FADEC - Full Authority Digital Engine Control

FAIL - Failed, Failure

FAP - Forward Attendant Panel

FC - Fully Closed

FCDC - Flight Control Data Concentrator

FCMS - Fuel Control Monitoring System

FCOM - Flight Crew Operating Manual

FCPC - Flight Control Primary Computer

FCSC - Flight Control Secondary Computer

FCTN - Function

FCU - Flight Control Unit

FCV - Flow Control Valve

FD - Flight Director

FDBK - Feedback

FDIU - Flight Data Interface Unit

FDU - Fire Detection Unit

FE - Flight Envelope

FF - Fuel Flow

FG - Flight Guidance

FIDS - Fault Isolation and Detection System

FIFO - First Input/First Output

FIG - Figure

FIN - Functional Item Number

FL - Flight Level

FLEX - Flexible

FLP - Flap

FLT - Flight

FM - Flight Management

FMA - Flight Mode Annunciator

FMC - Flight Management Computer

FMGC - Flight Management and Guidance Computer

FMGS - Flight Management and Guidance System

FMGS - Flight Management and Guidance System

FMS - Flight Management System

FMV - Fuel Metering Valve

FO - Fully Open

FOB - Fuel On Board

FPA - Flight Path Angle

FPEEPMS-Floor Proximity Emergency Escape Path Marking System

FPPU - Feedback Position Pick-off Unit

FPV - Flight Path Vector

FQ - Fuel Quantity

FQI - Fuel Quantity Indicating/Indication/Indicator

FR - Frame

FREQ - Frequency

FRU - Frequency Reference Unit

FRV - Fuel Return Valve

FSB - Fasten Seat Belts

FW - Failure Warning

FWC - Flight Warning Computer

FWD - Forward

FWS - Flight Warning System

G - Green

G/S - Glide Slope

GA - Go-Around

GAPCU - Ground Auxiliary Power Control Unit

GCR - Generator Control Relay

GCU - Generator Control Unit

GEN - Generator

GLC - Generator Line Contactor

GLR - Generator Line Relay

GMT - Greenwich Mean Time

GND - Ground

GPCU - Ground Power Control Unit

GPS - Global Positioning System

GPU - Ground Power Unit

GPWC - Ground Proximity Warning Computer

GPWS - Ground Proximity Warning System

GRU - Ground Refrigeration Unit

GS - Ground Speed

GSE - Ground Support Equipment

GW - Gross Weight

H - Hot (Electrical Point)

HCU - Hydraulic Control Unit

HDG - Heading

HEGS - Hydraulic Electrical Generating System

HF - High Frequency

HI - High

HLAC - High Level Alternating Current Voltage

HLDC - High Level Direct Current Voltage

HMU - Hydromechanical Unit

HP - High Pressure

HPC - High Pressure Compressor

HPT - High Pressure Turbine

HPTACC - High Pressure Turbine Active Clearance Control

HS - High Speed

HSI - Horizontal Situation Indicator

HSMU - Hydraulic System Monitoring Unit

HUDC - Head Up Display Computer

HYD - Hydraulic

I/O - Input/Output

I/P - Intercept Profile

I/P - Input

IAE - International Aero Engines

IAS - Indicated Airspeed

IDENT - Identification, Identifier, Identify

IDG - Integrated Drive Generator

IGB - Inlet Gear Box

IGN - Ignition

IGV - Inlet Guide Vane

ILS - Instrument Landing System (LOC and G/S)

IMM - Immediate

INB - Inbound

INBD - Inboard

INCR - Increment

IND - Indicator

INFO - Information

INHIB - Inhibition, Inhibit, Inhibited

INIT - Initial(ization)

INOP - Inoperative

INR - Inner

INT - Interrupt

INTCP - Intercept

INTFC - Interface

INTL - Internal

INTRG - Interrogate, Interrogator

INV - Inverter

IP - Intermediate Pressure

IPC - Illustrated Parts Catalog

IPPU - Instrumentation Position Pick-off Unit

IR - Inertial Reference

IRS - Inertial Reference System

ISA - International Standard Atmosphere

ISO - International Standardization Organisation

ISOL - Isolation

IVS - Inertial Vertical Speed

JAM - Jammed, Jamming

JAR - Joint Airworthiness Requirements

L - Left

L - Length

L/G - Landing Gear

LA - Linear Accelerometer

LAT - Lateral

LAT - Latitude

LAV - Lavatory

LBP - Left Bottom Plug

LCD - Liquid Crystal Display

LCIT - Load Compressor Inlet Temperature

LDG - Landing

LE - Leading Edge

LED - Light Emitting Diode

LGCIU - Landing Gear Control and Interface Unit

LIM - Limit, Limitation, Limiting, Limiter

LKD - Locked

LL - Lat/Long

LLDC - Low Level Direct Current Voltage

LMP - Left Middle Plug

LNG - Long

LMS - Leakage Measurement System

LO - Low

LOC - Localizer

LONG - Longitude

LONGN - Longeron

LOP - Low Oil Pressure

LP - Low Pressure

LPT - Low Pressure Turbine

LPTACC - Low Pressure Turbine Active Clearance Control

LRU - Line Replaceable Unit

LS - Loudspeaker

LSB - Least Significant Bit

LSI - Large Scale Integration

LT - Light

LTP - Left Top Plug

LV - Low Voltage

LVDT - Linear Variable Differential Transducer

LVL - Level

LW - Landing Weight

LWR - Lower

MAC - Mean Aerodynamic Chord

MAG - Magnetic

MAINT = Maintenance

MAN - Manual

MAX - Maximum

MCDU - Multipurpose Control & Display Unit

MCL - Maximum Climb

MCT - Maximum Continuous Thrust

MCU - Modular Concept Unit

MDA - Minimum Descent Altitude

MDDU - Multipurpose Disk Drive Unit

MECH - Mechanic, Mechanical, Mechanism

MED - Medium

MES - Main Engine Start

MI - Magnetic Indicator

MIC - Microphone

MICBAC - Micro-System Bus Access Channel

MID - Middle

MIN - Minimum

MISC - Miscellaneous

MKR - Marker (radio) Beacon

MLA - Maneuver Load Alleviation

MLG - Main Landing Gear

MLI - Magnetic Level Indicator

MLS - Microwave Landing System

MLW - Maximum Design Landing Weight

MMEL - Master Minimum Equipment List

MMO - Maximum Operating Mach

MMR - Multi Mode Receiver

MODLTR - Modulator

MON - Monitor, Monitored

MONG - Monitoring

MORA - Minimum Off Route Altitude

MOT - Motor, Motorized

MPD - Maintenance Planning Document

MSA - Minimum Safe Altitude

MSB - Most Significant Bit

MSG - Message

MSL - Mean Sea Level

MSU - Mode Selector Unit (IRS)

MSW - Microswitch

MTBF - Mean Time Between Failure

MTBUR - Mean Time Between Unscheduled Removals

MTG - Mounting

MTO - Maximum Take-Off

MTOGW - Maximum Takeoff Gross Weight

MU - Management Unit

MUX - Multiplex, Multiplexer

MVT - Movement

MZFW - Maximum Design Zero Fuel Weight

N - Normal, North

N/A - Not Applicable

N/P - Next Page

N/W - Nose Wheel

N/WS - Nose Wheel Steering

NAC - Nacelle

NAS - Navy and Army Standard

NAV - Navigation

NAVAID - Navigation Aid

NBPT - No Break Power Transfer

NC - Normally Closed

NCD - No Computed Data

ND - Navigation Display

NDB - Non-Directional Beacon

NEG - Negative

NLG - Nose Landing Gear

NMI - Non Maskable Interrupt

No - Number

NO - Normally Open

NO - Normal Operation in SSM

NORM - Normal

NS - No Smoking

NUM - Numerical

NVM - Non-Volatile Memory

N1 - Low Pressure Rotor Speed

N2 - High Pressure Rotor Speed

O - Open

O/P - Output

OAT - Outside Air Temperature

OBRM - On Board Replaceable Module

OC - Open Circuit

OC - Overcurrent

OF - Overfrequency

OFST - Offset

OFV - Outflow Valve

OGV - Outlet Guide Vane

OHU - Optical Head Unit

OIT - Oil Inlet Temperature

OK - Correct

OMS - Onboard Maintenance System

OOT - Oil Outlet Temperature

OP - Operational

OPP - Opposite

OPS - Operation

OPT - Optimum

OPV - Overpressure Valve

OUTBD - Outboard

OVBD - Overboard

OVHD - Overhead

OVHT - Overheat

OVLD - Overload

OVRD - Override

OVSP - Overspeed

OXY - Oxygen

P/B - Pushbutton

P/BSW - Pushbutton Switch

PA - Passenger Address

PATS - Passenger Air-to-Ground Telephone System

PAX - Passenger

PC - Pack Controller

PCB - Printed Circuit Board

PCM - Pulse Code Modulation

PCU - Passenger Control Unit

PCU - Power Control Unit

PED - Pedestal

PERF - Performance

PES - Passenger Entertainment (System)

PF - Power Factor

PFD - Primary Flight Display

PH - Phase

PHC - Probe Heat Computer

PIU - Passenger Information Unit

PMA - Permanent Magnet Alternator

PMG - Permanent Magnet Generator

PN - Part Number

PNL - Panel

POB - Pressure-Off Brake

POR - Point of Regulation

POS - Position

POT - Potentiometer

PPOS - Present Position

PR - Power Ready Relay

PRAM - Prerecorded Announcement and Music

PREAMP - Preamplifier

PRED - Prediction

PRESEL - Preselector/Preselection

PRESS - Pressure, Pressurization, Pressurize

PREV - Previous

PRIM - Primary

PROC T - Procedure Turn

PROF - Profile

PROG - Progress

PROM - Programmable Read Only Memory

PROT - Protection

PROX - Proximity

PRR - Power Ready Relay

PSCU - Proximity Switch Control Unit

PSDU - Power Supply Decoupling Unit

PSI - Pound per Square Inch

PSS - Passenger Services System

PSU - Passenger Service Unit

PT - Point

PTC - Positive Temperature Coefficient

PTT - Push to Test

PTT - Push-to-Talk

PU - Panel Unit

PVI - Paravisual Indicating

PVIS - Passenger Visual Information System

PWR - Power

Q - Pitch Rate

QAD - Quick-Attach-Detach

QAR - Quick Access Recorder

QAT - Quadruple ARINC Transmitter

QEC - Quick Engine Change

QFE - Field Elevation Atmospheric Pressure

QFU - Runway Heading

QNE - Sea Level Standard Atmosphere Pressure

QNH - Sea Level Atmospheric Pressure

QTY - Quantity

R - Red

R - Right

R/I - Radio/Inertial

RA - Radio Altimeter, Radio Altitude

RAC - Rotor Active Clearance

RACC - Rotor Active Clearance Control

RACSB - Rotor Active Clearance Start Bleed

RAD - Radio

RAM - Random Access Memory

RAT - Ram Air Turbine

RBP - Right Bottom Plug

RC - Repetitive Chime

RCC - Remote Charge Converter

RCCB - Remote Control Circuit Breaker

RCDR - Recorder

RCL - Recall

RCPT - Receptacle

RCPTN - Reception

RCVR - Receiver

RECIRC - Recirculate, Recirculation

RECT - Rectifier

RED - Reduction

REF - Reference

REFUEL - Refueling

REG - Regulator

REGUL - Regulation

REL - Release

RES - Resistance

RET - Return

REV - Reverse

REV - Revise, Revision

RF - Radio Frequency

RLA - Reverser Lever Angle

RLS - Remote Light Sensor

RLY - Relay

RMP - Radio Management Panel

RNG - Range

ROM - Read Only Memory

RPCU - Residual Pressure Control Unit

RPLNT - Repellent

RPM - Revolution per Minute

RQRD - Required

RST - Reset

RSV - Reserve

RSVR - Reservoir

RTE - Route

RTN - Return

RTP - Right Top Plug

RTS - Return to Seat

RTOK - Retest OK

RUD - Rudder

RVDT - Rotary Variable Differential Transducer

RVR - Runway Visual Range

RWY - Runway

S - South

S/C - Step Climb

S/D - Step Descent

SAF - Safety

SAT - Static Air Temperature

SC - Single Chime

SD - System Display

SDAC - System Data Acquisition Concentrator

SDCU - Smoke Detection Control Unit

SDN - System Description Note

SEB - Seat Electronic Box

SEC - Secondary

SEL - Select, Selected, Selector, Selection

SELCAL - Selective Calling System

SFCC - Slat Flap Control Computer

SH ABS - Shock Absorber

SHED - Shedding

SHT - Short

SIC - System Isolation Contactor

SID - Standard Instrument Departure

SIG - Signal

SLT - Slat

SMK - Smoke

SN - Serial Number

SOL - Solenoid

SOV - Shut-Off Valve

SPD - Speed

SPLY - Supply

SQ - Squelch

SRU - Shop Replaceable Unit

SSB - Single Side Band

SSEC - Static Source Error Correction

SSM - Sign Status Matrix

SSTU - Side Stick Transducer Unit

STA - Station

STAB - Stabilizer

STAR - Standard Terminal Arrival Route

STAT - Static

STBY - Standby

STD - Standard

STGR - Stringer

STS - Status

SVCE - Service

SW - Switch

SWTG - Switching

SYNTHR - Synthetizer

SYS - System

T - True, Turn

T/C - Top of Climb

T/D - Top of Descent

T/R - Thrust Reverser

T-P - Turn Point

TACT - Tactical

TAS - True Airspeed

TAT - Total Air Temperature

TBC - To Be Confirmed

TBD - To be Determined

TCAS - Traffic Alert and Collision Avoidance System

T2CAS - Traffic and Terrain Collision Avoidance System

TCC - Turbine Case Cooling

TDS - Technical Data Sheet

TE - Trailing Edge

TEC - Turbine Exhaust Case

TEMP - Temperature

TFU - Technical Follow-Up

TGT - Target

THR - Thrust

THRM - Thermal

THS - Trimmable Horizontal Stabilizer

TIT - Turbine Inlet Temperature

TK - Tank

TKE - Track Angle Error

TLA - Throttle Lever Angle

TLU - Travel Limitation Unit

TMR - Timer

TO - Takeoff

TOGW - Takeoff Gross Weight

TOT - Total

TPIC - Tire Pressure Indicating Computer

TPIS - Tire Pressure Indicating System

TR - Transformer Rectifier

TRA - Throttle Resolver Angle

TRANS - Transition

TRDV - Thrust Reverser Directional Valve

TRF - Turbine Rear Frame

TRIG - Trigger

TRK - Track (angle)

TROPO - Tropopause

TRPV - Thrust Reverser Pressurizing Valve

TRV - Travel

TSM - Trouble Shooting Manual

TTG - Time to Go

TTL - Transistor Transistor Logic

TTS - Trim Tank System

TURB - Turbulent, Turbulence

UF - Underfrequency

UHF - Ultra High Frequency

UNLK - Unlock

UNLKD - Unlocked, Unlocking

UNSD - UNUSED

UPR - Upper

UTC - Universal Time Coordinated

UV - Under Voltage

V/S - Vertical Speed

Vc - Calibrated Airspeed

VAC - Voltage Alternating Current

VAR - Variable, Variation

VBV - Variable Bleed Valve

VC - Ventilation Controller

VCO - Voltage Controlled Oscillator

VCU - Video Control Unit

VDC - Voltage Direct Current

VDEV - Vertical Deviation

VEL - Velocity

VENT - Ventilation

VERT - Vertical

VFE - Maximum Flat Extended Speed

VFTO - Final Takeoff Speed

VHF - Very High Frequency

VHV - Very High Voltage

VIB - Vibration

VLE - Maximum Landing Gear Extended Speed

VLO - Maximum Landing Gear Operating Speed

VLS - Lower Selectable Speed

VM - Voltmeter

VMAX - Maximum Allowable Airspeed

VMO - Maximum Operating Speed

VOR - VHF Omnidirectional Range

VOR.D - VOR-DME

VR - Rotation Speed

VRMS - Volt Root Mean Square

VRS - V2500 Repair Scheme

VSC - Vacuum System Controller

VSCF - Variable Speed Constant Frequency

VSV - Variable Stator Vane

VSWR - Voltage Standing Wave Ratio

V1 - Critical Engine Failure Speed

V2 - Takeoff Safety Speed

V3 - Flap Retraction Speed

V4 - Slat Retraction Speed

W - Weight

W - White

WARN - Warning

WBC - Weight & Balance Computer

WBS - Weight and Balance System

WD - Warning Display

WHC - Window Heat Computer

WHL - Wheel

WIPCU - Water Ice Protection Control Unit

WIPDU - Water Ice Protection Data Unit

WPT - Waypoint

WTB - Wing Tip Brake

WXR - Weather Radar

X FEED - Crossfeed

X-TALK - Cross-Talk

XCVR - Transceiver

XDCR - Transducer

XFMR - Transformer

XFR - Transfer

XMSN - Transmission

XMTR - Transmitter

XPDR - Transponder

Y - Yellow

Z - Zone

ZFCG - Zero Fuel Center of Gravity

ZFW - Zero Fuel Weight

3D - Three Dimensional (Lat, Long, Alt)

4D - Four Dimensional (Lat, Long, Alt, Time)