Power Electronics Technology that Supports Smart Grid

Shinsuke Nii † **Masaki Kato** †

ABSTRACT

A smart grid is a system that reduces the effect that the mass adoption of renewable energy has on the total power system. Because the generated power output from renewable energy is generally difficult to control, a power supply system capable of implementing high-speed and high-accuracy control is needed for the mass adoption of renewable energy in the system. Power electronics technology plays an important role in realizing such control. The main power electronics applied technologies are charging/discharging control technology and demand/supply control technology. Devices suitable for use in a smart grid include power electronics devices for power distribution, smart PCS and new energy packages, and the deployment of these devices to the "Fuji Smart Network System" is targeted.

1. Introduction

The adoption of renewable energy is being promoted as a measure to help mitigate the problem of global warming. The generated power output from renewable energy, however, is often difficult to control, and if adopted in large quantities, may cause frequency fluctuations throughout the entire power system and local voltage fluctuations may occur. A smart grid is a system that reduces the effect on the entire power system from the mass adoption of renewable energy, and ensures a stable supply of electrical power. By simultaneously controlling the generation, distribution and consumption of energy, the efficient use of energy can be achieved. With a smart grid, a compensating high-speed high-accuracy power supply system must be used to connect renewable energy, for which the generated output power is difficult to control, to the power system, and power electronics technology plays an important role in the realization of such a system. In particular, many types of distributed power sources generate DC power, and power electronics technology for performing power conversion is one of the most important technologies for smart grids.

This paper discusses the role, functions and devices of power electronics required in smart grids, and also describes application examples and initiatives for the future.

2. Trends in Power Electronics Devices for Smart Grids

The power electronics devices used in smart grids are required to have a function that is capable of accommodating fluctuations in frequency or voltage, as well as a function for safely interconnecting with a power system. This section describes the requirements and technical trends of recent power electronics devices.

2.1 Functions and technical trends of power system interconnection

(1) Low voltage ride through (LVRT)

As an example of a function necessary for power supply interconnection, the LVRT function is described below. LVRT is a function that enables a device to continue outputting without parallel off*1, even when the system voltage drops. In the case where only a small amount of renewable energy is introduced into a power system, even if a distributed power source disconnects due to a drop in the system voltage, the effect on the overall system will be minor and non-problematic. In the case where a large amount of renewable energy is introduced into a power system, however, if the distributed power sources disconnect from the power system all at once, an imbalance will occur between the amount of power generation and the amount of load, and the frequency stability of the system will decrease as a result. If the amount of simultaneous parallel off is large, then in order to maintain the power supply frequency, the load must be dropped. Accordingly, the following three characteristics are sought in order to connect distributed power sources to a power system.

(a) To accommodate frequency changes
(b) To connect to the power system and supply power to the extent possible, even when the voltage drops
(c) To connect to the power system and supply power as soon as the system voltage is restored

† Fuji Electric Co., Ltd

*1: Parallel off: Disconnection of electric power generating equipment or the like from a power system following a parallel off

(2) Isolated operation detection function

An isolated operation detection function is essential for connecting to a power system. Isolated operation is the state in which an isolated system that has been disconnected from the power system is supplied with electricity from the output of a distributed power source only. In the isolated operating state, there is the possibility of electric shock or equipment damage, and this state must be detected as soon as possible and the relevant distributed power sources must be disconnected. (See explanation on page 152).

The method used to detect isolated operation is either passive or active. The passive method detects sudden changes in voltage phase, frequency and the like resulting from imbalances between the generated output power and the load during the transition to isolated operation, while the active method continuously applies voltage and frequency fluctuations and utilizes the fact that the fluctuations become noticeable during transition to isolated operation. Presently, in power distribution systems, the load is larger than the generated power, and therefore the passive method operates reliably even when there is a transition to isolated operation. However, if the number of distributed power sources increases and the balance between the generated power and the load is realized within the power distribution system, then system fluctuations will be smaller when transferring to isolated operation, and detection of isolated operation based on the passive method may not be possible. In the past, the passive method had provided the main protection, and the active method had been used as a backup. However, because of the risk of being unable to detect isolated operation with the passive method when a large number of distributed power sources are introduced, in recent years, the active method has been considered as the main protection.

At present, especially for small-scale photovoltaic power generation, unification toward an active method that is free of mutual interference is underway. Also, the trend of isolated operation of medium and large capacity power conditioning systems*2 (PCS) must be watched closely.

2.2 Function for accommodating power generation fluctuations and power system fluctuations

In the past, generators have been controlled to absorb load fluctuations and to stabilize frequency. If the amount of renewable energy generated fluctuates, however, a balance between supply and demand is difficult to achieve with only generator control. For this purpose, the output at the renewable energy side must be adjusted to minimize the effect on the system. A power storage device is used to implement this function, and depending on the period of fluctuation, the power storage method may need to be changed to storage cells, lithium ion batteries, electric double-layer capacitors, and the like, and appropriate discharge control technology for the storage method is also needed.

If the fluctuation in renewable energy power generation is to be adjusted with individual power stabilizers, then the same number of stabilizers as power generators (or power plants) will be needed. In contrast, an area-type stabilizer allows the fluctuation to be averaged to that the total equipment capacity can be reduced, and is more economically efficient than the individual approach. This area-type stabilizer controls the amount of power generation, including the amount of renewable energy, over a wide area (such as a town, city, prefecture or larger). For this purpose, the capacity of the stabilizer must be increased by expanding the individual device capacity of the inverters used in power storage systems and arranging them in parallel configurations.

Additionally, in small-scale power systems at remote islands and the like, the generators have low inertia constant, and disturbances are likely to occur when a supply-demand imbalance arises due to a power fluctuation. Such unstable states can be stabilized with a power storage device, and for this purpose, high-speed and high-precision control are required of the inverter.

3. Usage of Power Electronics in Smart Grids

Recently, power electronics products incorporating the above technologies have become possible to manufacture, and the applicable range of power electronics technology has expanded. Additionally, complex control has become easier to implement in the distribution of energy, enabling more efficient utilization of the public infrastructure.

Figure 1 shows a conceptual diagram of a smart power distribution supply chain in a smart grid being promoted by Fuji Electric. In Fig. 1, sensors and smart meters monitor the system information, and power generation, distribution and consumption are optimized so that the system will operate more efficiently. Fuji Electric has experience with many such examples for this purpose. Of the power electronics technology that may be used in a smart grid, implementation examples involving power generation and distribution are introduced below.

3.1 Usage of power electronics technology in power generation

The power stabilizer is introduced below as an example application of power electronics for power generation.

The generators in a power system are mainly rotary-type generators, and this is essentially the same

---

*2: Power conditioning system: Device for converting generated electric power from a photovoltaic cell, storage cell or the like into system power .

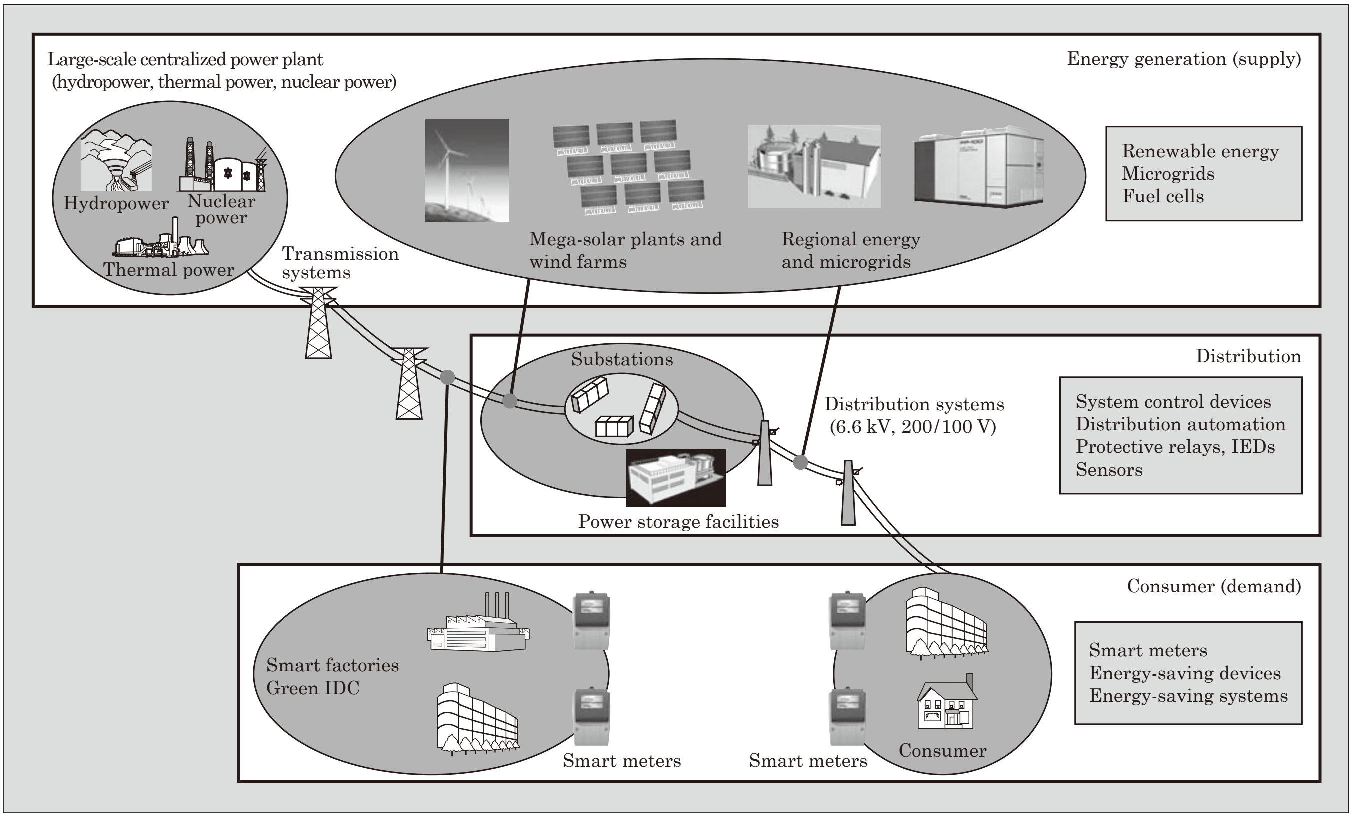

Fig.1 Conceptual view of a smart power distribution supply chain

for smart grids as well. As described above, however, when generating equipment that uses renewable energy is introduced in large amounts to a power system, the frequency control of the system will be affected due to the instability of the power generation. By using a power storage device to compensate for the power generation instability and by implementing control so that the output of the generating equipment is stable, stable power can be supplied to the system. Figure 2 shows the configuration of this power stabilizer. Figure 2 shows the case of wind power generation, but the same configuration could also be used for photovoltaic power generation.

Power stabilizers charge and discharge storage cells so as to compensate for the corresponding output fluctuation of renewable energy, thereby smoothing the combined outputs at points of interconnection with the power system. Charging and discharging can be performed according to bidirectional inverter control.

The purpose of smoothing is to stabilize the power system voltage and frequency. To stabilize the voltage, active power control and reactive power control are performed. To stabilize the frequency, governor-free (GF) control for short-duration fluctuations, load frequency control (LFC) for long-duration fluctuations, economic load dispatching control (EDC) for long-period fluctuations, and the like are performed. Each control method requires a different power storage capacity. Battery capacity has a significant impact on facility costs, and therefore, the smallest possible capacity is desired.

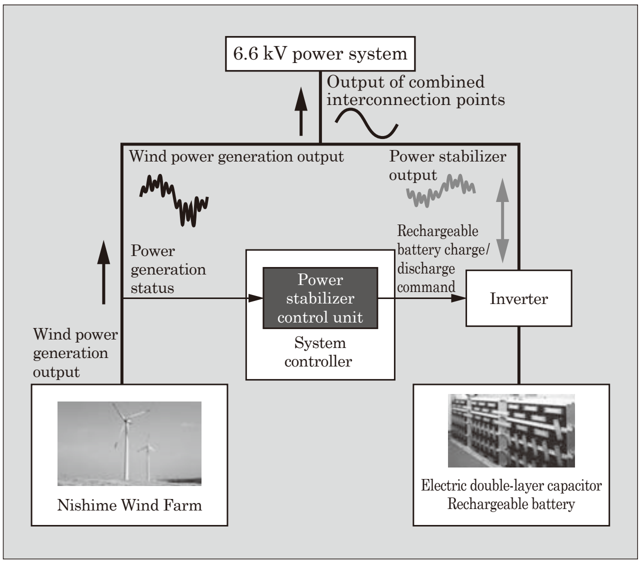

Fig.2 Overview of power stabilizer

Fuji Electric has installed this power stabilizer at the Nishime Wind Farm which is operated by Win-power Co., Ltd., an affiliated company, and has conducted an experimental study. The results of that study confirmed that a power stabilizer does have a stabilizing effect on the output of wind farms, and established a charge/discharge control method that realizes the required functionality with the minimum equipment capacity.

3.2 Usage of power electronics technology in power distribution

The area-type stabilizer described in section 2 attempts to stabilize power over a wide area. The "Demonstrative Project of a Regional Power Grid with Various New Energies, Kyoto Eco-Energy Project" (2003 to 2007) conducted by the New Energy and Industrial Technology Development Organization (NEDO) is introduced below as an example where supply/demand is adjusted and power stabilization is performed in a relatively narrow area.

An overview of the Kyoto Eco-Energy Project is shown in Fig. 3. In this demonstration project, biogas, photovoltaic and wind power generating facilities were established, and control to achieve a balance between demand and supply (5 minutes balancing control) was performed at specified times between several preselected end-users and a power plant where these renewable energies are used to generate power. The demonstration project was conducted as joint research among four companies and two government entities, and Fuji Electric participated mainly in the development of the control system.

In this system, sensors detect the generated output of photovoltaic power and wind power, and send monitoring information to a control center via a communication line. The control center calculates the rechargeable battery output to compensate for fluctuation, and issues an output command to the rechargeable battery via the communication line. As a result, fluctuation in the generated output of photovoltaic power and wind power is absorbed. The processing from data measurement and aggregation until the issuance of command value is completed in a time of approximately 20 seconds, and therefore compensation and demand/supply adjustment are possible for power generation fluctuations on the order of several tens of seconds. Because a general-purpose wide-area network (ADSL or ISDN) is used for monitoring and control, the measurement and control targets can be chosen without regard for distance. The realization of a large-scale supply/demand adjustment system at low cost is anticipated.

Additionally, when performing balancing control with this system, adjustment corresponding to the amount of load fluctuation is performed basically with a gas engine generator. In cases where the load fluctuation per unit time is large and difficult to track with a gas engine, adjustment corresponding to the amount of load fluctuation can be implemented as compensation by a rechargeable battery.

The demonstration project aims to achieve balancing control accuracy within 3% error in five minutes, and the results obtained mostly satisfy this aim. As a result, the project verified that high accuracy can be maintained even with control implemented via a general-purpose communications network. Moreover, the effectiveness of rechargeable batteries as a means for controlling supply and demand in a smart grid was confirmed.

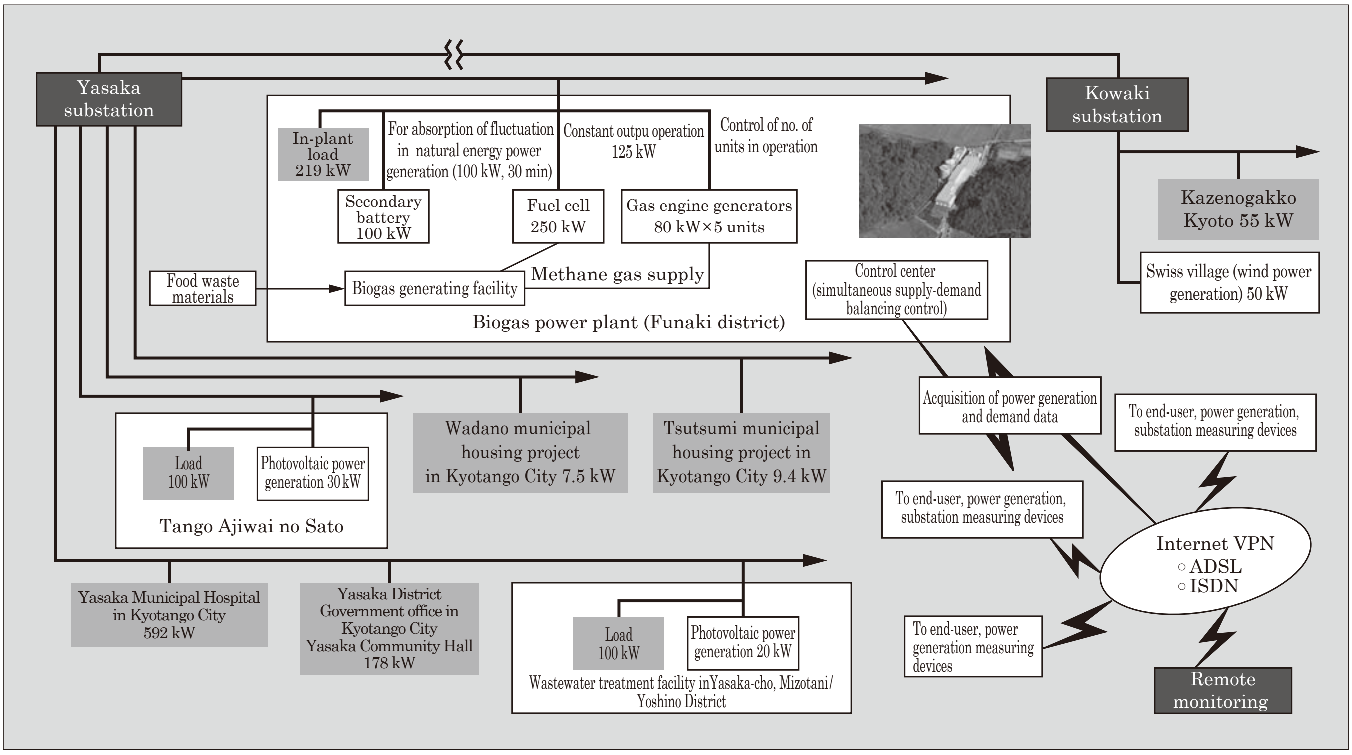

Fig.3 Overview of Kyoto Eco-Energy Project

4. Power Electronics Devices in Smart Grids and Fuji Electric's Future Initiatives

Fuji Electric is advancing various initiatives aimed toward constructing smart grids, and is also advancing the development of new technology for power electronics devices. This section describes technology essential for developing smart grids in the future.

4.1 Power electronics devices for power distribution

In power systems, large-scale centralized power generation plants are responsible for power generation, transmission and distribution equipment are responsible for power distribution, and the end-users are responsible for consumption. Electric power flows from large-scale centralized power plants toward end-users, and power systems have been constructed assuming a one-way flow of power from upstream to downstream.

In recent years, end-users have generated power by using home-use solar power generators and the like, but if they were to install a large amount of distributed power sources, the flow of power, at least in the distribution system, will not be unidirectional (see Fig. 4). Additionally, because the amount of power produced by generation from renewable energy cannot be controlled, new methods will be needed to manage the distributed power sources, and specific areas or wide areas in order to control the frequency, voltage or power flow.

Examples of power electronics devices used to solve these types of power distribution system problems are the self-commuted static var compensator for distribution and a distribution line loop balance controller (LBC). For power electronics distribution devices to become widespread, they must be compatible with outdoor and pole-mounted installations, provide maintenance free operation, have a low price, and so on.

To support outdoor installation, power electronics devices must meet specifications for environmental resistance, and the heat exhaust of the system, sealing technology and the like are also important factors. For pole-mounted installations, a light weight is essential, and the future development of technology that enables direct connections to high-voltage systems and eliminates the necessity for a transformer is needed. A fanless implementation is also needed for maintenance-free operation and to reduce cost. To develop equipment that fully satisfies the functional requirements of power distribution devices, the commercialization of next-generation devices made from silicon carbide (SiC) or the like is considered to be necessary, and therefore some time will be needed before such devices can be used in practical applications.

4.2 Smart PCS

The DC-side of a PCS is connected to solar panels, rechargeable batteries, capacitors (including electric double-layer capacitors), etc. In the case of solar panels, a photovoltaic PCS is connected; for rechargeable batteries, a power storage device is connected and in the case of a capacitor, a static var compensator is connected. The inverters used have many common parts in their configurations. A smart PCS is a multi-function inverter provided with the required communication capability and a system interconnection function, and has a configuration suitable for multi-purpose applications.

Standardization of the PCS communication specification is being advanced by the Japanese Ministry of Economy, Trade and Industry (METI), and standards for the communication interface, protocols and the like are expected to be established in the future. Fuji Electric plans to move ahead with the development of a PCS equipped with these standardized functions and that is suitable for multi-purpose applications.

System interconnection functions include an LVRT

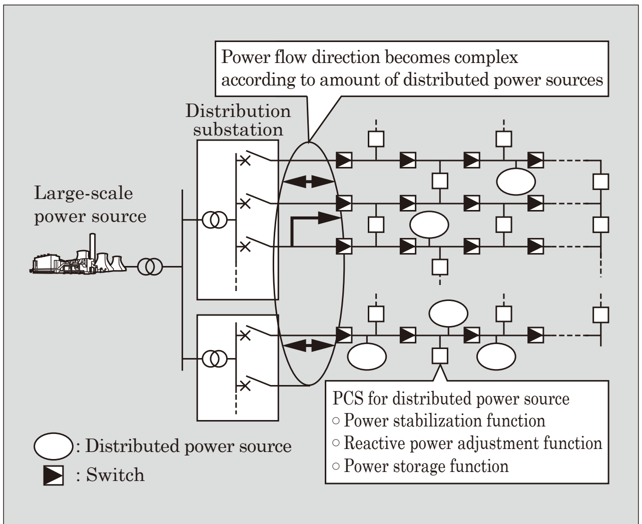

Fig.4 adoption of renewable energy in a power distribution system

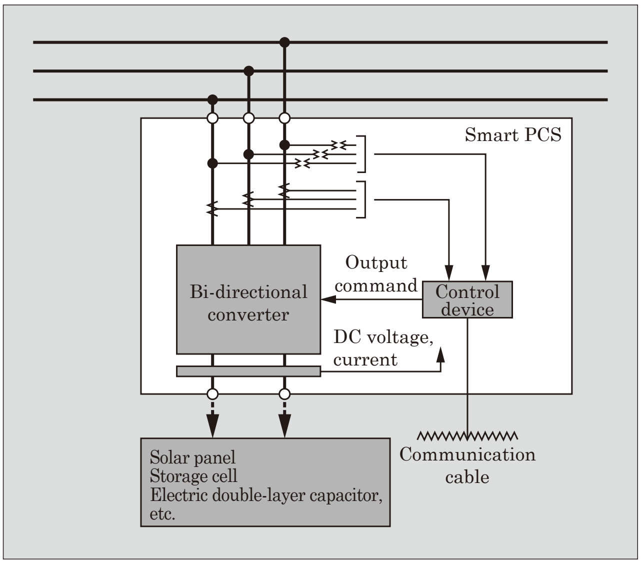

Fig.5 Overview of smart PCS configuration

function, an isolated operation detection function, an interconnection protection function, and so on, and through incorporating these functions and standardizing the equipment, various types of standardization will be supported (see Fig. 5).

4.3 New energy power supply package

Aiming to expand the utilization of renewable energy, and in order to facilitate the adoption of new energy, a new energy package constructed so as to combine a power generator and a power storage device is desired.

In the METI system forum final report concerning smart communities, power system types were compared by classifying them into the five categories shown in Table 1.

If relatively small-capacity power supply devices that use renewable energy can be packaged and applied for various purposes regardless of the power system configuration or type of renewable energy, then renewable energy will become easier to use. By using the same power supply package configuration regardless of the power system type, i.e., advanced country type (US, Europe), developing country type (urban type, rural type), or isolated island type, and by changing the control method according to the application target, power supply devices will be easily configurable, and will be applicable to many systems without changing their hardware specifications. For this purpose, scalability, safety and security, and maintainability (maintenance-free operation) must be realized.

Scalability is the ability to expand system capacity according to demand, and in addition to increasing device capacity, the ability to connect various power sources and to achieve system-wide harmonization easily are required. Safety and security are the ability to operate safely at all times and in various locations, even when operated by persons lacking experience with electricity. Good maintainability means to have a low failure rate, and to be easily serviceable in the case of a failure.

The new energy power package incorporates a

Table 1 Power system characteristics

Power system type	Operating method
Advanced country type (US) Advanced country type (Europe) Developing country type (urban type)	The distributed power sources are connected to a strong power system. In this case, maintenance of the frequency and voltage may depend upon the power system, and efficient operation of the distributed power sources becomes important.
Developing country type (rural type)	Since there is no pre-existing power system, the distributed power sources themselves constitute the core power supply. For this reason, the distributed power sources are responsible for constantly maintaining the frequency and voltage, and the ability to absorb fluctuations in the load as well as output fluctuations from other distributed power sources is essential.
Isolated island type	The distributed power sources are connected to a weak power system. In this case, the output of the distributed power sources may affect the power system. Accordingly, the state of the power system must be evaluated while operating the distributed power sources.

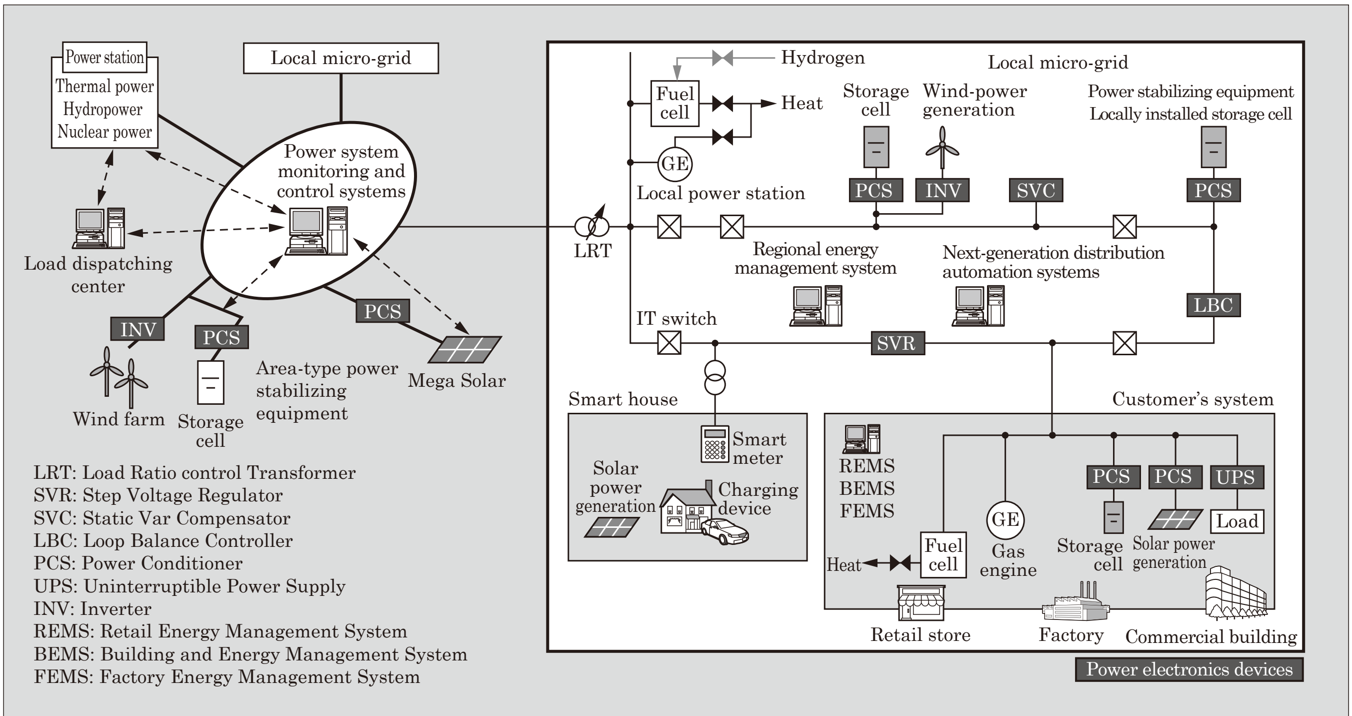

Fig.6 Areas of applied power electronics technology in the "Fuji Smart Network System"

PCS for photovoltaic power generation and a PCS for storage cells into the same package, and is optionally configurable as a system compatible with small-scale hydropower, wind power or the like.

Fuji Electric plans to develop a new energy package suitable for multi-purpose applications and to use this with smart grids.

4.4 "Fuji Smart Network System"

Figure 6 shows the areas of applied power electronics technology in the "Fuji Smart Network System." With the Fuji Smart Network System, in both the industrial and consumer sectors, end-user microgrids are constructed, and hybrid power supply equipment that combines photovoltaic power generation systems, storage cell PCS, fuel cells and the like is introduced to the system. Moreover, in the distribution system, regional microgrids are configured by combining conventional load ratio control transformers (LRTs) and step voltage regulators (SVRs) with reactive power compensation equipment for voltage stabilization, loop balance controllers (LBCs) for power flow control, power stabilizers to absorb fluctuations in renewable energy, and the like. Additionally, in the power transmission system, an area-type stabilizer is installed to stabilize the supply of power within a region.

With the Fuji Smart Network System, information from smart meters and from IT devices in the distribution system is collected by an energy management system (EMS), which monitors and controls the entire system. The EMS issues control commands to devices in order to achieve energy efficiency, and the power electronics devices respond to the commands quickly and accurately to support the realization of high efficiency.

5. Postscript

Smart grids are a part of the public infrastructure and assure energy security by incorporating a diversified range of power supplies to eliminate a dependency on fossil fuels, which traditionally had been the primary source of energy. Additionally, the transition to use of a smart grid entails not only modification of the power system, but also asks the question, in regard to energy generation and consumption, of what is the ideal grid configuration in which users can participate.

Aiming to protect the global environment, the stage is now being set for the creation of a sustainable energy system for future generations. In order to realize such an energy system, the capability of fine control of energy is prerequisite. Such capability can be achieved with power electronics technology, and the role of power electronics technology in smart grids will continue to increase in importance. With the goal of expanding usage of smart grids, Fuji Electric intends to continue to improve power electronics technology.