IEA INTERNATIONAL ENERGY AGENCY

Overcoming PV grid issues in the urban areas

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T10-06-2009

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Overcoming PV grid issues in urban areas

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This technical report has been prepared under the supervision of
PVPS Task 10 and PV-UP-SCALE by:
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Foreword

The International Energy Agency (IEA) is an autonomous body established in November 1974 within the framework of the Organization for Economic Cooperation and Development (OECD), which carries out a comprehensive programme of energy cooperation among its member countries. The European Commission also participates in the work of the IEA.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA. Since 1993, PVPS participants have conducted a variety of joint projects on photovoltaic conversion of solar energy into electricity.

The mission of the Photovoltaic Power Systems Programme is “enhancement of international collaborative efforts to accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option”. The underlying assumption is that the market for PV systems is gradually expanding from the present niche market for remote applications and consumer products to the rapidly growing market for building-integrated and other diffused and centralised PV generation systems.

The overall programme is led by an Executive Committee composed of one representative from each participating country, while individual research projects (tasks) are managed by Operating Agents. By the end of 2007, 12 tasks were established within the PVPS programme

Task 10 is intended to enhance the opportunities for wide-scale, solution-oriented application of photovoltaics (PV) in the urban environment as part of an integrated approach to maximizing building energy efficiency and solar thermal and photovoltaic usage. The long-term goal is to ensure that urban-scale PV becomes a desirable and commonplace feature of the urban environment in IEA PVPS member countries.

This technical report was prepared by Tomoki Ehara of the Mizuho Information Research Institute, Japan under the supervision of PVPS Task10 in collaboration with PV-Upscale, European funded project. The main reviewers of this report were Shogo Nishikawa (Japan), Kenn Frederiksen (Denmark) and Christy Herig (United States of America).

The report expresses, as much as possible, the international consensus of opinion of the Task 10 and PV Up-scale experts on the subjects addressed.

Further information on the activities and results of Task 10 can be found at:
http://www.iea-pvps-task10.org and http://www.iea-pvps.org

Introduction

In order to achieve the goal of "mainstreaming PV systems in the urban environment", which is the overall objective of Task 10 activities, several technical issues must be resolved. Grid interconnection, one of the most important issues, has been contended in detail within IEA PVPS Task 5 activities in the 1990s. At that time, experience and knowledge regarding PV grid interconnection issues were limited, but the situation has changed drastically since then. The installed capacity of PV systems has been increasing and most systems are now "grid connected". Research and demonstration projects have been implemented to investigate the impacts and benefits of high-density interconnection of PV systems on the power quality of the main grid.

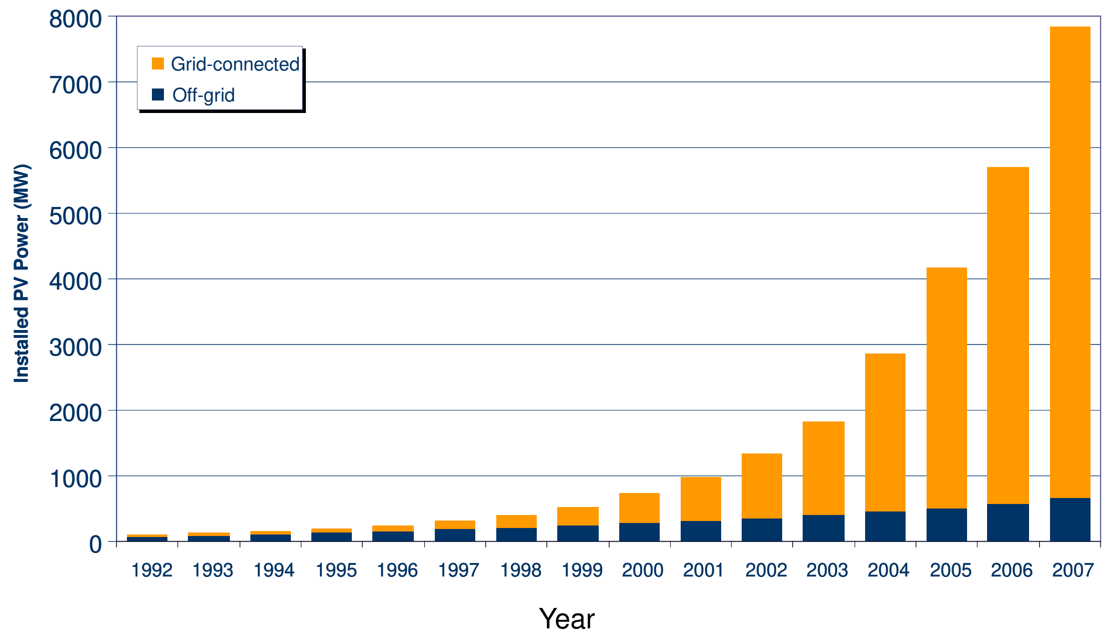


Fig Cumulative installed grid-connected and off-grid PV power in the reporting countries (MW) (Ref. IEA PVPS 2008, "Trends in photovoltaic applications. Survey report of selected IEA countries between 1992 and 2007")

For the mass distribution of urban-scale PV projects in the future, it is important to share experiences and knowledge related to PV grid issues. In this report, PV grid interconnection issues and countermeasures based on the latest studies are identified, summarized, and appropriate and understandable information is provided for all possible stakeholders.

First, the possible impacts and benefits of PV grid interconnection are identified by reviewing existing studies (Chapter 2). Second, technical measures to eliminate negative impacts and enhance possible benefits are presented (Chapter 3). In addition to the existing technological approaches described in Chapter 3, new approaches have emerged for maintaining the power quality of distribution lines from a broader perspective by managing systems as a whole, as well as focusing on single technologies. The status of research and demonstration projects is introduced and the latest outcomes are summarized (Chapter 4). Recommendations and conclusions based on the review process are summarized and presented in Chapter 5.

Executive Summary

The main objective of this study is to share the latest experiences and knowledge related to PV grid issues. Within the report, potential impacts and expected benefits of distributed PV grid interconnections are identified. The countermeasure technologies that may be applied to minimise the impacts as well as technologies that can enhance the benefits are summarized in Table 2-1 below. Within the report, details of each countermeasure technology, including application diagrams are then provided.

Table 0-1 Summary of countermeasures

	Countermeasures		
	Grid side	Demand side	PV side
Overvoltage/ Undervoltage	LDC (Line voltage drop compensator) Shunt capacitor, Shunt reactor SVR (Step voltage regulator) Electric storage devices	Shunt capacitor, Shunt reactor Electric storage devices	Voltage control by PCS Electric storage devices
Instantaneous Voltage Change (Sags/Swells)	TVR SVC STATCOM Electric storage devices	DVR Electric storage devices	Electric storage devices
Voltage Imbalance	STATCOM	DVR	
Harmonics	Shunt capacitor, Shunt reactor STATCOM Passive filter Active filter	Shunt capacitor, Shunt reactor DVR Passive filter Active filter	Advanced PCS
Unintended islanding Protection	Electric storage devices Protective devices Transfer trip equipment	Electric storage devices Protective devices	Electric storage devices Advanced PCS
Short-Circuit Capacity			Advanced PCS
Disconnection Time for Intersystem Fault	Transfer trip equipment		
Increase in DC Offset from PC			Advanced PCS DC offset detector
Frequency Fluctuation	Electric storage devices	Electric storage devices	Electric storage devices
Supply Security	Electric storage devices	Electric storage devices	Electric storage devices
Peak Cut	Electric storage devices	Electric storage devices	Electric storage devices Advanced PCS

In addition to the existing technological approaches, new approaches have emerged for maintaining the power quality of distribution lines from a broader perspective by managing systems as a whole, as well as focusing on single technologies. The status of research and demonstration projects is introduced and the latest outcomes are summarized. The key conclusions of the study include;

- Most of the potential problems indicated have yet to become tangible problems at the present time. Furthermore, even the issues with the potential to become problems in the future are generally not serious issues, and can either be dealt with sufficiently with existing technologies or else avoided with proper planning and design.
- Of the problems selected in this examination, dealing with overvoltage concerns is a top priority. Overvoltage incidents are more likely to occur on rural grid in which, generally speaking, the line impedance is higher and the load is relatively low. Where inverters are used, like in Japan, that reduces outputs when a certain voltage threshold is exceeded, the problems are more likely to be social (unfairness) in nature than a grid quality issue.
- The impact of harmonics is now extremely small with the recent advancements in PCS and other technologies. Increase in even harmonics observed in the French case study seems to be a consequence of DC injection from the transformerless inverters. The impact of transformerless inverter on even harmonics should be assessed in a future study.
- Although the possibility of unintended islanding operations is extremely slim, the risks involved if unintended islanding does occur are great. There are significant differences between nations in the recognition of the problem’s importance. These differences depend largely on the value judgments of each country.
- Many constraints, including overvoltage, can be eliminated when infrastructure and other facilities are upgraded by designing distribution capacities and grid configurations to meet future capacity growth.

In addition, the following characteristics are identified as key recommendations for the future grid systems free of constraints on PV grid interconnections.

- Integrated system management using ICT (Information and Communication Technology)
- Extension of distribution capacities
- Development and widespread use of storage technologies or integration of either grid load control or building load control with PV generation output.
- Provision of power quality that fits the corresponding application

1. Identification of benefits and impacts of PV grid interconnection

For many years the standard electric power distribution model has been to generate power at large-scale power plants and distribute power to customers via power transmission lines. Power distribution infrastructure has also been designed with this model in mind. In recent years, however, we have been witnessing the appearance of many small-scale power plants on power networks, as distributed power sources — such as photovoltaic power, wind power, and various types of co-generation power — gain traction. One side effect of this multiplication of power sources has been to make network electricity flow patterns much more complex, which in turn requires more sophisticated power regulation technologies than have been employed in the past. Another concern with PV and other renewable energy forms is that they are intermittent power sources with substantial output fluctuations. As more of these power sources are interconnected with power grids, various risks come into view, such as lower electric power quality and stability.

AC power quality is a general term for indices that describe the impact on customer-device operation due to deviations from prescribed tolerances in the sinusoidal voltage's amplitude, frequency, phase, and waveform. Various schemes have been proposed of parameters to evaluate the quality of electric power. Europe created the power quality standard EN 50160[1] in 1994 (revised in 1999), and the United States set out the IEEE Standard 1159[2] on electric power quality in 1995. The International Electrotechnical Commission (IEC) worked on establishing measurement methods for AC power quality parameters in conjunction with the global trend to deregulate the power industry. It set forth these methods in the IEC 61000-4-30[3] standard in 2003. In this paper, we focus on several of these power quality parameters that indicate the impacts of PV grid interconnections and sort through the latest knowledge of and experience with these PV grid impacts.

1 EN 50160 (Voltage. characteristics of electricity supplied by public. distribution systems)
2 IEEE 1159-1995 (Recommended Practice for Monitoring Electric Power Quality)
3 IEC 61000-4-30 (Testing and measurement techniques-power quality measurement methods, Electromagnetic compatibility (EMC))

1.1. Possible impacts

1.1.1 Overvoltage/undervoltage

In general terms, electricity current flows from a higher voltage point to a lower voltage point, similar to the way that running water flows from a higher pressure point to a lower pressure point. The water flow is affected by a change in the water pressure. The water pressure and flow weakens as water is consumed along the way. In a similar fashion, the voltage of electricity decreases as it is consumed.

For this reason, generally, line voltage decreases relative to the distance the measurement is taken from the voltage source, as well as the types of loads encountered. However, the voltage must be kept in a certain range as designated by laws, standards or guidelines, which vary region to region, for the purposes of appliances and machinery operating properly. In order to control the voltage within the range, utility companies apply various technology countermeasures.

On the other hand, when the power generated by PV is more than the energy consumed at the point of use, the surplus electricity will flow back to the grid. In this case, the electricity current flow reverses direction and the voltage rises as it goes to the end. This is not a significant issue in the urban grid, which can be characterized as a strong network with high grid impedance, and limited PV capacity, However, as PV penetration increases or currently when a number of PV systems are installed on a rural grid with lower impedance, the voltage could exceed the upper limit. This issue is called overvoltage.

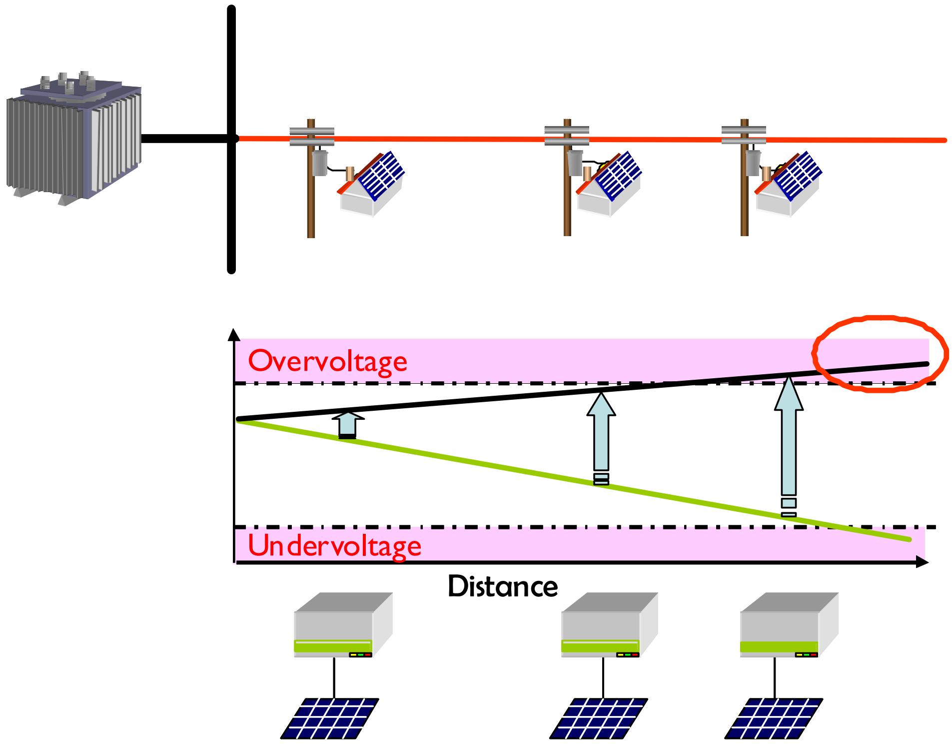


Fig. 1-1 Conceptual diagram of overvoltage

It is possible to control the line voltage to some extent by controlling (reducing) the sending voltage from the bank (transformer); however, this may cause undervoltage of neighbouring lines connected to the same bank with little backward flow, since it is difficult to independently control sending voltage from the same bank.

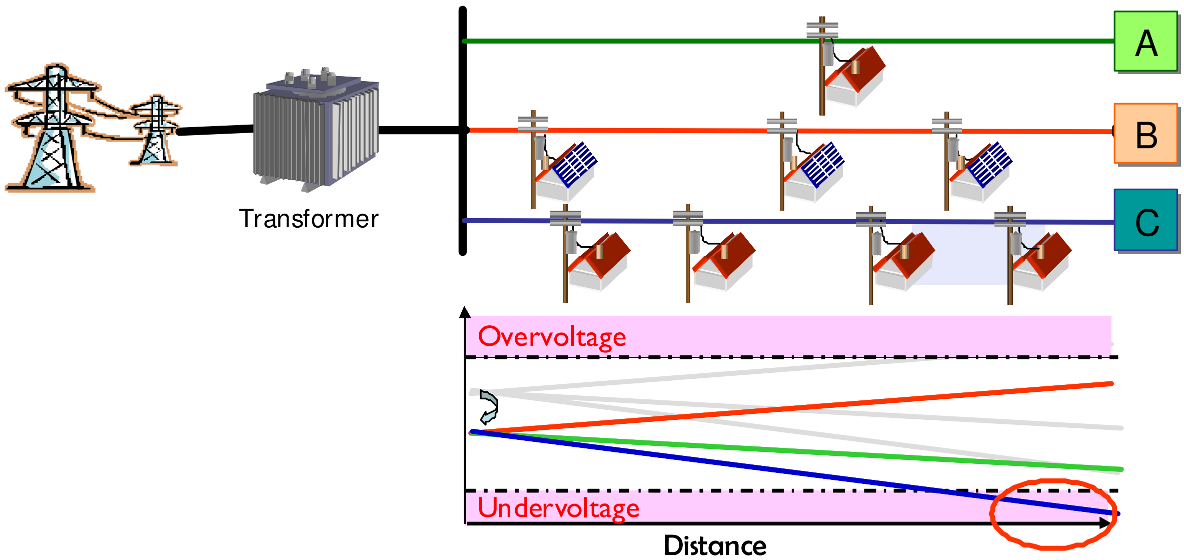


Fig. 1-2 Undervoltage problem

Both overvoltage and undervoltage would have a negative impact on stable operation of the supply-side devices including generators and transformers. Additionally, there would also be an impact on the demand-side equipment. Overvoltage might shorten the lifetime and undervoltage could constrict the normal performance of electric equipment.

In Japan, power conditioners[4] for PV systems are designed to control the voltage rise so as not to exceed the limit. Overvoltage can be completely prevented with this technology. However, a disadvantage is that the PV power output is dumped to control the voltage, leading to lower efficiency of the PV system. This can also lead to unfairness among users since the PV output at the end of the line tends to be restricted with higher priority. When investments are based on the PV production such as a feed-in tariff, the grid operation will affect the investment.

Overvoltage and undervoltage can be one of the biggest barriers to mass distribution of urban-scale PV systems; however, these issues apply to other distributed power generators as well.

[4] In Japan, the PV system inverters have been designed with additional power quality enhancing features such as voltage rise prevention and thus referred to as power conditioners. Since the other high grid penetration markets in Spain and Germany emerged from feed-in-tariff policies where the economic benefits depend on maximizing the energy output the enhanced power conditioning function is not included, because it controls the voltage by dumping power.

1.1.2 Instantaneous voltage change

When faults such as lightning occur on the grid network, the voltage around the fault point drops until the protective relay detects the fault and isolates the fault from the main grid by means of breakers. This is the typical case for instantaneous voltage change. The duration of the voltage drop is dependent on the operational time of protective relays and breakers.

Instantaneous voltage change may also happen when distributed AC generators are connected to the grid under certain conditions. In the case of synchronous generators, considerable inrush current will flow if the generators are not properly synchronized in the grid connection processes. For induction generators, instantaneous inrush current may reach as high as 5 to 6 times the rated current. Inrush flow is another cause of instantaneous voltage drop in the main grid.

PV systems, on the other hand, have little impact on instantaneous voltage change since fluctuations in the power output are relatively slow and the grid interconnection processes are appropriately controlled by power conditioners. One possibility for instantaneous voltage change occurrence by a PV system is simultaneous disconnection of PV systems by an unintended islanding[5] function in the inverter being too sensitive and the PV dropping off line.

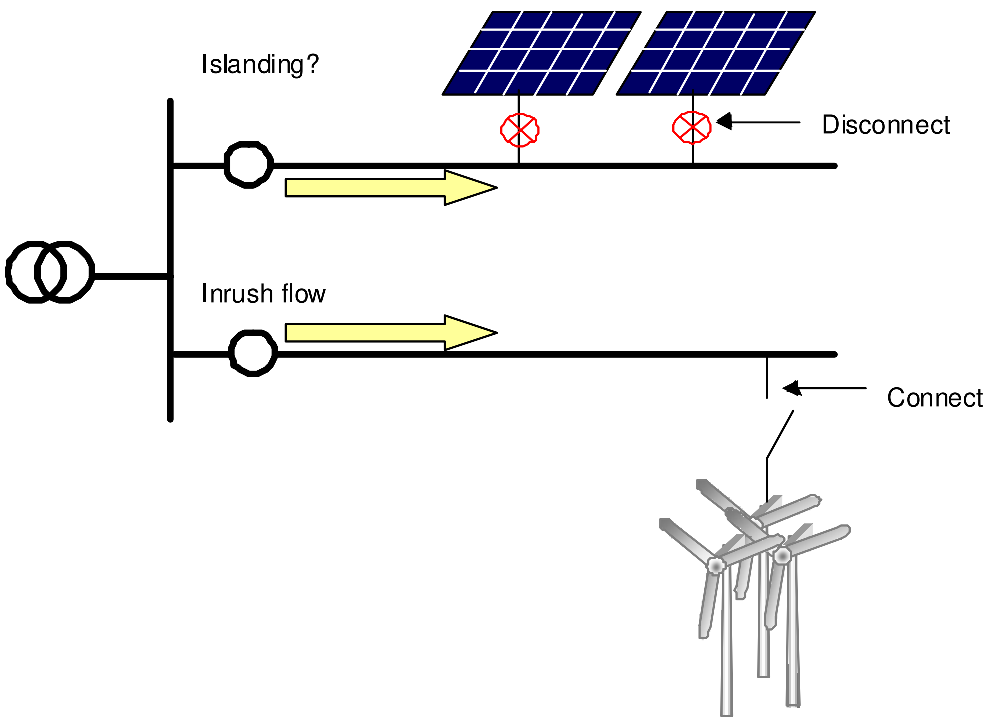


Fig. 1-3 Instantaneous voltage change caused by distributed power generators

[5] The term islanding has historically been used to describe the undesirable event of a grid-connected PV generator failing to disconnect during a grid outage. However, as grid-connected PV systems have emerged to provide the dual purpose of acting as stand-alone generators during a grid outage, the term has been refined to intentional and unintentional islanding.

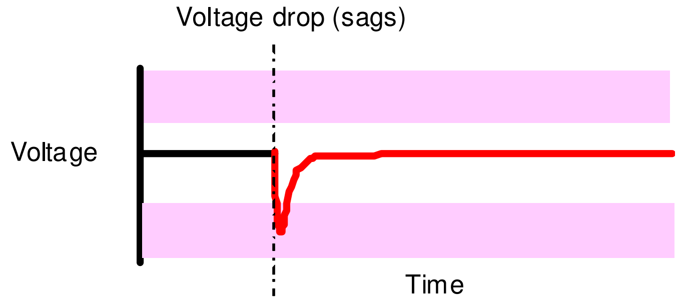


Fig. 1-4 Conceptual diagram of instantaneous voltage change (sag)

Computers, office automation equipment and industrial robots are vulnerable to instantaneous voltage change. In Japan, some of those devices are designed to stop operating if the voltage drops by more than 10% of the rated voltage. In addition to the impact on demand-side equipment, the lifetime of grid equipment such as voltage regulators could also be affected by the increase in operating frequency.

As mentioned earlier, the impact of PV grid interconnection on this issue is not significant so far, although an advanced unintended islanding detection scheme should be developed in the near future to minimize the risk of simultaneous disconnection of PV systems. There is discussion in Europe and the US to change the time for the PV system to drop off to have a slight (a fraction of the power frequency cycle) delay.

1.1.3 Voltage imbalance

Voltage imbalance is a condition in which the amplitude of each phase voltage is different in a three-phase system or the phase difference is not exactly 120°.

Difference in load or power supply from PV systems on each phase of the three-phase circuit could cause voltage imbalance between the phases in the distribution line. Voltage imbalance will generate current with twice the frequency and a backward magnetic field in three-phase synchronous machines, and will have a negative impact on generators, such as temperature rise of rotors, noise, and vibration. It will also have an impact on induction machines and power electronic devices.

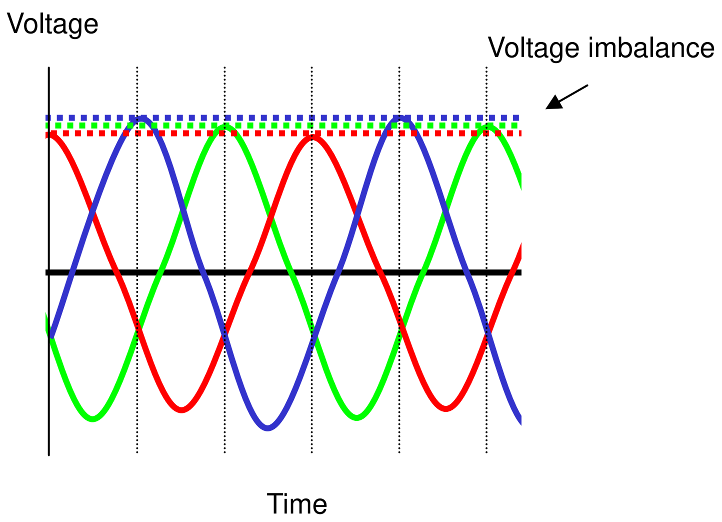


Fig. 1-5 Voltage imbalance

Greater imbalance may cause overheating of components, especially motors, and intermittent shutdown of motor controllers. Motors operating on unbalanced voltages will overheat, and many overload relays cannot sense the overheating. In addition, solid-state motor controllers and inverters often include components that are especially sensitive to voltage imbalance.

1.1.4 Harmonics

The harmonic of a wave is defined as a component frequency of the signal that is an integer multiple of the fundamental frequency. Grid load such as from appliances and computers use power electronics technologies to change the grid AC to the desired current waveform. In this process, these devices generate “harmonics” that may distort the grid waveform as shown below.

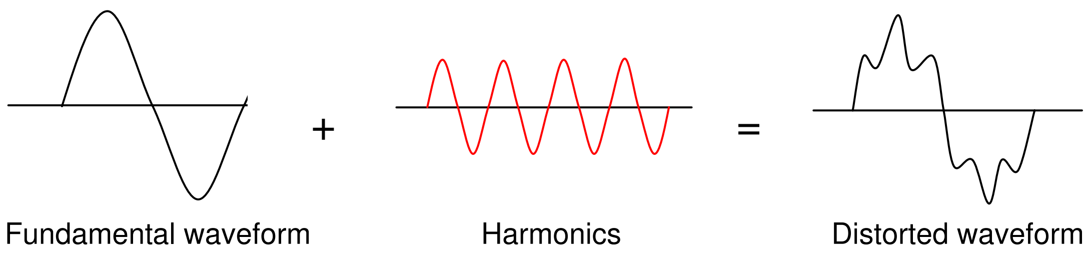


Fig. 1-6 Conceptual diagram of harmonics waveform

Inverters of the PV system convert DC current to AC current through a semiconductor switching circuit, but the AC wave obtained from the devices will not be a perfect sinusoidal wave. The latest model inverters generate little harmonics, but an older poor-quality inverter may generate severe harmonics when converting PV output to AC. There have been instances when harmonics measured at a PV system were caused by the load and not the inverter.

A recent commercial PCS for PV was designed to minimize harmonics. The applied scheme is called pulse width modulation (PWM). In PWM, the voltage is controlled by changing the interval and width of the pulse so that the average value of the voltage becomes equal to the desired fundamental waveform.

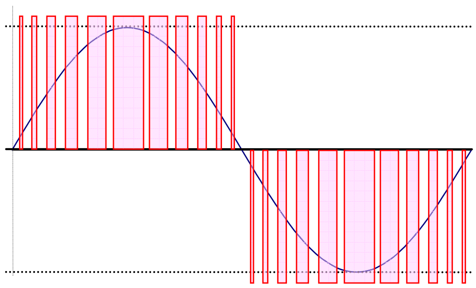


Fig. 1-7 PWM control scheme

This technology can prevent severe harmonics. Additionally, most power conditioners have a harmonic filter that removes the majority of harmonics from the PV output.

Recent studies show that by using a commercial power conditioner system (PCS), harmonics from PV systems do not become a big issue at the current installed PV capacity. Since the harmonics generated from a PCS are much lower than from other appliances, it is possible that the PCS filters the harmonics from other electronic loads to improve the power quality. R&D projects have been carried out to ascertain the impact of harmonics from a PV community, and to develop a more advanced PCS to minimize harmonics.

Electronic devices such as series reactors or static capacitors, installed at indoor substations of factories or office buildings for power quality, are harmonic filters. If the harmonics are severe, beyond the filtering capability, this leads to overheating and in the worst case, a fire could result.

The impact on demand-side equipment includes vibration of elevators, flickering of TV monitors and fluorescent lamps, degradation of sound quality, and malfunctioning of control devices.

If the disturbance occurs in the odd numbers of harmonics 3, 5 or 7th, it could even result in a high current running in the neutral wire. If the wire has been reduced in size compared to the active wires it could in worst case be overheated.

1.1.5 Unintended islanding

Unintended islanding is an electrical phenomenon in which PV systems within a certain network continue to supply power to the load even after the network is disconnected from the main grid for some reason (e.g., electrical problem). When a network is disconnected from the main grid, the PV systems in the network are designed to detect the abnormal power quality in voltage, frequency and grid impedance and to disconnect from the network immediately. However, if the power generated from the PV systems and that consumed in the load are by chance identical, the PV systems might not be able to detect the unintended islanding and will continue to supply power.

It should be noted that there is little impact from unintended islanding since the possibility of unintended islanding operation is quite low (See Fig 1-8)

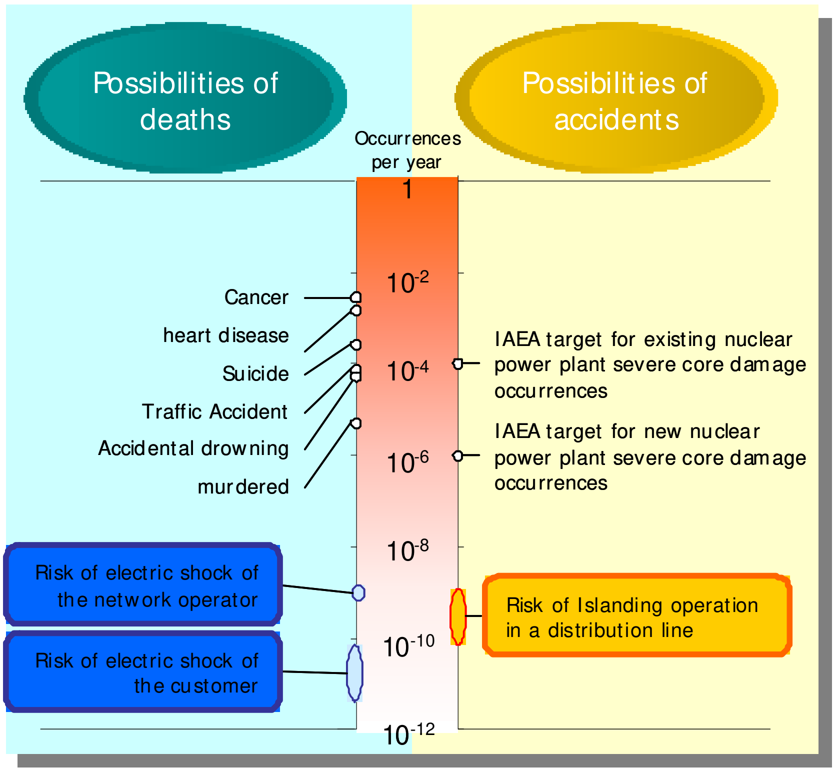


Fig 1-8 Risk of unintended islanding compared to other causes of deaths/accidents in Japan

Islanding operation can only be possible when the following three conditions happen at the simultaneously.

1) The power supply from the main grid stops for some reasons,
2) The power generated from the PV systems accidentally matches load
3) Islanding protection functions in the PCS failed to detect the islanding conditions

According to the IEA PVPS Task 5 report, the possibility of unintended islanding operation that continues for more than 5 seconds in a distribution line is 8.3×10^{-10} to 8.3×10^{-11}/year. In addition, the risk of severe accident such as electric shock to the customer is even lower and the magnitude is at least five orders less than other major causes of death in Japan. No such accident has been reported relating to PV islanding.

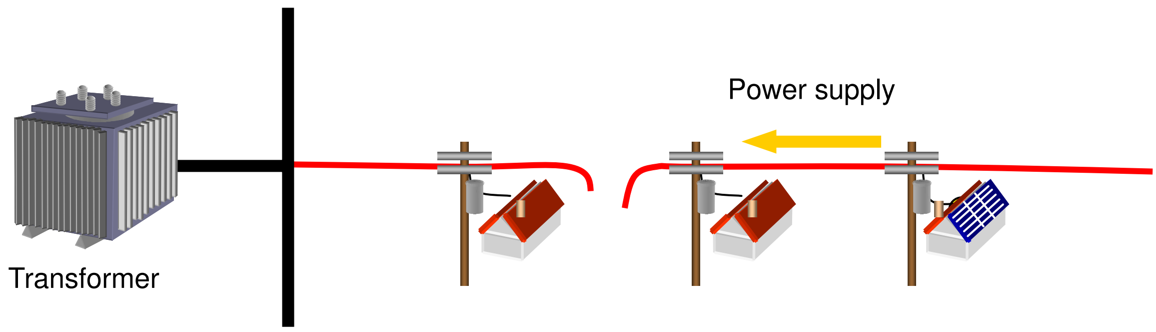


Fig. 1-9 Conceptual diagram of unintended islanding operation

One of the biggest concerns about unintended islanding is the "increased risk of accident". In the case of grid fault or planned grid maintenance, the network operators must repair the distribution lines as soon as possible. Before starting the work, it must be confirmed that the lines are disconnected from the main grid, in other words, out of electricity. However, if PV systems or other distributed power generators are still supplying power to the lines, it could lead to electric shock of workers. It has also been pointed out that since the power is continuously supplied to the fault point, the public is also exposed to the risk of electric shock. In addition to human physical injury, studies indicate that unintended islanding could also damage grid/end-users' devices. Another unintended islanding problem is the "risk of overcurrent" during the breaker reclosing process. With the main grid and the distribution line operating independently during unintended islanding, the voltages are not in synchronised operation and could be out of phase. If the breaker is reclosed with a large voltage phase difference, a strong current will flow into the line, which is very dangerous.

Although unintended islanding may lead to serious damage, it is important to bear in mind that the possibility of unintended islanding operation is quite low.

1.1.6 Short-circuit capacity

Short-circuit capacity is an indicator representing the level of electric current when a short-circuit fault occurs. If a number of distributed generators are connected to a distribution line, the short-circuit current might exceed the rated amount. If the short-circuit current is higher than the capacity of the breaker, the breaker cannot block the current and the grid devices will be damaged. In the case of PV systems, the impact is not as crucial compared with that of synchronous generators since all inverters which meet international grid connection standards the power conditioner will detect the overcurrent (1.1–1.5 times the rated short-circuit current) and disconnect the system immediately.

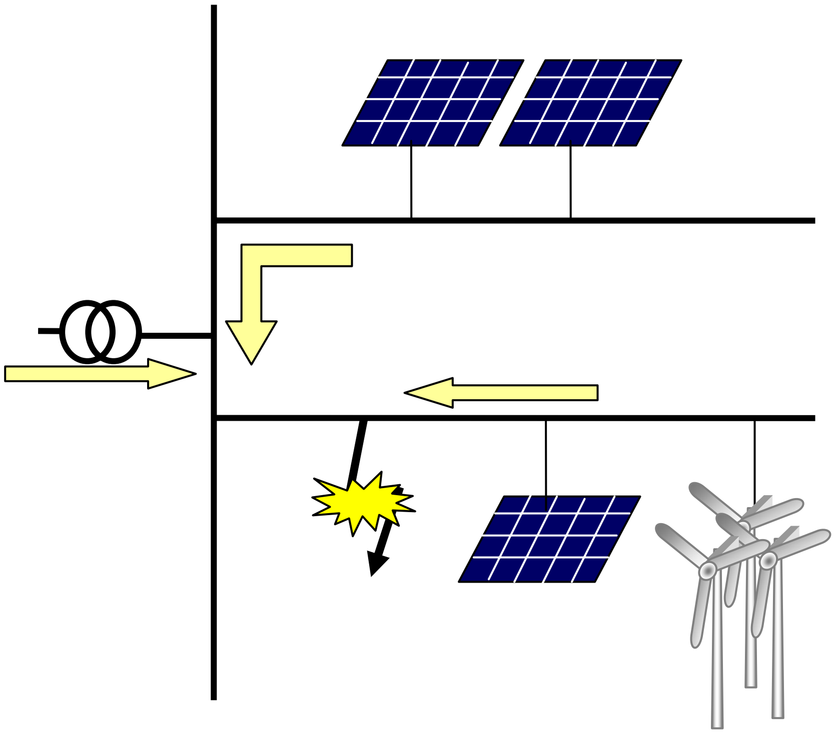


Fig. 1-10 Conceptual diagram of short-circuit capacity

If the short-circuit current exceeds either the short-circuit capacity of the breakers or the limit for instantaneous current of the underground cables, it can damage those devices.

1.1.7 Disconnection time of intersystem fault

In the transformer box, high-voltage winding and low-voltage winding are insulated from each other. However, if any abnormal voltage, such as lightning, flows into the transformer, breakdown of the insulation may occur. This is called an intersystem fault (see figure below).

When an intersystem fault occurs in the network, power plants must stop operation and disconnect from the grid network. However, PV systems cannot detect the incident until the substation opens the breaker and unintended islanding operation occurs. Research[34)] points out that it takes too much time for the PV system to disconnect.

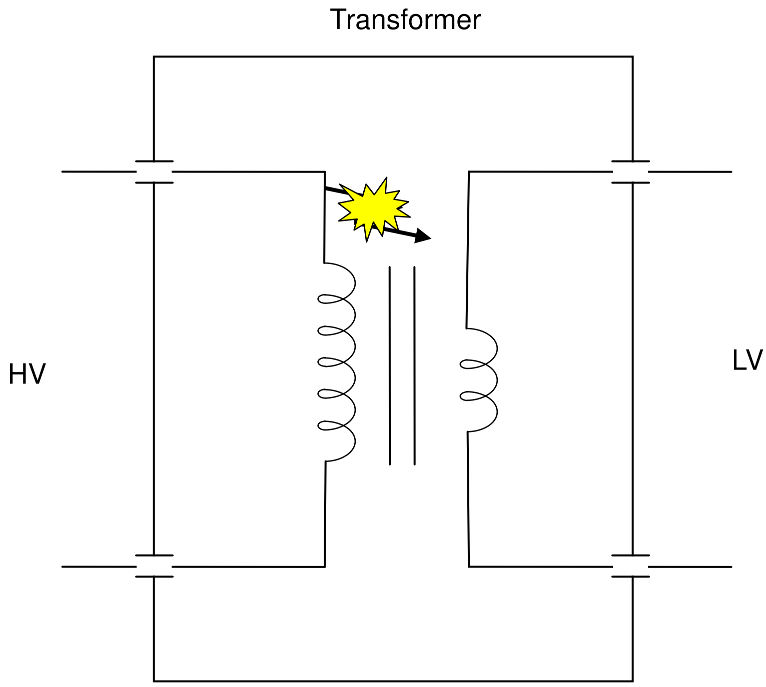


Fig. 1-11 Conceptual diagram of intersystem fault

Low-voltage circuits and electronic devices including domestic wiring and appliances cannot withstand those higher voltages, leading to a risk of electric shock or fire. The PV inverter can be designed to react faster to minimise the risk. This type of inverter was designed for the Ota, Japan project (case study at end of report).

1.1.8 Frequency fluctuation

Storing electricity is difficult, in both economic and physical terms; on the other hand, it is necessary to supply power to meet demand fluctuations. The disruption of balance between supply and demand leads to frequency fluctuation. Frequency is one of the most important factors in power quality and it must be kept equal throughout the grid. With the increasing share of power from intermittent energy sources such as wind and solar, it becomes more difficult for utilities to control the power quality. Generally, the extent of power fluctuation from PV systems is much smaller than that from wind generators, because of the capacity differences. However, the issue of frequency fluctuation from PV systems becomes more noticeable as the number of grid-connected PV systems increase.

Power sectors apply several measures to control the grid frequency along with its frequency components.

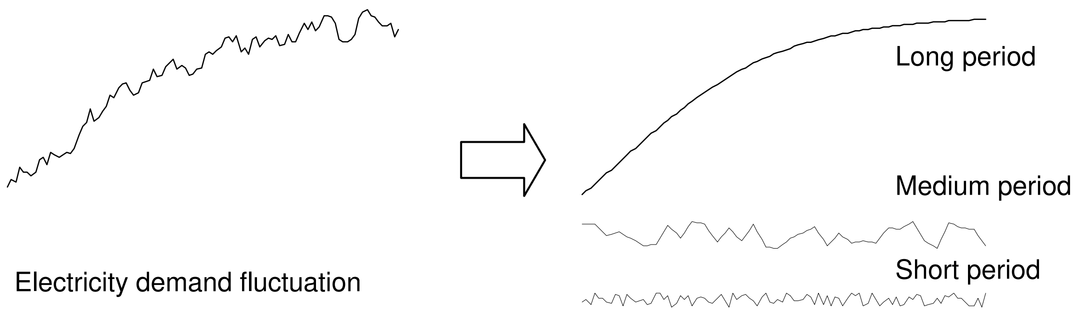


Fig. 1-12 Breakdown of frequency components

Short-period element (less than a few minutes): Governor-free operation; each generator detects the difference in frequency from the rated value and controls the output.

Medium-period element (a few minutes to twenty to thirty minutes): AFC control; central load dispatching centre detects the frequency of the grid and issues an order for load dispatching to each power plant.

Long-period element (more than ten minutes): Output from the power plants is controlled based on load prediction. The control measures are called EDC (economic load dispatching control).

The impact of frequency fluctuation on the demand side includes:

- Impact on product quality due to change in winding speed (chemical fibre industry, paper industry)
- Impact on pressure control systems for desulphurization and degradation processes, and inability to remove impurities (oil industry)

- Impact on rolling process, resulting in irregular thickness of products (steel and aluminium industry)
- Impact on welding strength and apparent condition derived from change in energizing time of automotive body panels (automotive industry)

It is also pointed out that resonance from frequency fluctuation may damage generators and possibly lead to a chain-reaction power outage.

1.1.9 DC offset

The DC component is a deviation of the average power output to either the positive side or negative side for a certain period.

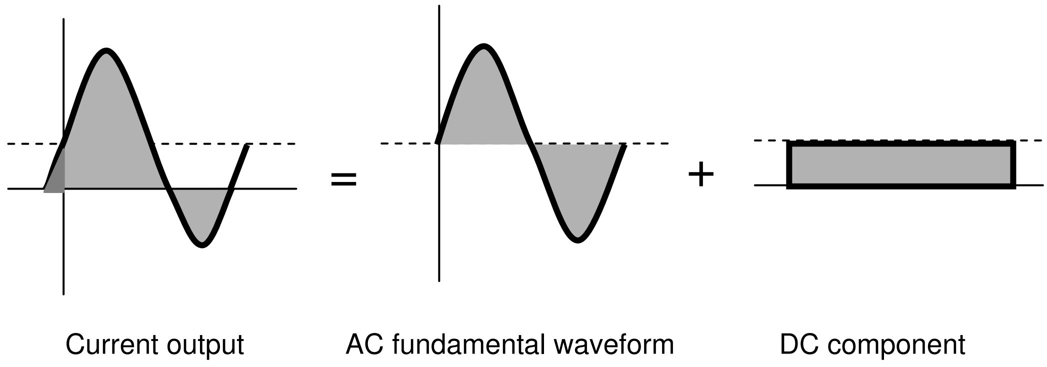


Fig. 1-13 Conceptual diagram of DC component

Most power conditioners used in PV systems are “transformerless inverters” for reduced size and weight, and the DC component cannot be completely eliminated. Alternatively, in order to prevent leakage of DC component current to the AC side, the power conditioner is equipped with a DC component detector so that the PV system can be disconnected in the case of serious DC component leakage.

The actual impact of the DC component from high-density PV systems on the distribution line is not yet fully understood. No serious impact has been observed so far.

1.1.10 High-frequency waves

The power conditioner (inverter), a major piece of equipment in photovoltaic power generation systems, utilizes a high frequency of 10–20 kHz to convert the DC current generated by solar cells to AC current. It is anticipated that electromagnetic noise associated with this frequency is generated from the power conditioner, and that the noise transmitted via space and electric cable has a negative impact on other electronic devices.

Mutual impact of electromagnetic waves generated by electronic devices in homes and offices as well as by PV power conditioners is anticipated, although few problems have been reported so far. The possible impact of electromagnetic waves generated from PV power conditioners would affect communication and IT equipment such as TVs and radios, and vice versa.

1.1.11 Impact of active signals from PCS

Power conditioners are normally equipped with an unintended islanding detection system in order to disconnect the system from the grid in the case of unintended islanding operation. The many types of unintended islanding detection systems can be divided into two main groups: active systems and passive systems.

Many power conditioners apply both active and passive systems. The active system sends out a signal and generates minimum disturbance in order to check the frequency and voltage. The signal is quite small and normally has no impact on grid power quality. However, if a number of PV systems are connected in a distribution line and the signals from the systems interfere with each other, there is a risk of negative impact.

No practical impacts have been reported so far and the actual risk of this issue is not well understood. Possible impacts include degradation of grid power quality due to extreme interference by signals from the active systems. As high PV penetration scenarios emerge there is also the possibility of power conditioner signal mix affecting the control operations.

If the disturbance caused by the signals is considerable, there is a risk of damage to the equipment on both the supply side and demand side.

There is also a possibility of negative impact on grid parameters such as voltage or frequency. In addition, it is anticipated that the sensitivity of the unintended islanding detection function would be weakened by the degradation of grid power quality.

1.2. Expected possible benefits

1.2.1 Reduced transmission and distribution loss

In many cases, large power plants are constructed miles away from the point-of-demand, with large amounts of energy lost as the power is transmitted and distributed to the loads. The loss is proportional to the distance that the power travels on the line and falls within the range of 3–9% of the total output in industrialized countries, although it is heavily dependent on regional conditions. PV systems can generate power at points-of-use anywhere that solar radiation is available, with the advantage of reduced/minimal line loss. Since PV can be integrated or mounted on the building requiring electricity, land is not required. The value of PV to the grid is also strongly enhanced. Many IEA member countries use the value of on-site generation of PV output at the point-of-demand as much as possible. If the power is generated at the point-of-use, transmission and distribution losses are minimized.

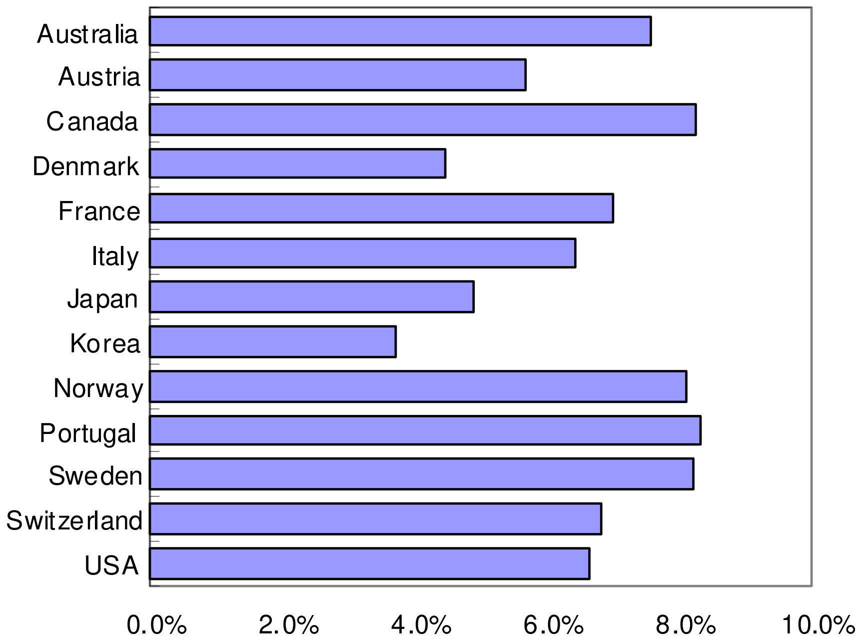


Fig. 1-14 Transmission/distribution loss by country (39)

1.2.2 Supply security

The power supply from the main grid can be disrupted by an accident or natural disaster. Japan, a country that frequently experiences natural disasters, installs PV systems designed to supply power even in the case of power outages during emergencies. Users can switch the PV system from "normal" to "stand alone" mode, enabling the use of an electrical outlet on the PCS. This function is extremely valuable when the electric supply lifeline is cut-off, however, a battery bank needs to be added to the system. People can have access to updated information through TV or radio, and use communication devices.

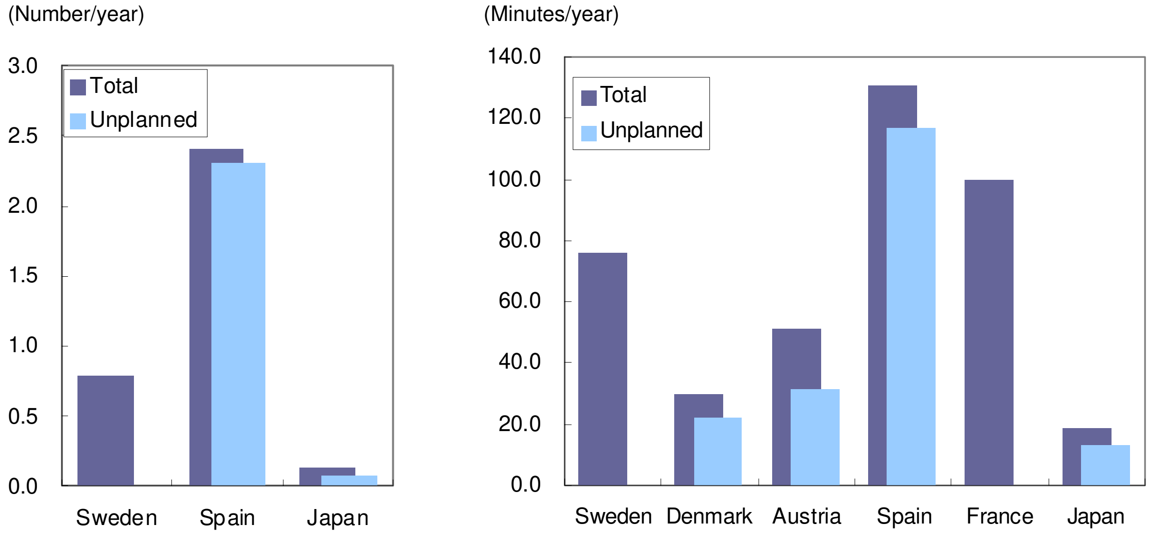


Fig. 1-15 Annual number of power outages (left) and duration (right) by country

*Planned interruptions are for maintenance of grid devices and systems, and customers are informed in advance
*Sweden, Austria: Number and duration of system interruptions lasting more than 3 minutes in 2004
*Denmark: Number and duration of interruptions per entry point to 10–20 kV stations in 2004
*Spain: Number and duration of system interruptions in 2005
*France: Data is from EDF-ERD, the main distribution grid operator

PV power output is intermittent and heavily dependent on the time of day and the weather conditions. Cloudy or rainy days cause considerable fluctuation in PV power output. When the PV system is operating in "stand alone" mode, instantaneous output changes may damage certain appliances such as PCs. Therefore, facilities such as hospitals or communication businesses that use expensive, sensitive machines will need to combine PV systems with an appropriate capacity of energy storage devices or other distributed generators.

Examples of past major power outages caused by natural disasters

Europe

On November 4, 2006, the European grid was affected by a serious disturbance originating from the North German transmission grid. More than 15 million households in Europe (mainly France Germany, Belgium, Italy and Spain) were affected, and the blackout lasted about an hour.

Sweden

During 2005, a huge disaster was caused by the storm "Gudrun". The major problem was broken trees falling over the distribution lines, as well as houses and roads. About 750,000 customers were without electricity, and for many it lasted weeks. This forced the state to take measures to protect customers from future incidents and a new regulation (from January 1, 2011) was adopted stating that outages must not last longer than 24 hours and customers shall receive compensation after 12 hours outage.

Denmark

In November 2006, floods hit the coastal towns in Zealand, Denmark and cable cabinets and substations on lower-current levels were flooded in several places when the water rose up into the streets. It is reported that some 6000 consumers lost power during the incident.

United States

On August 14, 2003, large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout. It was a cascading blackout leaving more than 50 million people without power at great financial loss. The world witnessed the mayhem in New York City when the mass transit subway system was not available at the close of business. The joint US-Canada report attributes the causes of the outage to both human and technological failures. However, there is much evidence that, had a local dispersed PV generation base amounting to at most a few hundred MW been on line, power transfers would have been reduced, point of use generation and voltage support would have been enhanced and uncontrolled events would not have evolved into the massive blackout and loss of nearly 61 gigawatts of load. [61,44]

Reliable electric supply is a quality of life expected from customers in industrialised countries. Securing power supply will benefit almost all end-users. Substantial economic loss can be prevented in the case of severe power outage as shown above. For developing and transition countries, power supplies are often unreliable so that PV systems could provide valuable back-up.

1.2.3 Peak power supply

In general terms, the electricity demands increases during the daytime and decreases during the night-time, although it is heavily dependent on regional conditions. Since PV systems generate electricity in the daytime, it has been discussed that PV can contribute to supplying the peak load. Especially for countries with a relatively hotter climate, PV is expected to offset the increase in cooling demand during the summer. Large office buildings in urban areas have to cool year round due to heat loads from both people and electronic equipment. On the other hand, it is not easy to quantitatively assess the effect of peak power supply by PV systems. For example, PV systems cannot supply electricity in the evening when the demand remains relatively high in many countries; therefore, the effect is limited. It is also pointed out that solar energy is an intermittent energy source that requires a back-up generation plant to some extent in order to ensure supply security.

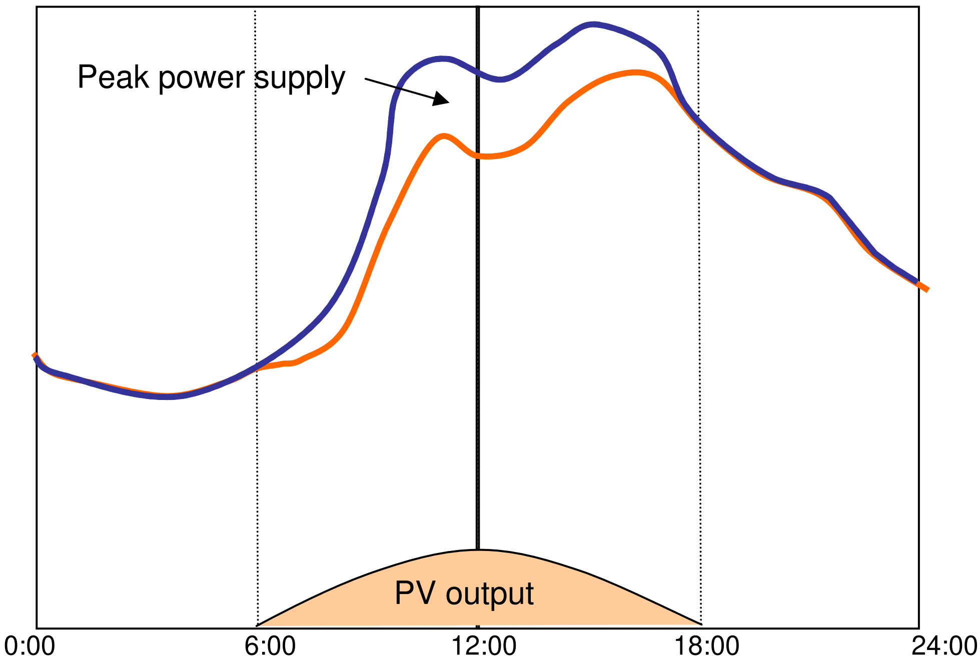


Fig. 1-16 Conceptual diagram of peak power supply

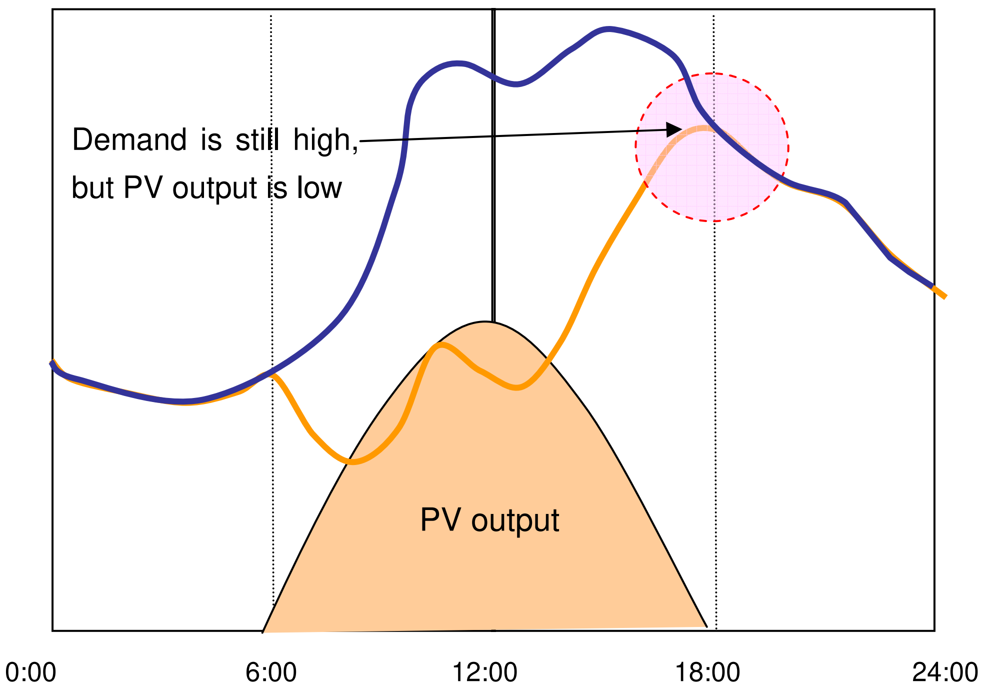


Fig. 1-17 Conceptual diagram of peak power supply - 2

The peak power supply effect of a PV system can be significantly enhanced through coupling with a small-scale energy storage system such as batteries (peak-shifting). If the system stores power during times of high PV output and discharges the power when it is needed, the power supplied from the grid during peak hours would be reduced. Also, in large buildings with cooling loads, the energy controller of the cooling equipment can be interfaced with the operation of the PV to effectively use the thermal mass storage of the building to support the intermittency.

The imbalance between power supply and demand leads to fluctuation of grid frequency or voltage, which could cause equipment damage on the demand side. However, electricity demand (load) changes every minute. In order to efficiently respond to the changes, utility companies generally classify and operate power plants independently. Example classifications are: base load power for constant output, middle load power for changing load and peak load power for peak demand.

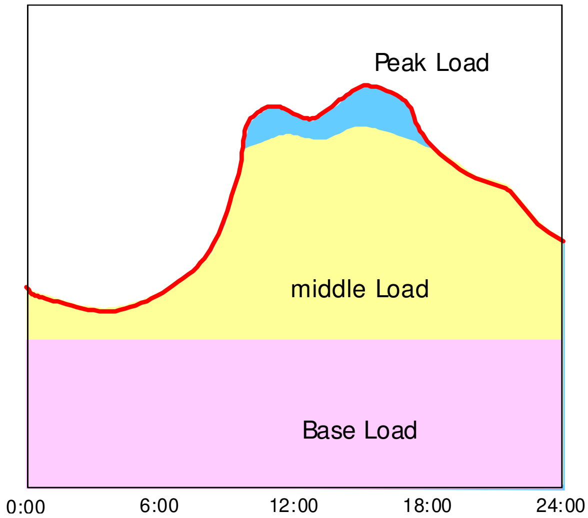


Fig. 1-18 Daily load curve

Peak-power generators do not usually operate during off-peak hours. Therefore, the capacity factor for power plants is relatively low and the cost is high. To reduce the need, and therefore the cost, for peak-power generators, utilities strive to reduce the peak demand through demand-side management programs. Utilities also price electricity higher during peak periods with time-of-use and demand-rate tariffs. Consequently, utilities benefit from reduced peak demand via supply of PV power, and the PV owner benefits as well. Moreover, if the PV owner is on a demand rate or time-of-use rate, the PV electricity is displacing higher-priced electricity, and the benefit of energy cost savings is greater.

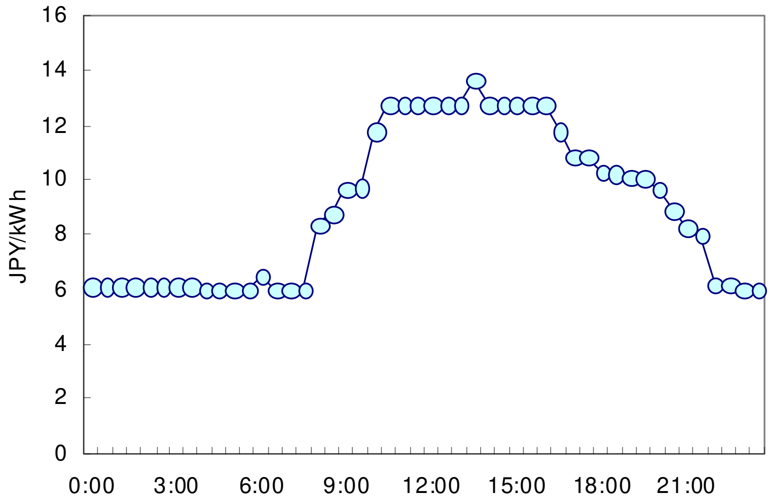


Fig. 1-19 Spot electricity price (Sept. 1, 2007): JPEX[32]

1.2.4 Power quality management

The anticipated negative impacts of PV interconnection such as voltage fluctuation, short-circuit capacity, and harmonics can be turned into positive effects if a high-performance power conditioner is developed and applied. It is possible to add the functions of an active filter, static var compensator (SVC), and superconducting fault current limiter (SFCL) to the power conditioner. Putting such power conditioners into practice would substantially improve the power quality of the grid.

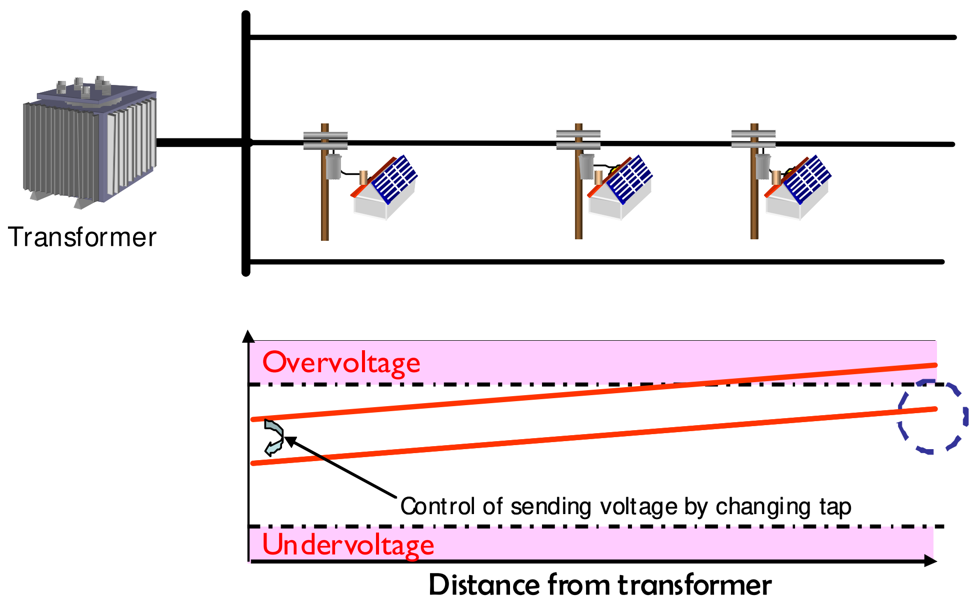
Although some technical and institutional issues must be resolved before the advanced power conditioner becomes available, this technology could significantly strengthen PV systems and consequently provide opportunities for the urban-scale PV market in the future.

2. Available countermeasures

The impacts and benefits of PV grid interconnection were summarized in the previous chapter. For each issue, various countermeasures and technologies are available to resolve the impacts and enhance the benefits, from the grid side, demand side and PV side. In this chapter, existing countermeasures are identified. Table 2-1 summarizes the information collected with more detailed information on selected measures following.

Table 2-1 Summary of countermeasures

	Countermeasures		
	Grid side	Demand side	PV side
Overvoltage/ Undervoltage	LDC (Line voltage drop compensator) Shunt capacitor, Shunt reactor SVR (Step voltage regulator) Electric storage devices	Shunt capacitor, Shunt reactor Electric storage devices	Voltage control by PCS Electric storage devices
Instantaneous Voltage Change (Sags/Swells)	TVR SVC STATCOM Electric storage devices	DVR Electric storage devices	Electric storage devices
Voltage Imbalance	STATCOM	DVR	
Harmonics	Shunt capacitor, Shunt reactor STATCOM Passive filter Active filter	Shunt capacitor, Shunt reactor DVR Passive filter Active filter	Advanced PCS
Unintended islanding Protection	Electric storage devices Protective devices Transfer trip equipment	Electric storage devices Protective devices	Electric storage devices Advanced PCS
Short-Circuit Capacity			Advanced PCS
Disconnection Time for Intersystem Fault	Transfer trip equipment		
Increase in DC Offset from PC			Advanced PCS DC offset detector
Frequency Fluctuation	Electric storage devices	Electric storage devices	Electric storage devices
Supply Security	Electric storage devices	Electric storage devices	Electric storage devices
Peak Cut	Electric storage devices	Electric storage devices	Electric storage devices Advanced PCS

Name	LDC (Line voltage drop compensator)
Development Stage	Practical use
Installation	Grid side (transformer)
General Description	Line voltage drop compensator (LDC) is a device for controlling the secondary voltage (sending voltage) of the transformer. It is designed to compensate for line voltage drop by observing changes in the line current. The device is normally installed next to the transformer and is capable of flexibly controlling the line voltage according to daily changes in current/load. The voltage is mechanically controlled by switching between taps in the device.  Fig. 2-1 Conceptual diagram of LDC
Relevant Impact/Effect	Overvoltage suppression
Problems	・ Response time is one of the disadvantages of LDCs. The device is unable to respond to instantaneous voltage change since switching between taps is a mechanical process. ・ LDCs can control only the sending voltage from the transformer and cannot control each line voltage independently. Therefore, as more distributed power generators are installed, it becomes more difficult to control the voltage by LDC only.

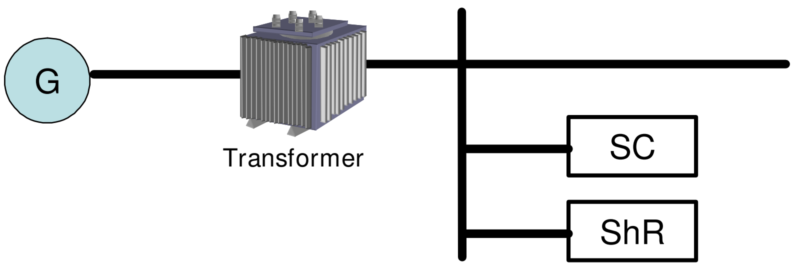
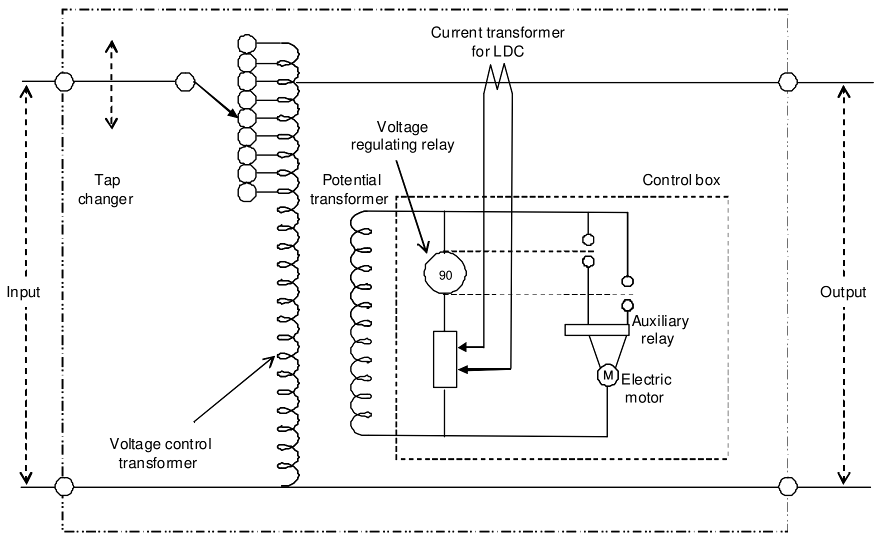
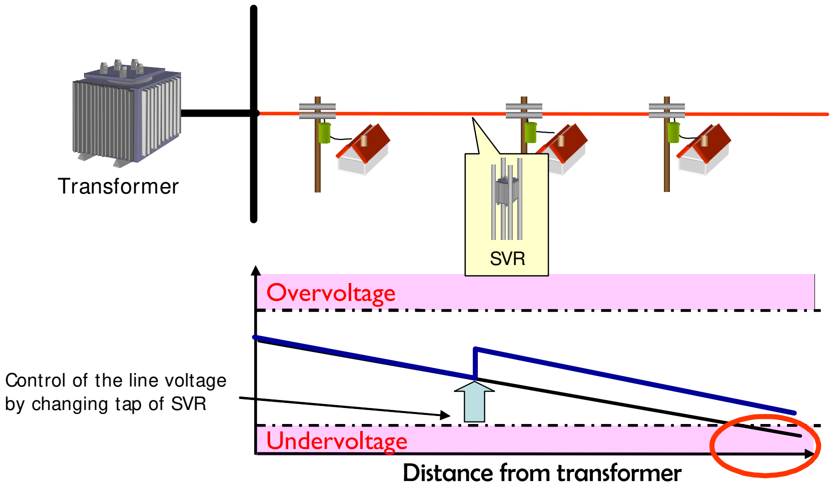
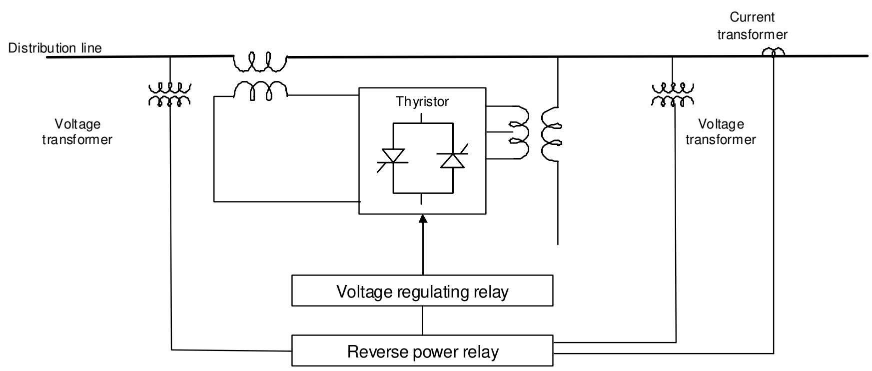
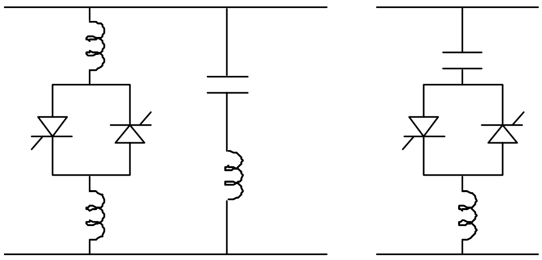
Name	Phase modifying equipment (Static capacitor, shunt reactor)
Development Stage	Practical use
Installation	Grid side (transformer), demand side (e.g., factory)
General Description	Phase modifying equipment is used to control the reactive power of the line. The equipment is normally installed in a transmission substation or a factory with a heavy load. It is usually composed of two devices, a static capacitor and a shunt reactor. In terms of grid electricity, it is important to maintain a balance between supply and demand not only for active power but also for reactive power. Generally speaking, during peak hours in the daytime, the static capacitor provides reactive power; on the other hand, the shunt reactor consumes reactive power at a time with low load.  Fig. 2-2 Installation of phase modifying equipment  Fig. 2-3 Static capacitor (Copyright: CRIEPI)

	 Fig 2-4 Static capacitor (Copyright: CRIEPI)
Relevant Impact/Effect	Voltage control, harmonics control

Name	SVR (Step voltage regulator)
Development Stage	Practical use
Installation	Grid side (on distribution line)
General Description	In a distribution line, where many loads are connected to the grid, the voltage at each receiving point must be kept within a certain range, without exception. Especially in rural areas, the line tends to be longer compared to lines in urban areas, and the line voltage can easily drop below the lower limit of the regulated voltage if no countermeasures are taken. The SVR is a transformer with an on-load tap changer for regulating the voltage when it gets close to the limit.  Fig. 2-5 Circuit diagram of SVR(15) SVRs are connected in series on the distribution line (whereas the LDC is installed next to the transformer substation) and the line voltage is controlled automatically based on the current passing through the devices.

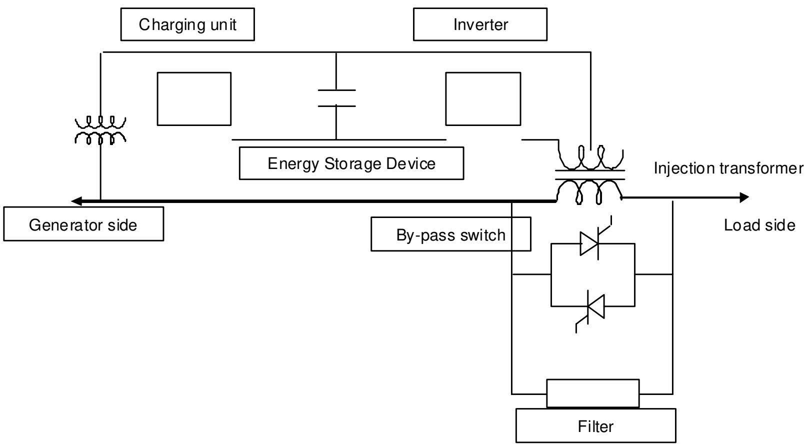
	 Fig. 2-6 Conceptual diagram of SVR
Relevant Impact/Effect	Voltage control
Problems	The SVR has the following limitations: ・ Response time is one of the disadvantages of the SVR. The device is unable to respond to instantaneous voltage change since switching between taps is a mechanical process. ・ Tap changer (mechanical connection point) has limitations in switching time (contact erosion). In order to lengthen the replacement period of the device, it is designed not to respond to transient behaviour.

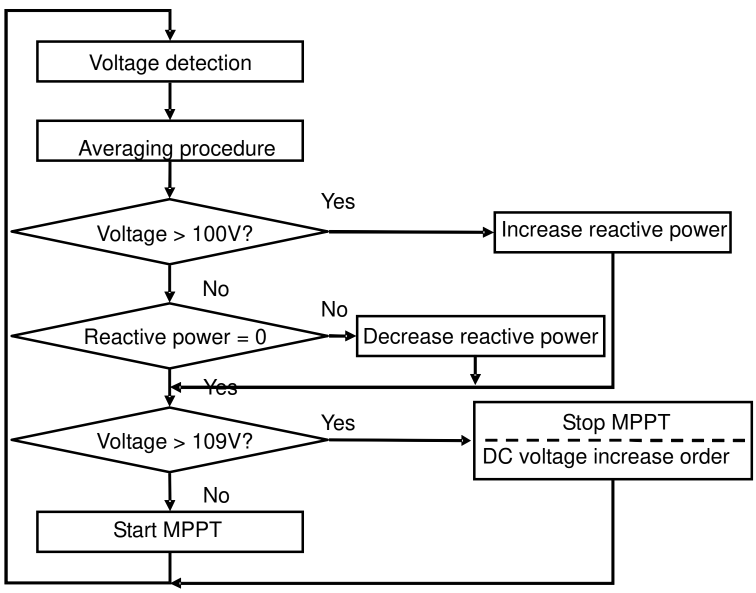
Name	TVR (Thyristor voltage regulator)
Development Stage	Demonstration stage
Installation	Grid side (on distribution line)
General Description	General SVRs can only respond to gradual voltage change, and cannot follow instantaneous change because of limitations in the lifetime of the tap changer. The TVR is a device using a thyristor in the tap changer to respond to this issue. This change allows SVRs to respond more quickly and frequently. TVRs are more expensive than SVRs (by approximately 50%) but have better response time (0.1 s), and cost less than SVCs.  Fig. 2-7 Circuit diagram of TVR(15)
Relevant Impact/Effect	Overvoltage, undervoltage, instantaneous voltage change
Problems	Long-term reliability of the device under conditions of installation on a pole is not fully understood, and further demonstration might be needed.

Name	SVC (Static var compensator)
Development Stage	Practical use
Installation	Grid side
General Description	Presently, the voltage of a high-voltage distribution line is controlled by LDCs or SVRs; however, these devices can only respond to relatively gradual voltage changes in the order of a few minutes. Therefore, they may not be able to respond to instantaneous voltage changes caused by connection/disconnection of the distributed generators or by sudden changes in heavy loads. SVCs, on the other hand, can follow the quick changes in distribution line voltage by applying an advanced power electronics circuit. SVCs are basically voltage source inverters connected in parallel to the grid for supplying reactive power.  TCR (Thyristor Controlled Reactor) TSC (Thyristor Switched Capacitor) Fig. 2-8 Various types of SVC (15)  Fig 2-9 SVC (Copyright: CRIEPI)

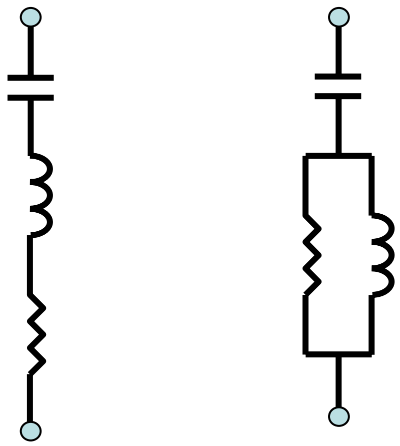
	Phase modifying equipment and STATCOM are other devices that can control reactive power continuously. The response rate of the SVC is approximately 10 ms and quicker than phase modifying equipment but slower than STATCOM. In addition, the SVC does not have any moving parts, an advantage in terms of maintenance.
Relevant Impact/Effect	Overvoltage, undervoltage, instantaneous voltage change, voltage imbalance, flicker
Problems	Cost is a bottleneck in this technology

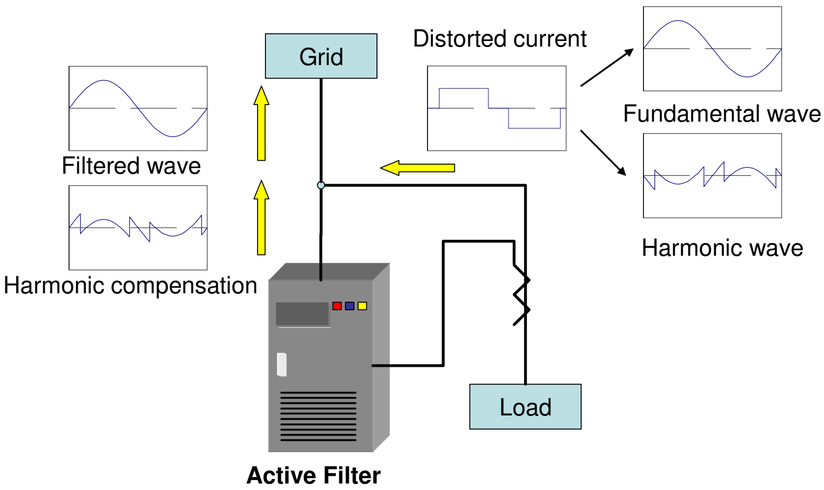
Name	STATCOM (STATic synchronous COMpensator)
Development Stage	Practical use
Installation	Grid side (transformer substation)
General Description	STATCOM, also referred to as “self-commutated SVC”, supplies reactive power to the grid in order to control and stabilize the grid voltage as an SVC. It can continuously compensate reactive power from the leading phase to lagging phase. In addition, the device can be smaller than the SVC that uses both a capacitor and reactor.  Fig. 2-10 Example of STATCOM http://www.ece.umr.edu/power/Energy_Course/energy/Electric_Trans/shunt.htm
Relevant Impact/Effect	Instantaneous voltage change, flicker, harmonics, voltage imbalance
Problems	Relatively high initial cost is a barrier of STATCOM

Name	DVR (Dynamic voltage restorer)
Development Stage	Practical use
Installation	Demand side (e.g., semiconductor factory, paper factory)
General Description	The DVR is a device that prevents serious damage on sensitive loads such as electronics or semiconductor factories. It can compensate the voltage, and stabilize the load voltage and frequency. When a grid problem such as instantaneous voltage drop occurs, the device controls the voltage at the receiving points by means of an inverter. Active power can also be controlled to some extent by DVRs as well as reactive power; however, the capacity to control active power is heavily dependent on the capacity of the energy storage devices. Capacitors, SMES, and flywheel systems are commonly used as energy storage devices. DVRs are connected in series with loads; therefore, a significant amount of current continues to flow in the inverter; however, output power is negligible since the inverter voltage is quite small except at the time of voltage compensation. In the case of voltage compensation, the inverter generates voltage and outputs active/reactive power associated with voltage, current, and phase.  Fig. 2-11 Circuit diagram of DVR[15)]
Relevant Impact/Effect	Voltage control, flicker control, harmonics control, voltage imbalance

Name	PCS with function to suppress rise in grid voltage
Development Stage	Practical use
Installation	PV side
General Description	By adding a function for grid voltage rise suppression to the PCS, the issue of overvoltage derived from PV can be avoided. In Japan, every PV system interconnected to the grid must have this additional function to keep the voltage within the required range. The voltage control flow of the grid voltage rise suppression function in a PCS installed in Japan is illustrated below. When the voltage of an AC output point from the inverter exceeds the set value (107V in Japan), the system starts controlling the reactive power output. In addition, if the voltage continues to rise and reaches close to the upper limit, the system starts restricting active power output from the PV up to 0A.  Fig. 2-12 Control scheme of voltage rise suppression function
Relevant Impact/Effect	Overvoltage suppression
Problems	・ Decrease in efficiency of PV system by restricting power output

	・ The system could lead to unfairness among users

Name	Passive filter
Development Stage	Practical use
Installation	Grid side, Demand side
General Description	Passive filters (also called LC filters) are composed of passive elements such as capacitors or reactors. They absorb harmonic current by providing a low-impedance shunt for specific frequency domains. There are two different kinds of passive filters: tuned filters and higher-order filters. Tuned filters are targeted to eliminate specific lower-order harmonics; on the other hand, higher-order filters can absorb entire ranges of higher-order harmonics. In general terms, those filters are used in combination for practical application.  Tuned filter Higher-order filter Fig. 2-13 Passive filters[15)]
Relevant Impact/Effect	Harmonics control
Problems	Passive filters can end up increasing the harmonics of a specific order.

Name	Active filter
Development Stage	Practical use
Installation	Grid side, Demand side
General Description	Active filters detect harmonic current from a load and generate harmonics with the opposite polarity for compensation. Active filters have the following advantages over passive (LC) filters: ⇒ By applying a highly responsive IGBT (Insulated gate bipolar transistor), several harmonic currents can be eliminated at the same time ⇒ By applying IGBT, the system size becomes smaller and the noise is reduced. ⇒ Active filers do not require a system setting change even when a change occurs in the grid. The advantages listed above allow many applications for active filters such as in theatres and office buildings as well as manufacturing facilities.  Fig. 2-14 Active filter
Relevant Impact/Effect	Harmonics control

Name	Sodium-sulphur battery (NaS battery)
Development Stage	Demonstration/Practical use
Installation	Grid side, demand side
General Description	NaS batteries are secondary batteries that charge/discharge electricity by exchanging sodium ions through beta-alumina solid electrolyte. The batteries operate at approximately 300°C in order to maintain the electrodes in a molten state and to obtain adequate electrolyte conductivity. The general aspects of NaS batteries are as follows: ⇒ High energy density: 3 times higher than lead batteries in terms of energy density ⇒ High efficiency: Efficient energy storage due to high charge/discharge efficiency and minimum self-discharge ⇒ Long lifetime: More than 2,500 times the charge/discharge cycle is possible. Long-term durability is one of the advantages of NaS batteries ⇒ Environment friendly: No pollutants are emitted (no combustion process) ⇒ Maintenance: Easy maintenance because there are no moving parts in the system  Fig. 2-15 NaS battery[37] - Storage efficiency: 70–80% - Storage density: 50–200 kWh/m^3

	- Response speed: A few seconds - Lifetime: 10–15 years Applications for NaS batteries include: improved grid power quality, additional power source for emergencies, uninterrupted power supply and electric load levelling. Grid-side application NaS batteries installed at transformer substations normally have several MW of capacity. The main contribution to the grid is its function as distributed pumped storage in urban areas. The additional functions of power quality control as well as energy storage are also important advantages. Demand-side application In addition to load levelling, the function of UPS and energy storage for emergency facilities can be used more effectively.
Relevant Impact/Effect	Instantaneous voltage change from large-scale PV, peak cut, frequency & voltage control
Problems	Relatively high cost is a bottleneck for the battery: 4300–13000 $/kW

Name	SMES (Superconducting magnetic energy storage)
Development Stage	Developing stage
Installation	Grid side, Demand side (e.g., factory)
General Description	Superconducting magnetic energy storage (SMES) systems, which store electrical energy in superconducting coils, offer properties not exhibited by previous technologies. SMES systems can simultaneously control both active and reactive power, quickly charge/discharge large amounts of power, and endure repeated use. The expected application of SMES is control of grid power quality. SMES systems are composed of a refrigeration unit, inverter, and insulated unit containing superconducting coils. The resistance of the superconducting substance under very low temperature becomes zero and theoretically, no energy is consumed in the system. The electric current stored in the devices would continue to flow forever. SMES applies this principle. ⇒ High efficiency: Efficient energy storage due to the application of superconductors ⇒ Long lifetime: Long lifetime because there are no moving parts in the system ⇒ Flexible: Various capacity ranges are available - Storage efficiency: 70% - Storage density: 1 kWh/m^3 - Response speed: less than 1 s - Lifetime: 30 years - Cost: 870–2600 $/kW

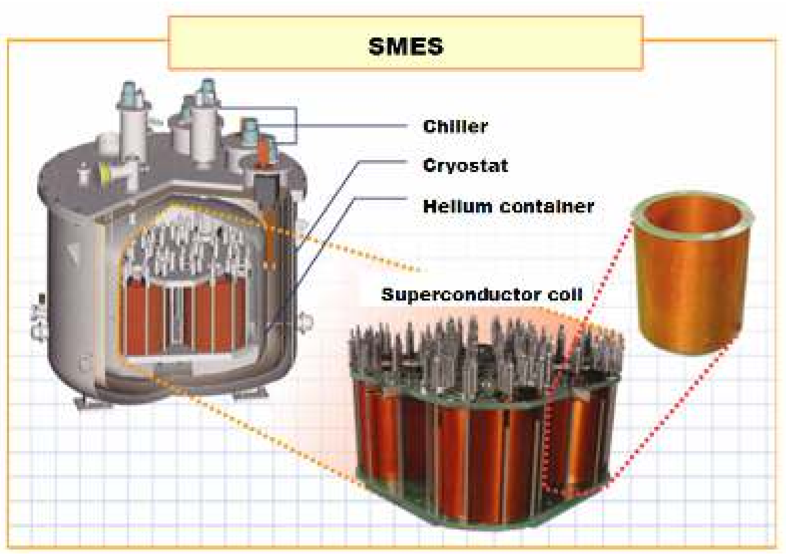


Fig. 2-16 SMES system[38]

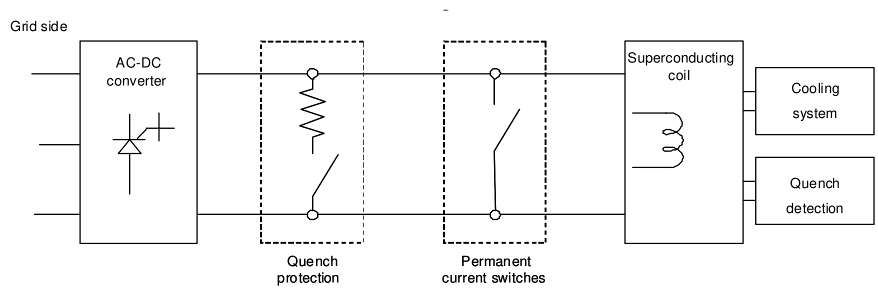


Fig. 2-17 Circuit diagram of SMES system[15)]

Application

Possible applications for SMES are shown below. Currently, only the upper two applications are on the way to practical use:

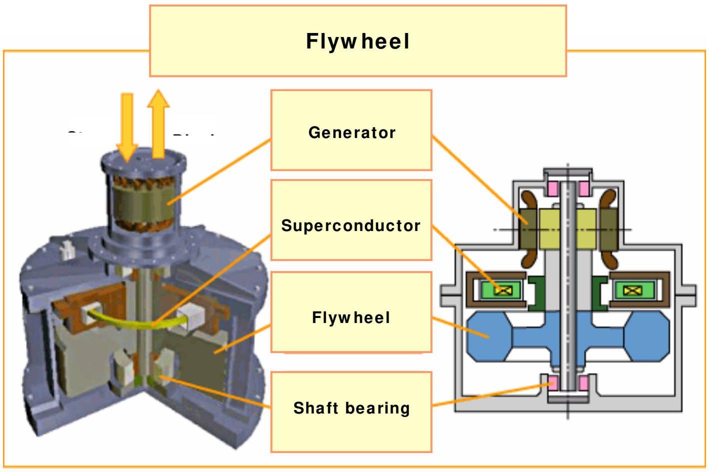
(a) Compensation for instantaneous voltage drop / electrical outage

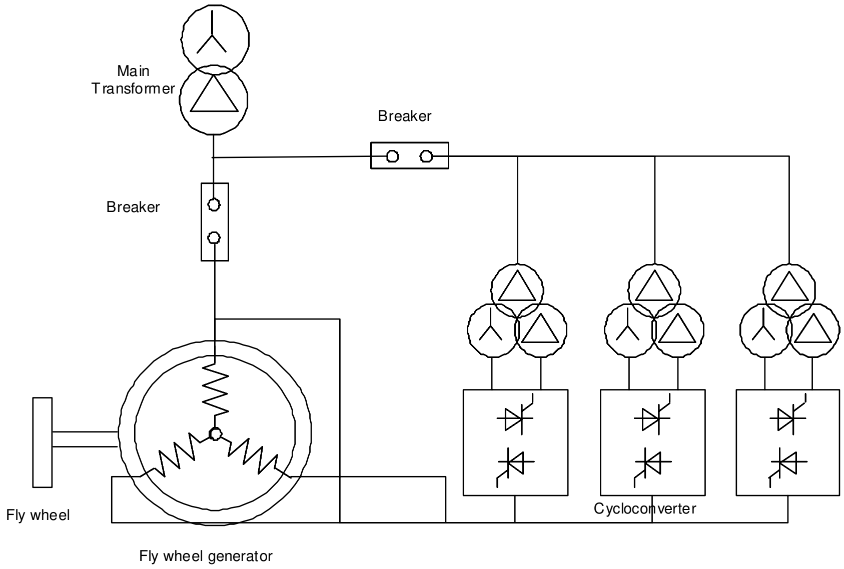
(b) Compensation for load change (absorption of short-time load change)

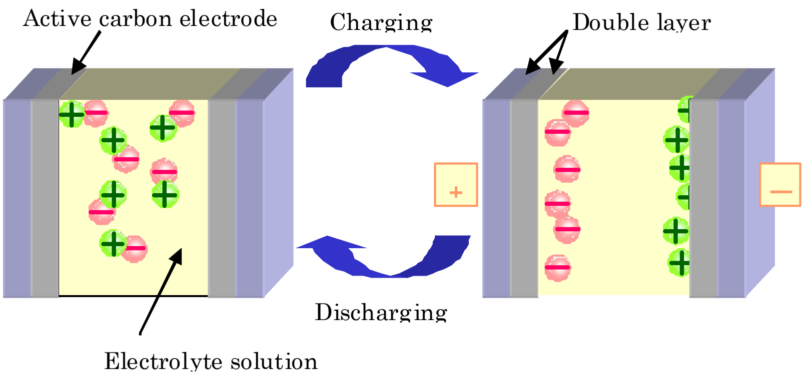
(c) Stabilization of grid voltage

(d) Load levelling

Relevant Impact/Effect	Instantaneous voltage change from large-scale PV, peak cut, frequency & voltage control

Name	FES (Flywheel energy storage)
Development Stage	Practical use
Installation	Grid side, demand side
General Description	FES systems store energy as kinetic energy by means of rotating disks and can be used for stabilizing frequency fluctuations in grid electricity. Shaft bearing technology is a key to improving the storage efficiency of the system. In order to reduce the loss from the rotors, a non-contact shaft bearing system using superconductivity technology has been proposed and developed. A system response speed of 15 MW/0.3 S has been achieved. The system provides reactive power as well as active power.  Fig. 2-18 Flywheel [38] - Storage efficiency: 80% (target) - Storage density: 80 kWh/m^3 (target) - Response speed: Less than 1 s - Lifetime: 30 years - Cost: Less than 3000 $/kW

	 Fig. 2-19 Example of circuit for flywheel frequency stabilization devices[15)]
Relevant Impact/Effect	Instantaneous voltage change from large-scale PV, peak cut, frequency & voltage control
Problems	Although relatively higher loss from the rotors has been a major issue of this system, smaller systems have reached the practical stage due to advancements in new materials, magnetic levitation technologies, superconducting shaft bearing technologies, and variable-speed synchronous technologies.

Name	Electric double-layer capacitor (EDLC)
Development Stage	Basic research / Demonstration
Installation	Grid side, Demand side, PV side
General Description	Batteries store electricity by converting it into chemical energy. Capacitors store electricity as it is without carrying out any conversion. Capacitors are used in radios and televisions, but their storage capability is much smaller than that of batteries. EDLCs, often referred to as super/ultra capacitors, have much higher energy storage capacity. For general capacitors, the electrolytic capacitor has dielectric polarization. On the other hand, EDLCs store electrical charge on the surface of the electrode, activated charcoal. Long charge/discharge cycles and high response speed is possible; therefore, EDLCs are expected to become high-versatility products.  Fig. 2-20 Conceptual diagram of EDLC - Storage efficiency: 80% (target) - Storage density: 15–50 kWh/m^3 (target) - Response speed: Less than 1 s - Lifetime: 20 years - Cost: Less than 1750 $/kW
Relevant Impact/Effect	Instantaneous voltage change from large-scale PV, peak cut, frequency & voltage control
Problems	Technological development is targeted toward systems with higher capacity and power. Improved cost, productivity, durability, safety and charge/discharge characteristics are also important issues.

Name	Unintended islanding detection system (Passive system)
Development Stage	Practical use
Installation	Grid side, PV side
General Description	PV systems (PCS) are designed to disconnect from the grid during a power outage in order to avoid the condition referred to as "unintended islanding". In unintended islanding, PV systems in the network continue feeding power to connected loads, even though there is no power flow from the main supply at the distribution transformer. Unintended islanding is dangerous because it could lead to a serious accident such as electric shock to utility workers. In order to avoid unintended islanding operation, commercial PV systems are equipped with an unintended islanding detection system in the PCS. One type is the passive system, which detects any sudden changes in grid parameters such as voltage, frequency, and harmonics. Its advantages include high-speed response; however, the system cannot detect unintended islanding if the power generated by the PV system is equal to the power consumed by the loads.
Relevant Impact/Effect	Unintended islanding protection
Problems	・ There is a risk of malfunction with grid disturbance (instantaneous voltage change, disconnection of loads, and switching of the grid) ・ If the power generated is balanced with the network load, the system cannot detect unintended islanding ・ There are some "blind zones" ・ Trade-off between sensitivity and suppression of malfunction

Name	Unintended islanding detection system (Active system)
Development Stage	Practical use
Installation	Grid side, PV side
General Description	Although PV systems (PCS) are designed to disconnect from the grid during a power outage, it is difficult to detect the incident if the power output from the PCS and the power consumed in the loads are balanced. In such cases, PV systems will continue to supply power to the grid. This situation is called “unintended islanding”. In order to avoid unintended islanding, PV systems are equipped with an unintended islanding detection system in the PCS. One of the unintended islanding detection systems is an active system that sends out signals to continuously generate a small fluctuation in the grid voltage or frequency. The system detects the disturbance in the grid power associated with those signals in the case of unintended islanding. Compared with the passive system, the response time is slower, but the active system does not have any “blind zones”. It also should be noted that the signals would have some impact on the grid if many PV systems were interconnected.
Relevant Impact/Effect	Unintended islanding protection
Problems	・ Slower response time ・ Impact from the signals on the grid electricity ・ System sensitivity drops if there are massive generators close to the connecting point ・ Trade-off between sensitivity and suppression of malfunction

<table>
<tr><td>Name</td><td>Protective relay</td></tr>
<tr><td>Development Stage</td><td>Practical use</td></tr>
<tr><td>Installation</td><td>Grid side, demand side</td></tr>
<tr><td>General Description</td><td>
Protective relays detect short circuits or ground faults of various grid devices at power generation plants, transformer substations, and load facilities. In addition, they identify the affected areas and send out disconnection signals to all relevant devices as soon as possible in order to minimize the impact.
In order to set the conditions for disconnection, the characteristics of each relay device should be considered in advance and operational tests should be conducted at the actual site of installation.
There are many types of protective relays, and each device has different characteristics and operation conditions. Several devices are generally used in practice.
Table 2-2 Types of protective relays
<table>
<tr><th>Name</th><th>Abbreviation</th><th>Operation conditions</th></tr>
<tr><td>Overcurrent relay</td><td>OCR</td><td>Current over the set value</td></tr>
<tr><td>Ground fault relay</td><td>GR</td><td>Ground fault current over the set value</td></tr>
<tr><td>Overvoltage relay</td><td>OVR</td><td>Voltage higher than the set value</td></tr>
<tr><td>Undervoltage relay</td><td>UVR</td><td>Voltage lower than the set value</td></tr>
<tr><td>Ground fault overvoltage relay</td><td>OVGR</td><td>Zero-phase voltage</td></tr>
<tr><td>Differential relay</td><td>DFR</td><td>Difference in vector of the current within a protected area is higher than the set value</td></tr>
<tr><td>RDFR</td><td></td><td>Ratio between the operating coil current and restraint coil current is higher than the set value</td></tr>
<tr><td>Underfrequency relay</td><td>UFR</td><td>Frequency under the commercial value</td></tr>
<tr><td>Overfrequency relay</td><td>OFR</td><td>Frequency over the commercial value</td></tr>
</table>
</td></tr>
<tr><td>Relevant Impact/Effect</td><td>Unintended islanding protection</td></tr>
</table>

Name	Transfer trip equipment
Development Stage	Practical use
Installation	Grid side
General Description	When an accident occurs in the grid, the protective relays operate and the circuit breakers at the transformer substation disconnect. In this case, the distribution line is cut off from the grid, but if the power output from the distributed generators is balanced with the load, a condition called unintended islanding occurs. Transfer trip equipment can prevent unintended islanding by sending out signals from the transformer directly to each device via communication lines. Transfer trip equipment is composed of signal sending devices at transformers, receiving devices at generators and communication lines.
Relevant Impact/Effect	Unintended islanding protection, improved disconnection time
Problems	Transfer trip equipment is reliable technology in terms of unintended islanding protection; however, the need for communication lines in addition to the main devices makes the system more costly and complicated.

Name	DC offset detecting devices
Development Stage	Practical use
Installation	PV side (in PCS)
General Description	Inverters are usually equipped with a transformer in order to eliminate the DC offset component that could have a negative impact on pole transformers. On the other hand, if the DC component could be detected at the AC side of the inverter, the transformer would not be required. Many of the inverters used for PV systems are the transformerless type that has DC offset detecting devices instead.
Relevant Impact/Effect	DC offset prevention
Problems	Impact on the grid in the case of intensive installation is not fully understood

3. Demonstration projects for next generation of grid power quality management

The standalone device countermeasures presented in the previous chapter are extremely effective, but as more PV sources come online, regulation by these means alone will become increasing difficult. Therefore, in addition to individual technology measures, countries around the world are advocating and demonstrating various initiatives that take full advantage of the characteristics of distributed power sources while ensuring stable power supplies by rethinking the grid regulation systems themselves. In this chapter, we introduce some of the cutting-edge grid regulation technologies in practice in various locations around the world.

3.1. Demonstrative research on clustered PV systems

3.1.1 Basic concept and objectives

In 2002, NEDO (New Energy and Industry Technology Development Organization) initiated a new R&D program for PV grid interconnection. The objective of this program was to demonstrate that a power system for several hundred residences, where each residence has a PV system, could be controlled by the technologies developed in this program without any technical problems.

The focus of research is on countermeasures from the PV side rather than the grid side. The following areas were set as research sub-themes for this project (See Table 3-1).

Table 3-1 Research sub-themes for the project

Overvoltage (technologies to avoid PV output suppression)	As explained in section 2.1, Power conditioner systems (PCS) in Japan are generally equipped with a function to suppress the rise in grid voltage in order to control the line voltage within a certain range. Therefore, power output from the PV system can be limited even under good solar conditions, resulting in decreased system efficiency. The target of this research was the development of technologies to avoid PV output suppression by integrating power storage devices with the PV system, and evaluation of performance.
Harmonics	Features of harmonic distortion on a distribution line with highly concentrated PV systems were investigated, and the impact analyzed. Limitations of PV grid interconnection from the perspective of harmonic distortion were also assessed.
Unintended islanding	Unintended islanding conditions under concentrated PV systems were studied and new unintended islanding detection devices were developed and evaluated.
Development of applied simulation system	Simulation systems for analyzing the effects and functions of PV output suppression, harmonics, and unintended islanding detection systems were developed.

3.1.2 General Information

Ota City is an industrial city in the Kanto area with approximately 220,000 inhabitants. Many factories are located in the area including Fuji Heavy Industry Co., which is a major automobile company in Japan. Jyosai, the demonstration site for the PV project, is a new residential area in the central part of Ota City.

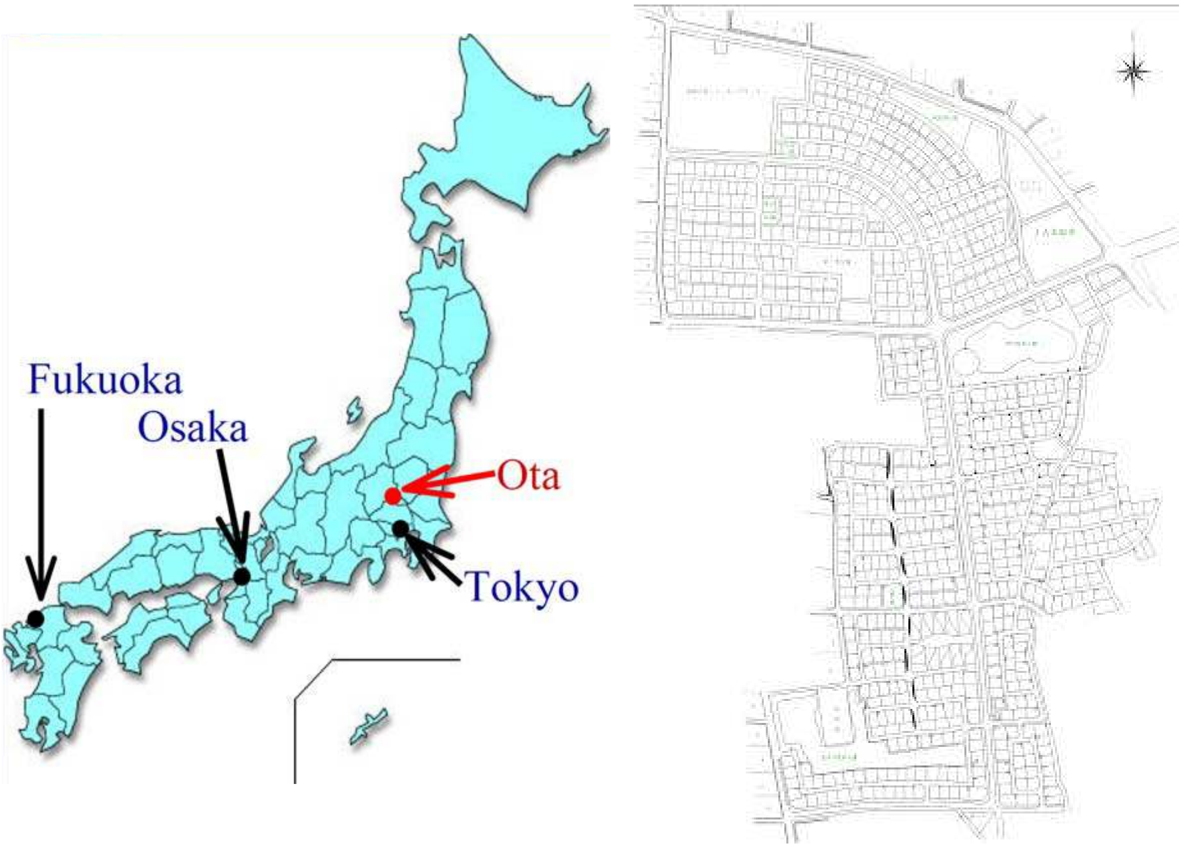


Fig. 3-1 Location of Ota City and site map of the demonstration area (Jyosai)

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For this research, 553 PV systems were installed on newly built houses in the area. The total capacity of the PV systems is 2130 MWp (Average 3.85 kW/system). Operation of the first PV system in the project commenced in December 2003, and installation of all PV systems was completed in May 2006.

Fig. 3-2 Overview of the demonstration site

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Stakeholders from various fields participated in this research project. The leader of the project was Kandenko Company Ltd., an electrical engineering and installation company.

Meidensha Corporation (electronics manufacturer), Electric Power Engineering Systems Company Ltd. (power consultant), Shin-Kobe Electric Machinery Company Ltd. (battery manufacturer), Matsushita Ecology Systems Company Ltd. (electronics manufacturer), Tokyo University of Agriculture and Technology (academic), and Ota City (local government) were the other members who participated in this project from the beginning. Omron Corporation (electronics manufacturer), Nihon University (academic), and JET[6] (official testing organization for electronic devices) joined the project later.

3.1.3 Outcomes of the project

3.1.3.1. Overvoltage/Undervoltage (technologies to avoid PV output suppression)

The basic idea for avoiding suppression of PV output is to store the excess power by charging power storage devices such as batteries. Several control schemes for charge/discharge systems were proposed and the overall performance was evaluated in this study.

1) Voltage control operation

This control scheme charges the battery when the voltage exceeds a certain threshold and discharges the battery at night. The disadvantage of this approach is that the voltage rise for

6 JET: Japan Electrical Safety & Environment Technology Laboratories

each house differs considerably due to differences in impedance and interconnection conditions, and the lifetime of the battery would be influenced by those conditions.

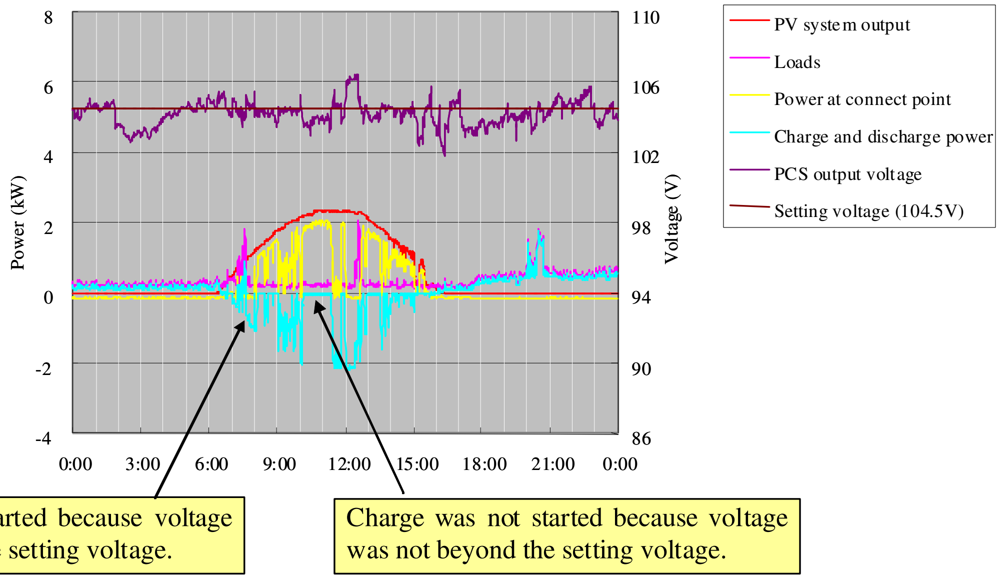

Fig. 3-3 Voltage control operation

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2) Reverse flow control operation

This control algorithm charges the battery at the start of reverse flow from the PV system and discharges the battery at night. When the battery is fully charged, PV output suppression cannot be managed.

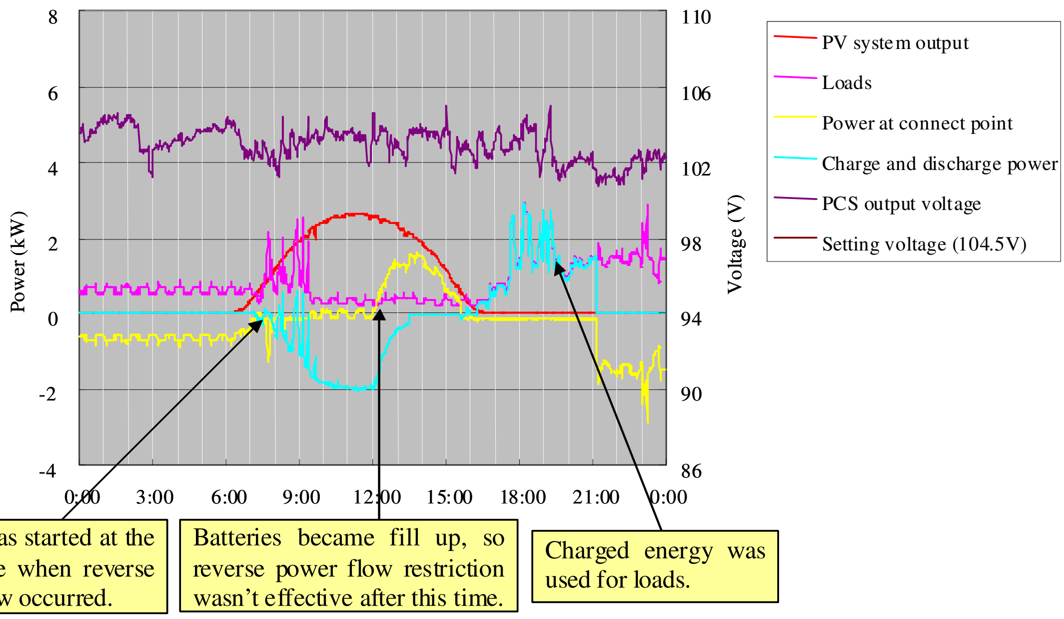

Fig. 3-4 Reverse flow control operation

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3) Schedule control operation

This control algorithm charges and discharges the battery as scheduled in advance.

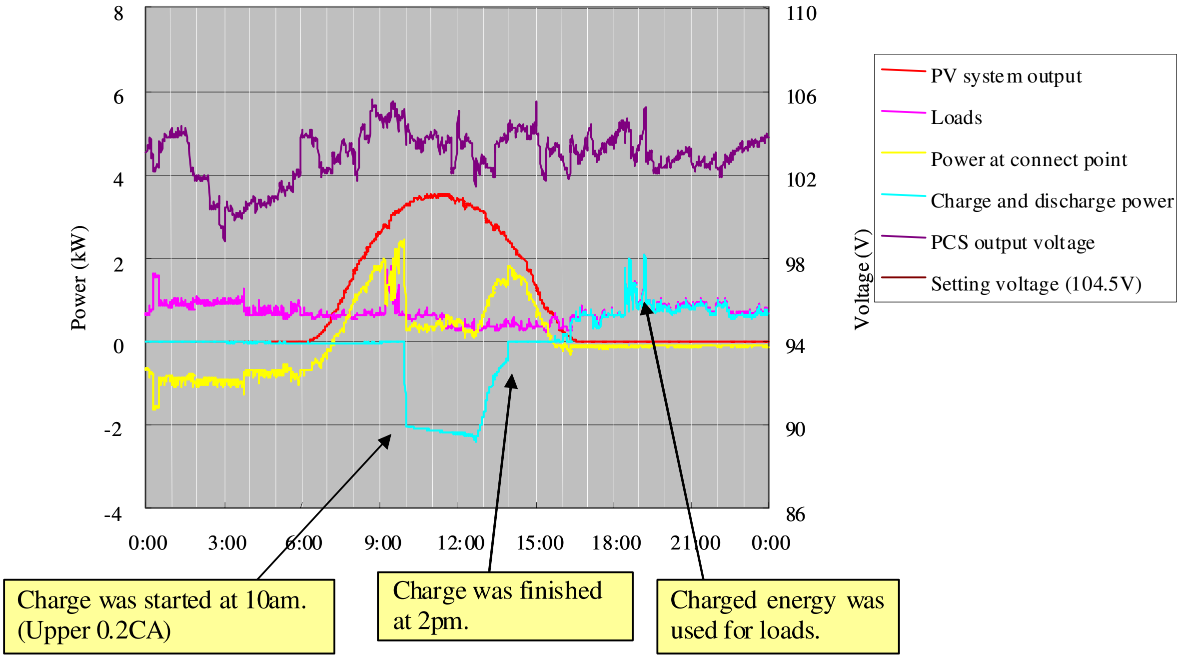

Fig. 3-5 Schedule control operation

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Each control operation scheme was evaluated by changing the threshold and control conditions. A typical residential area was applied for the simulation conditions.

As a result of the evaluation, the report concludes the following:

- Voltage control scheme is the most effective in terms of mitigating output loss.
- Power charged in the batteries varies in the case of the voltage control scheme since it is heavily dependent on the grid voltage.
- Total power loss (loss caused by PV output suppression + charge/discharge loss) varies widely for all control schemes, but the variation is relatively small for voltage control scheme.
- The effects of schedule control operation are not a significant improvement even when integrated with the voltage control scheme.
- In order to minimize the fluctuation in battery charging status, the schedule control operation is the most effective.
- Power generation cost of PV systems using these control schemes can compete with conventional PV systems only if the battery cost is reduced to 30% of the current level.

3.1.3.2. Harmonics

In order to analyze the impact of PV systems on grid power quality, harmonic current at the power conditioner and the connection points was monitored and analyzed.

The results show that although harmonic current from the PCS tends to increase when the system starts or stops, the voltage at the connection point is not affected by the harmonics and it remains stable throughout the day.

The demonstration test also confirmed that the third, fifth, and seventh current from both the residential load and PCS have little impact on grid voltage distortion even if the overlap factor is 1,0. THD (total harmonic distortion) increased by only 2% when the number of PV systems connected in the distribution lines increased by seven times from the current level of 553 systems in the area.

3.1.3.3. Unintended Islanding

The target of this part of the research is to develop an unintended islanding detection system with the following features:

1) Preventing degradation of unintended islanding detection sensitivity caused by interference
2) Fast detection of unintended islanding in a case of intersystem fault
3) Compatibility between fast detection and suppression of malfunction
4) No negative impact on grid power quality by active signals

The proposed detection system sends reactive power signals to the grid and detects unintended islanding by monitoring frequency fluctuation feedback. Tests confirmed that the new system can detect unintended islanding operation faster than commercial PCSs and that it operates properly during a disturbance in grid power quality (voltage, phase and harmonics disturbances).

3.2. Autonomous Demand Area Power System (ADAPS)

3.2.1 Basic concept and objectives

Highly concentrated interconnection of decentralized power generation systems to a grid may have a negative impact on power quality, protection, and safety in the near future. In response, the “Autonomous Demand Area Power System” was proposed by the Central Research Institute of Electric Power Industry (CRIEPI) as a new power supply system concept looking towards 2010 and beyond. The Autonomous Demand Area Power System can prevent those issues and enhance harmonization between grid and decentralized power generation, benefiting both the electricity supplier and the end-users through effective use of decentralized power generation. The basic concept of the Autonomous Demand Area Power System is modification of the existing grid infrastructure. The objective of the project was to develop a grid system with the following features.

- A system that can flexibly adapt to various decentralized power generation, operation, and load profile from both a real and temporal perspective. It should be as simple as possible, using the existing power infrastructure in order to reduce the total cost.
- A system that can easily adapt to a future device control system combined with advanced information and communication technologies and to new services including end-users’ participation from the perspective of both hardware and software.
- A system that can proactively contribute to efficient operation of the entire grid by minimizing any negative impact of a decentralized power system on the grid and enhancing the load levelling.

The proposed measure to achieve the first target is to shift the present “tree” configuration of the distribution grid system to a “loop” configuration and to form a wide-area network. At the connection point of the loop, “loop balance controller (LBC)”, devices that can actively control line voltage and power flow, are installed to add further flexibility for interconnection of decentralized power generators. The LBC should be able to connect lines of different voltage or phase, and to prevent expansion of fault-affected areas such as in the case of a blackout.

As for the second and third targets, application of a “supply & demand interface” that can autonomously manage and control the loads and decentralized power generators to attain supply security, and economic and efficient supply by using relevant information such as electricity prices and end-user information is proposed.

The basic configuration of the autonomous grid is presented below.

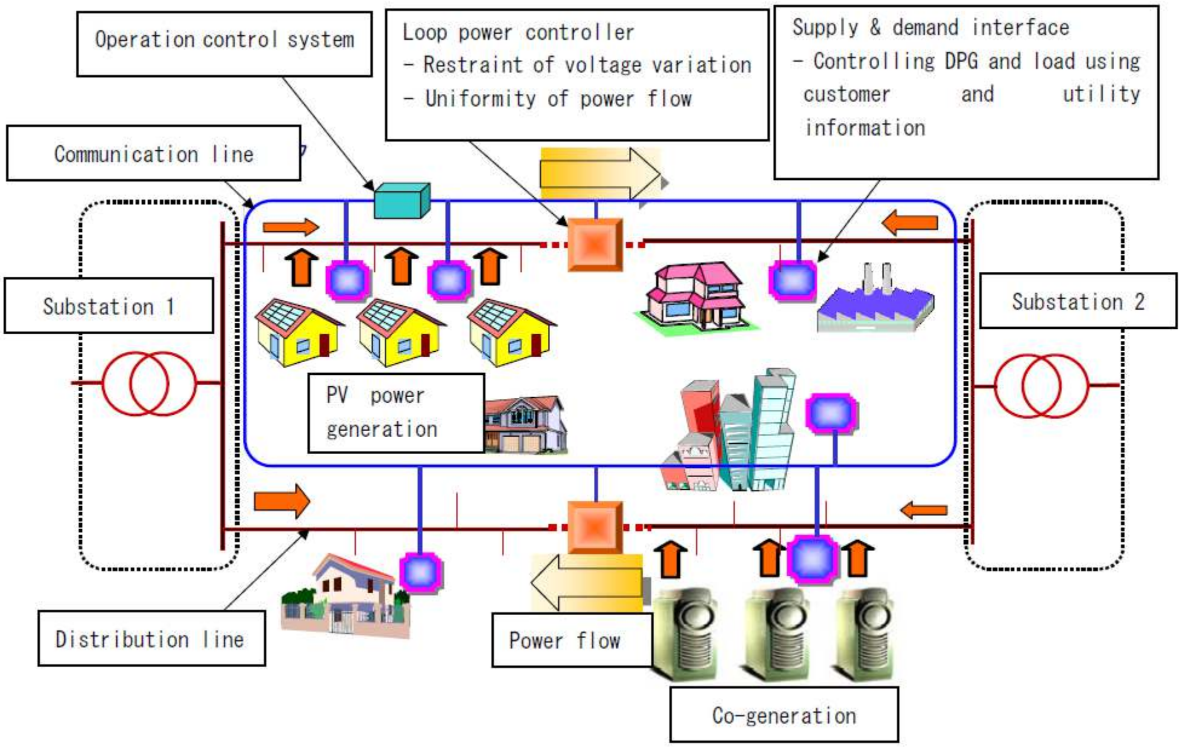

Fig. 3-6 Basic concept of ADAPS

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3.2.2 General Information

The ADAPS concept was proposed by CRIEPI based on a national research project carried out in 1999–2000. The demonstration test facility was built at the Akagi Testing Center, Gunma Prefecture, Japan. The system configuration of the test facility is summarized below

- Total grid capacity: 4000 kW (two 2000-kW banks)
- Total line length: 5 km (more than 20-km line length is possible by using simulator)
- Decentralized generator capacity: 1200 kW
- Virtual experiment facilities for simulating higher voltage grid conditions

The basic configuration of the test facility is presented in Fig. 3-7 and the capacity of each decentralized power generator is given in Table 3-2.

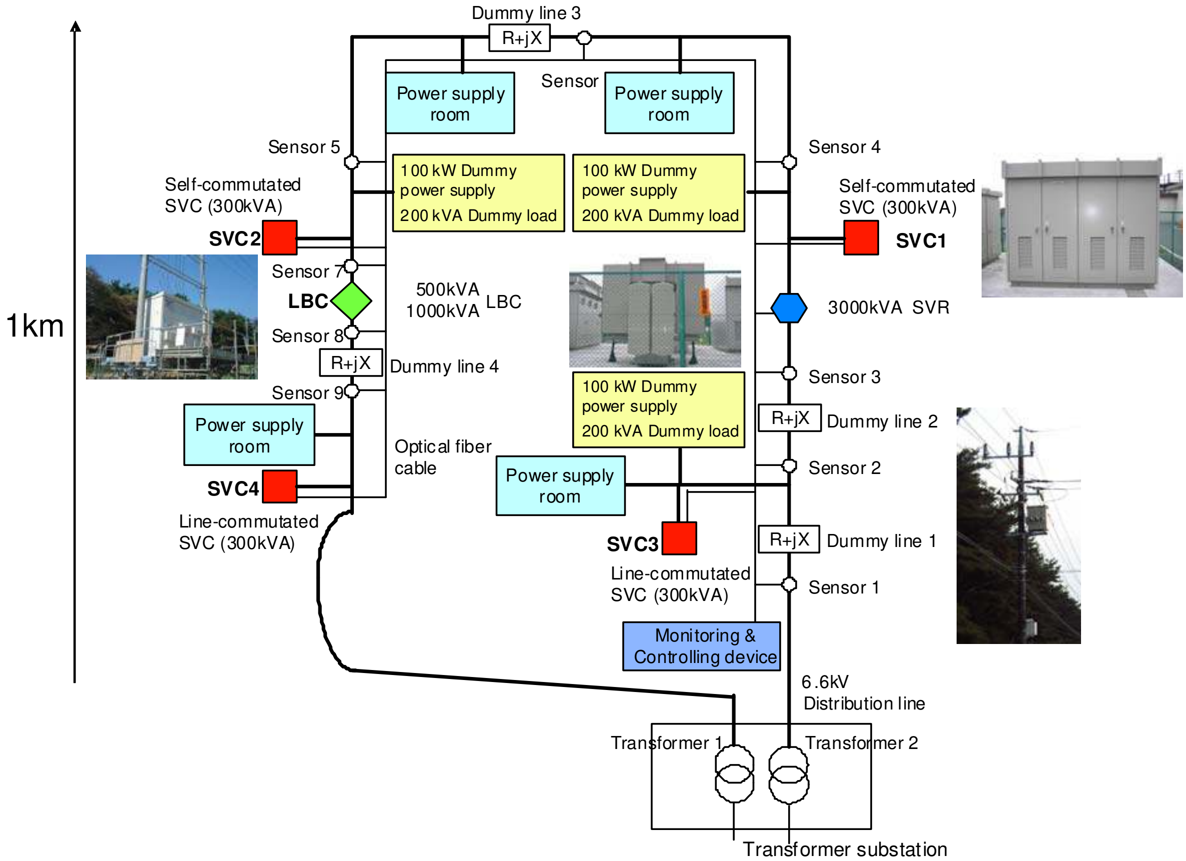


Fig. 3-7 Installation of grid devices at demonstration site

* Commercial use of this figure is strongly prohibited

Table 3-2 Capacity and number of installed distributed generators

Systems	Capacity of each system	Number of systems	Total capacity
Synchronous generator (CHP; virtual)	25–150 kW	4	415 kW
Induction generator (Wind turbine; virtual)	35–100 kW	2	185 kW
Solar PV (Actual and Virtual)	5 kW	16	80 kW
Inverter-type virtual power generator A (PV & batteries; virtual)	20 kW	12	240 kW
Inverter-type virtual power generator B (PV; virtual)	100 kW	3	300 kW
Microturbine (Actual)	30 kW	1	30 kW
Total	-	38	1250 kW

3.2.3 Outcomes of the project

A number of outcomes have been presented already from this research project. One of the main issues addressed in this project is voltage control (Overvoltage/Undervoltage) and main outcomes regarding the voltage issues are introduced in this paper.

1) Development of grid control devices and methods for voltage control

Two voltage control methods were proposed in the project: “Autonomous voltage control” and “Remote voltage control”. The concept of autonomous voltage control is to set a reactive power threshold in addition to the existing voltage threshold for voltage control.

It was confirmed that the line voltage can be effectively controlled by the autonomous voltage control method if the concentration level of PV systems is moderate. The simulation results showed that the total power generation of a distribution line improved by up to approximately 7%, and each household by up to 60% compared to existing methods.

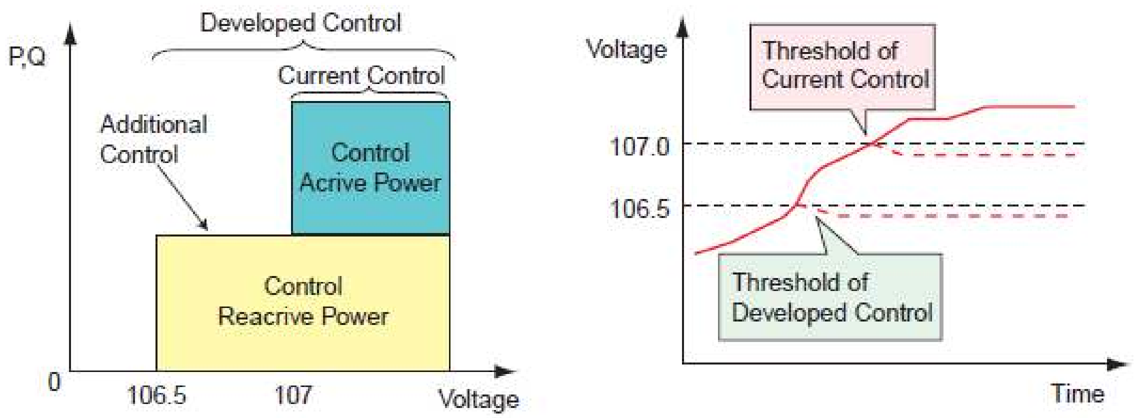
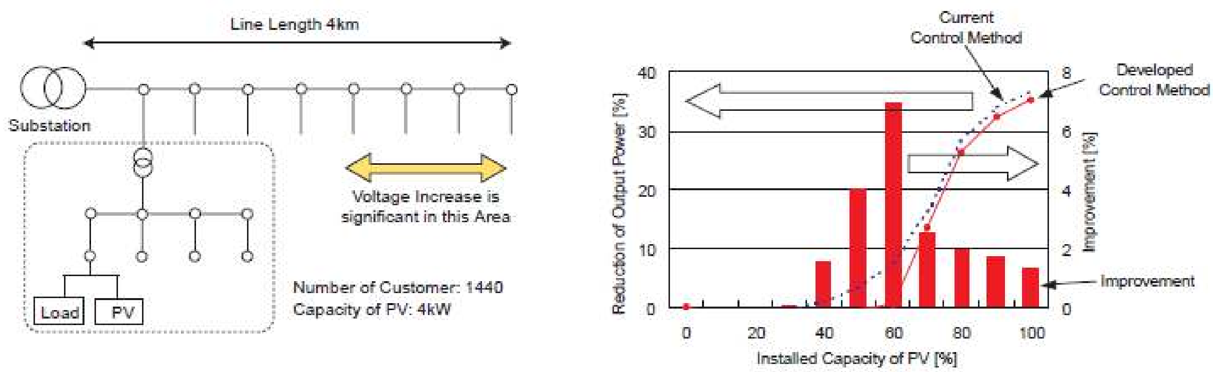


Fig. 3-8 Autonomous voltage control method[19]



(a) Model Distribution System with PV (b) Simulation Result

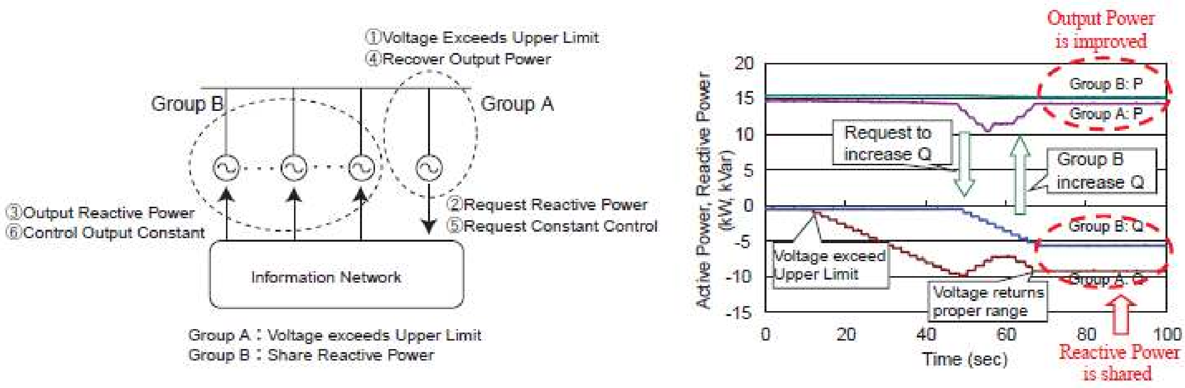
Fig. 3-9 Results of simulation for autonomous voltage control method [(19)]

Remote voltage control, on the other hand, is designed to control the line voltage even with a high concentration of PV systems. It is also designed to achieve the following:

- Control an unspecified number of decentralized power generators regardless of the conditions of the distribution grid and decentralized power generators
- Avoid the concentration of reactive power output to certain end-users

- Respond promptly against instantaneous output fluctuation

It was confirmed that the developed remote voltage control method functions properly as designed in the demonstration test facility.



(a) Developed Remote Control Method (b) Demonstrated Test Result

Fig. 3-10 Remote control method and test results (19)

The effects of the two methods in cooperation with grid control devices (SVC and SVR) were also evaluated in the demonstration and simulation tests by assuming a basic distribution model (i.e., residential area with line length of 4–5 km, total capacity 3000 kVA, evenly distributed PV system, and PV concentration rate of 30–50%). The results are summarized below.

In the case of one SVC system with autonomous voltage control, the line voltage at some points starts to exceed the voltage threshold if the concentration level of decentralized power generators is more than 30% of the distribution grid capacity.

In the case of instantaneous output fluctuation from a decentralized power generator, SVRs may not be able to promptly respond to the change and the voltage cannot be controlled within the required range.

In the case of one SVC system with remote voltage control, the line voltage can be controlled within the required range even in the case of instantaneous output fluctuation.

2) Development of Loop Balance Controller LBC

Considering power flow control performance and security issues in the case of a grid fault, the BTB-type LBC is applied. Two types of LBC were developed in the project: 500 and 1000 kVA. The 500-kVA system applies existing technologies, pursuing lower, more feasible cost. The 1000-kVA system, on the other hand, applies advanced technologies to achieve a smaller and lighter system with higher performance for the next generation. The system configuration for both types is shown below.

Table 3-3 Specifications of the developed LBC

	System configuration (500 kVA)	System configuration (1000 kVA)
Type	Three-phase bridge BTB type (with transformer)	Three-phase bridge BTB type (transformerless)
Rated voltage	6.6 kV (switching point voltage; 400 V), DC 720V	6.6 kV DC 13.2 kV
Capacity	500 kVA (limited capacity due to the limitations of pole installation)	1000 kVA (pole installation is possible)
Efficiency	More than 93%	More than 93%
Harmonic current	Each harmonic distortion: less than 3% Total harmonic distortion: less than 5%	Each harmonic distortion: less than 3% Total harmonic distortion: less than 5%
Response	Current STATCOM level (90% compensation time; minimum less than 40 ms)	Current STATCOM level (90% compensation time; minimum less than 40 ms)
Power outage control	Continued operation under 30% of voltage sags (0.3 s)	Continued operation under 30% of voltage sags (0.3 s)
Protection coordination	Equipped with required protection function	Equipped with required protection function

The developed LBCs were tested and improved where necessary. Although further improvement will be required for the 1000-kVA system (noise, electromagnetic waves, etc.), the LBCs demonstrate satisfactory performance. In addition, a remote voltage control system that can supplement grid devices (SVCs, etc.) and LBCs in an integrated manner was developed.

3) Evaluation of the total system

Based on the developed devices and voltage control system, overall performance as a total system was evaluated. The following are examples of the evaluation results:

If the SVC can be installed at the appropriate point (intermediate point) and frequent changes in grid configuration are not required, one SVC with autonomous voltage control can manage the line voltage of a residential area and downtown area up to a PV installation rate of 80% and 60%, respectively. In a case where the above conditions cannot be fulfilled, remote voltage control with the SVC installed at the grid end would be more effective. It is important to bear in mind that power loss in this system is relatively high compared to that of other systems; therefore, the running costs should be carefully taken into account.

The advantages of LBC are strongly enhanced in the case of two feeders compared to one feeder. The required capacity or number of SVCs will be considerably reduced.

Generally speaking, downtown areas have longer lines and the supply and demand (PV output) match well. Consequently, no measures are required up to a concentration of 50%

3.3. Impact of the “Association Soleil-Marguerite” photovoltaic generator on the quality of the public distribution network

3.3.1 Basic concept and objectives

Within PV-UPSCALE, a EU funded project, a summary of a monitoring campaign related to power quality has been realised[51]. This study undertaken in 2004 by EDF R&D [(59)] aimed at assessing the impact of a 13-kWp PV system composed of 6 SMA inverters (4 SWR 1700E and 2 SB 2100 TL) on the voltage quality of the low-voltage network in terms of:

- Overvoltage/Undervoltage,
- Instantaneous voltage change,
- Harmonics in the 0–9 kHz range.

This campaign was based on two types of measurements:

- Measurement, during one month, of current, voltage, power, harmonics and flicker taken at the connection point to the distribution network in order to draw up a quality check on the installation
- Measurement, during one day, of transients in order to assess the impact on the grid from start-up/disconnection phases

The following three issues were addressed in this project:

- Harmonics
- Increase in DC offset from PCS
- Others impacts (consumption of reactive power)

3.3.2 General Information

“Soleil-Marguerite” is an association dedicated to the promotion, installation and management of renewable energy systems made by Hespul, a non-profit French organization for the promotion of renewable energies, and La Nef, a public cooperative and ethical financial services bank. The Soleil-Marguerite photovoltaic system is installed on an office building owned by La Nef in Lyon. The total rated PV capacity is 13 kWp composed of three different PV arrays. The capacity of each system is 6.1, 2.1, and 4.6 kWp, respectively.

Fig. 3-11 “Association Soleil-Marguerite” project site

3.3.3 Outcomes of the project

1) Frequency, voltage fluctuation, and voltage imbalance

The results of this measurement campaign revealed that this PV system has very little or no impact on frequency, voltage fluctuation, voltage imbalance, and other parameters that represent power quality at 175 Hz frequency (remote control frequency) as measured values stay within the range defined by the EN 50-160 standard for electricity quality.

2) Harmonics and DC injection

This PV system generates very little current harmonics except for H6 and H8, which are higher than the upper limit set by the EN 50-160 standard. The origin of both measured effects remains unexplained expect for the H6 and H8 current harmonics that could be a consequence of DC injection due to the use of transformerless inverters.

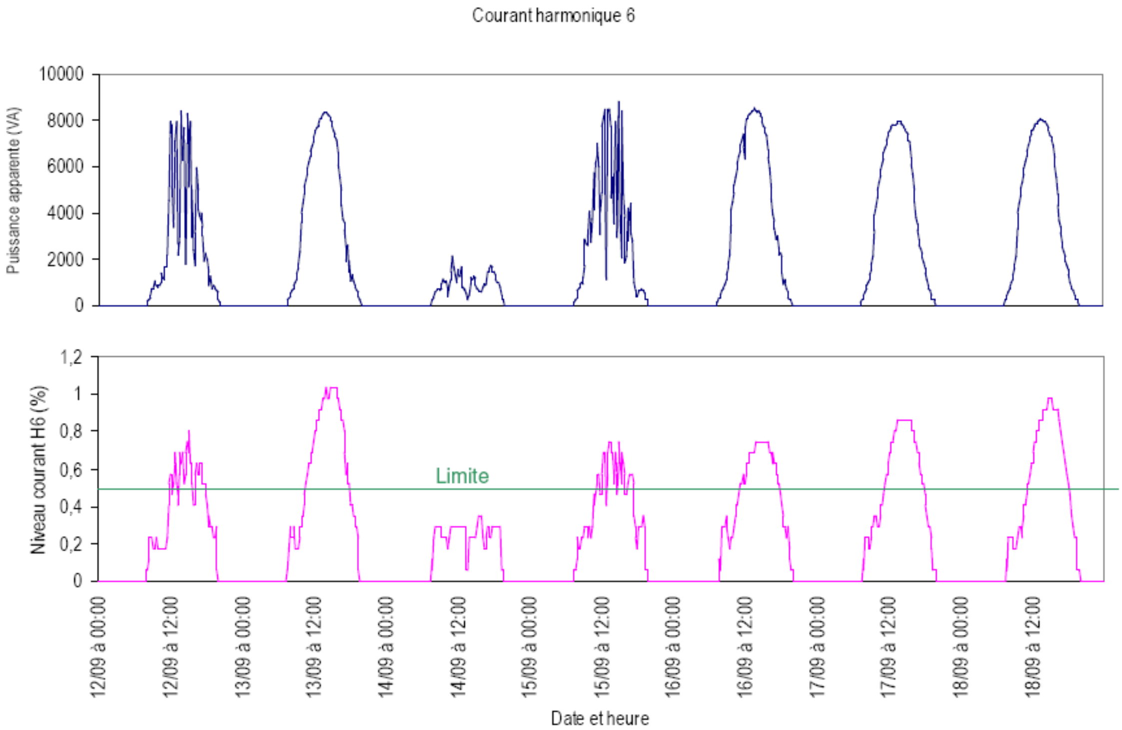


Fig. 3-12 H6 and H8 current harmonics

3.4. Monitoring campaigns of “Solarsiedlung am Schlierberg”

3.4.1 Basic concept and objectives

In the summers of 2006 and 2007, the Fraunhofer Institute took grid quality measurements at various network nodes in a newly developed area called “Solarsiedlung am Schlierberg” in order to assess the effect of high-capacity distributed generation. The focus of the study was on maximum tolerable capacity and voltage rise from DG since past German theoretical study showed that increased voltage due to reverse power flow is the limiting factor for penetration of PV systems on the LV grid.

The following issues were addressed in the measurement study:

- Power quality in relation to the EN 50-160 standard
- Voltage level at the remotest network nodes
- Power flow across the transformer
- Harmonic current injection by inverters

3.4.2 General Information

“Solarsiedlung Am Schlierberg” is an urban development project in Freiburg completed in 2006. Every single house is equipped with a PV system, and in total, 60 PV systems with 440 kWp were installed in the area, in addition to 160 inverters. The electrical network in the area was designed according to conventional wisdom for urban areas.

Fig. 3-13 “Solarsiedlung Am Schlierberg” project site

Structure of the LV network and size of PV arrays are presented below. It should be noted that to the south, more apartment blocks are wired to the same transformer, adding to the load flow. MP1 to MP4 shown in the figure are the measurement points of this project (MP1: at the end of Feeder 1, MP2: at the end of Feeder 2, MP3: at transformer LV terminals, and MP4: at the transformer connection for Feeder 2)

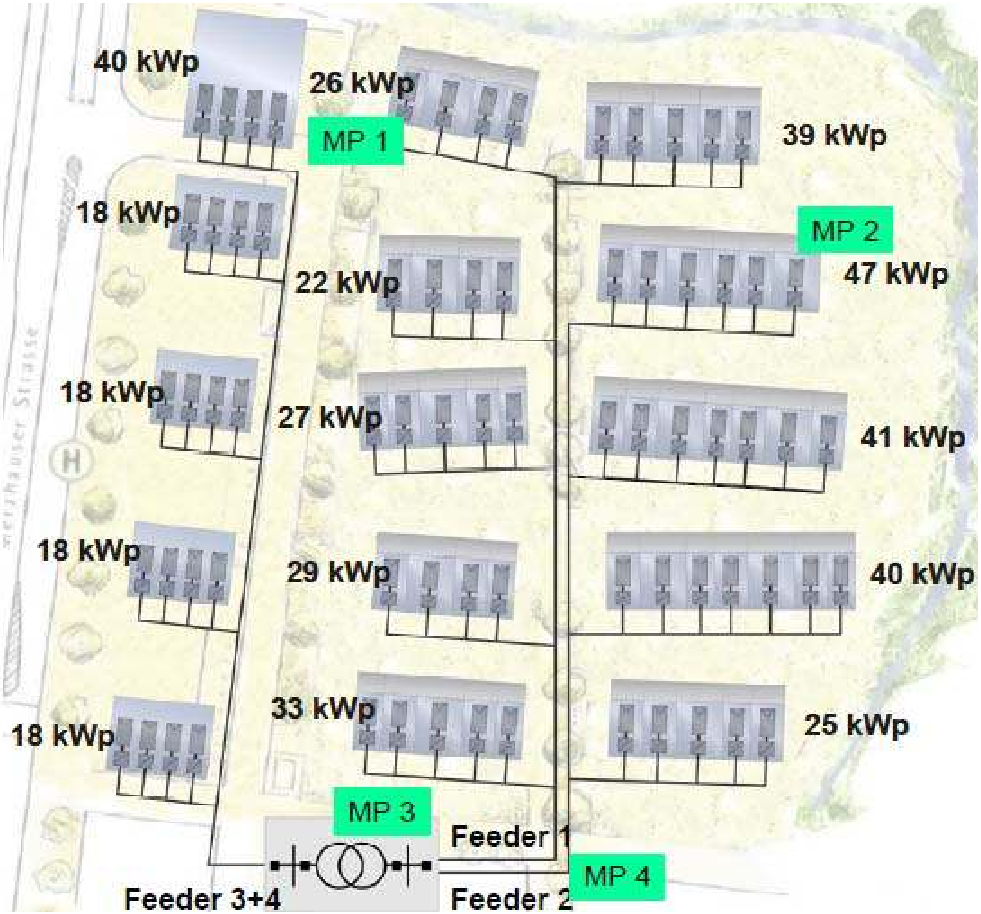


Fig. 3-14 Diagram of PV interconnections at the project site

3.4.3 Outcomes of the project

According to a report presented from the PV upscale project, it was confirmed that the EN 50-160 standard for power quality can be fulfilled even at such a high concentration of PV systems. Impact from the PV systems on harmonics was not observed and that on overvoltage was below the tolerance level.

Although a certain degree (well below the permitted limit of 2%) of power imbalance between phases was observed during the measurement, the report stated that the reason for the imbalance was uneven distribution of inverters over the three phases, which could be avoided by integrated planning of inverter distribution.

In addition, the maximum tolerable capacity of PV systems on a single LV feeder was found to be 7 kWp per apartment, which could be further increased by reducing the set voltage of the transformer.

4. Discussion and conclusions

The electric grid has been designed for the traditional central generation, regional high voltage transmission and lower voltage customer-sited distribution. This design is for one-way power flow and has proven to be safe, reliable, and least cost - historically. However, the paradigm is quickly changing due to price increases of traditional generation, price decreases of PV, policy drivers for PV and value shifts with awareness of climate change. Grid-connected PV is still a small portion of generation for most grids, but with 30% growth annually during the past decade and a potential doubling in 2008[7], integration of PV into the traditional grid design will quickly become an issue. Within the report, potential impacts and expected benefits of distributed PV grid interconnections are defined. Next, the countermeasure technologies that may be applied to minimise the impacts as well as technologies that can enhance the benefits are summarized in a table. Details of each countermeasure technology, including application diagrams are then provided. With millions of miles of existing grid designed for a central generation electric service system, it is important to understanding the impacts, benefits and countermeasures to accommodate distributed, customer-sited, PV generators. However, ideally, grid expansion and upgrades will incorporate design aspects of recent demonstration tests presented in the report as case studies.

Generally, the penetration of PV on the grid is still small enough that grid operators are not experiencing issues [(50,51)]. However, it is difficult to directly apply the demonstration test outcomes to other areas because of inherent factors in each area (line length, demand characteristics, grid configurations, distribution capacities, PV inverter characteristics, and distribution of PV systems, among others) that greatly influence the impacts on grids. Nevertheless, the following valuable implications can be surmised from the results obtained so far.

- Most of the potential problems indicated have yet to become tangible problems at the present time. Furthermore, even the issues with the potential to become problems in the future are generally not serious issues, and can either be dealt with sufficiently with existing technologies or else avoided with proper planning and design.
- Of the problems selected in this examination, dealing with overvoltage concerns is a top priority. Overvoltage incidents are more likely to occur on rural grid in which, generally speaking, the line impedance is higher and the load is relatively low. Where inverters are used, like in Japan, that reduces outputs when a certain voltage threshold is exceeded, the problems are more likely to be social (unfairness) in nature than a grid quality issue.
- The impact of harmonics is now extremely small with the recent advancements in PCS and other technologies. Increase in even harmonics observed in the French case study seems to be a consequence of DC injection from the transformerless inverters. The

[7] Preliminary estimates from International Energy Agency, PV Power Systems, Task 1

impact of transformerless inverter on even harmonics should be assessed in a future study.

- Although the possibilities of unintended islanding operations are extremely slim, the risks involved if unintended islanding does occur are great. There are significant differences between nations in the recognition of the problem’s importance. These differences depend largely on the value judgments of each country.
- Many constraints, including overvoltage, can be eliminated when infrastructure and other facilities are upgraded by designing distribution capacities and grid configurations to meet future capacity growth.

Initiatives are essential to deal with both the “retrofit” of existing grid, as well as new grid designs to accommodate distributed generators Considerations for optimizing complete systems, in addition to developing individual technologies, to prevent PV grid issues. To realize such systems, infrastructure investments must be made founded on the precept that PV will, become mainstream in the future. Power infrastructures, once constructed, are generally not updated for decades, meaning the public is locked into the conditions of the infrastructure. Thus, it is imperative to refer to the experiences presented here while actively exchanging information and setting the groundwork for future large capacity installations.

The following characteristics should be referred to when contemplating the construction of future grid systems free of constraints on PV grid interconnections.

- Integrated system management using ICT (Information and Communication Technology)
- Extension of distribution capacities
- Development and widespread use of storage technologies or integration of either grid load control or building load control with PV generation output.
- Provision of power quality that fits the corresponding application

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