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Smart grid in Japan associated with lightning protection of renewable energies

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***Abstract*—This paper studies roles of power distribution systems in smart grid and their protection from lightning in order to present our country's technical levels and philosophies in smart grid and renewable energies. Existing lightning protection technologies and predicted changes after electricity deregulation and large penetration of distributed generations are stated.**

Keywords-smart grid; lightning protection; renewable energy; distributed generation

I. INTRODUCTION

This paper studies roles of power distribution systems in smart grid and their protection from lightning in order to present our country's technical levels and philosophies in smart grid and renewable energies. Existing lightning protection technologies and predicted changes after electricity deregulation and large penetration of distributed generations are stated.

II. SMART GRID IN JAPAN

In this chapter, outline of today's power systems and large penetration of distributed generations into them are stated. Then philosophy of smart grid in Japan is stated.

A. Today's power systems

In Japan, electricity is available any time we need it. Electrical power systems support this availability. Electric power utilities operate power systems and supply good quality power by controlling power flow through transmission, distribution and consumption systems. And also, utilities make plans for expansion of power generation stations and power transmission facilities and then establish stable supply of electrical energy.

When the electrical power usage was limited and establishment of power systems were not completed, power to be supplied to a specific customer was generated by a specific generation station and transmitted through specific transmission lines and distribution lines. But, in today's sophisticated electrical power systems, it is rare that transmission and distribution facilities are made for specific customers. Transmission and distribution facilities are made for whole power system's demand and it is typical that power apparatus are designed by supposing transmitting power from large capacity power sources to many customers.

In our country, we have about 1,200 power generation stations, about 7,000 substations, transmission and distribution lies with about 1, 400 thousands km long and also about 80 million of customers.

B. Large penetration of distributed generations

In Japan, large penetration of distributed generations with renewable energy (RE) sources such as photovoltaic power generations and wind power generations, is going due to government policy towards construction of low carbon society aiming at sustainable society. Although these RE sources are free from exhaustion and do not generate greenhouse gas emissions at time of power generation, some of RE sources have a demerit such as output instability by weather conditions. With large penetration of such variable output sources, it will be difficult to maintain supply and demand balance in a total power system. And also, considering RE sources penetrations to customer's side, it is required to consider new phenomena such as that one way power flow will be changed to both ways power flow, which was not considered in a conventional electric power system's design philosophy.

Due to these backgrounds, to have large integration of RE sources, it is required to make evolution in today's power systems. They must be changed to smarter power systems, where ICT (Information and Communication Technology) is utilized for cooperation of power apparatus and a total optimization is aimed such as minimizing total society cost. In Japan, challenging Japanese style smart grids has been started aiming at realizing a low carbon society without losing power system's reliability, economics and resistance to environment.

Fig.1 shows Long-term change in total supply from power-generating facilities of new energy, etc. Since the introduction of the RPS system in 2003, electric power supply by renewable energy has doubled. Moreover, since the surplus electricity purchase system was introduced in 2009, the introduction of residential photovoltaic power generation has largely increased.

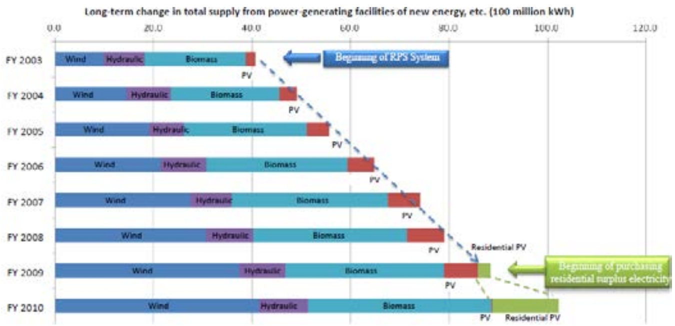

Figure 1. Changes in Electric Power Supply by Renewable Energy [1]

C. Concept of smart grids [2]

The world's electricity systems face a number of challenges, including ageing infrastructure, continued growth in demand, the integration of increasing numbers of variable renewable energy sources, electric vehicles and other distributed networks, the need to improve the security of supply and the need to lower carbon emissions. To move forward, we need a new kind of electrical grid, one that is built from the bottom up to handle the groundswell of digital and computerized equipment and technology dependent on it—and one that can automate and manage the increasing complexity and needs of electricity in the 21st century. SG technologies offer ways not just to meet these challenges but also to develop a cleaner energy supply that is more energy efficient, more affordable and more sustainable.

A SG is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. SGs co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability. A SG includes centralized and distributed power generation produced substantially by renewable energy sources. It integrates distributed and active resources (i.e. generation, demand, storages and electricity vehicles) into energy markets and power systems. SGs can be characterized by a controllable multi-directional power flow. The general features of a SG system are [3]:

- Wide-area monitoring and control.
- Information and communication technology integration.
- Renewable and distributed generation integration.
- Transmission enhancement.
- Distribution grid management.
- Advanced metering infrastructure.
- Electric vehicle charging infrastructure.
- Demand-side management systems.

An emission free SG system includes distributed renewable sources, PEV, energy demand, and control system. The integration of DG and flexible loads in a distribution network will benefit the network when managed appropriately. To lessen distribution losses, voltage regulation within the acceptable range, smooth the power flow at the interconnection point, and stable power output to the power network are vital issues for the SG system, when DGs are integrated as power generation sources. The combination of DG and other active sources into a distribution system is needed in order to fully exploit the benefits of active resources in the network management. With proper management of active resources the overall system performance may be enhanced from presently used practices.

One important control task in power systems is to maintain balance between power production and consumption which means keeping the power system's frequency at a proper level. This procedure is becoming more and more challenging due to an increase in the penetration level of intermittent renewable power production. In recent years, there have also been many serious frequency unsteadiness related wide-area power system blackouts in Europe and USA, and their costs, both economic and social, are high [4].

D. Components of smart grids

Components of smart grids in Japan are as follows.[2]

(1) Distributed generations

Distributed generations are integrated into distribution systems in smart grids as follows.

- Photovoltaic generation systems
- Wind generation systems
- Combined Heat and Power (CHP)
  - Static CHP
    - Fuel cell
  - Alternator type CHP
    - Gas engine
    - Diesel engine

(2) Equipment for supply and demand balancing control

Supply and demand balancing control equipment might be used responding to power systems stabilizing and customer oriented needs in smart grids.

- Battery energy storage systems (BESS)
- Electric vehicles (EVs), Plug-in Hybrid Electric vehicles (PHEVs)

- Heat pump water heater
- Intelligent household electrical appliance

(3) Supervisory and control equipment

Supervisory and control equipment for estimation and optimizations of energy consumption in houses, buildings and farms might be introduced into smart grids.

- Energy management systems (EMSs)
- Smart meters
- Static Var compensators (SVCs)
- Static synchronous compensators (STATCOM)
- Step voltage regulators (SVRs)
- DC equipment

(4) Information and Communication equipment

ICTs are needed in distribution automation systems (DASs) and smart meters. Communication paths must be secured in both normal and emergency conditions.

E. Renewable energy resources in Japan [1]

(1) Photovoltaic power generation

As for residential photovoltaic generation, Japan is ranked third in the world in terms of installed photovoltaic generation capacity (3,618 thousand kW), of which, residential use accounts for 80% and non-residential use accounts for 20% (the ratio is opposite in Europe and the U.S.). Following the introduction of the surplus electricity purchase system in 2009, the installed photovoltaic generation capacity for residential use has increased rapidly. PV generation has spread to 900,000 households (the total number of detached houses in Japan is 27 million). In the future, the key is to make PV systems “household appliances” in cooperation with rechargeable batteries and smart meters.

As for mega solar power plants, there are about 40 mega solar facilities across the country. Most of them are built for the purpose of CSR and experiment studies based on existing subsidies. Now is the transitional period moving towards commercialization. The cost is still high, usually around ¥400,000–500,000/kW (there are cases where the cost is less than ¥300,000 abroad). With China’s entry in this field, the cost of panels has sharply dropped. The panel industry is rapidly shifting to the smile-curve phenomenon. In terms of international competitiveness, the costs of installing holders and supplementary equipment and the capacity of integrators will be important factors.

Challenges for photovoltaic power generations are;

- Coping with the panel market, which has an overabundance of stocks
- Discovering untapped idle land that is suitable for mega solar, and reviewing location regulations including the Building Standards Act and the Factory Location Act.
- Exploring measures to diffuse PV in the medium-sized market ranging from 10 kW to 1 MW (public facilities, plants, etc.)

(2) Wind power generation

Among 479 operators of onshore wind power generations in Japan, 393 have installed at most 5 generators. Greatly biased to small-scale business. (The largest farm in China, now under construction, has 2,500 generators.) Japan is mountainous, while Europe and the US are flatter. Because of Japan's unique wind conditions, such as upward turbulence from the ground affecting wind turbines installed on the roof, many businesses became unprofitable due to unexpected maintenance costs. The key is concentrated geographical location. Deregulation and system organization are required.

Offshore wind generation systems are ongoing business. Costs are high, but geographical potential is not low. At present, generators anchored to the seabed are feasible. European seas have shallow, small-gradient beds suitable for seabed anchored-type generators, whereas floating types should be considered for Japanese oceans which quickly become deep. However, the cost including connection lines may soar. At the request of Fukushima prefecture, a 5-year demonstration project to create the world's largest floating-type offshore wind power farm started this fiscal year.

- Challenges for photovoltaic power generations are; Technical development to address Japan's unique conditions, such as lightning protection, wind forecasting/control, etc. Increase of the operating rate by using such techniques, and cost reduction.
- Regulatory reform to encourage large-scale wind farms (conversion from agriculture land, use of national parks, landscape regulations, utilization of national forest, etc.)
- Improvement of electric system measures, such as against night-time surplus production (so-called insufficient reduction margin), reinforcement of power system to consumption areas, etc.

(3) Geothermal power generation

Japan has the third largest volume of geothermal resources in the world. However, only 10% of potential resources are currently used because installed capacity is at most 0.54 million kW. No new development plans have been concretely submitted since the Hachijyojima geothermal power plant was set up in 1999, and output capacity is also decreasing. Japanese companies have a big advantage in the geothermal power plant market, with an almost 70% share of the world market. It is our opinion that this field holds great potential.

Since most geothermal resources are located in natural parks, a review of relevant regulations is required to expand geothermal power generation. Detailed drilling surveys of geothermal resources, etc. is also necessary. Problems of cost increases including electric cable wiring and material transportation, etc need to be considered because of site location.

(4) Hydroelectric power generation

As of FY 2009, installed capacity of hydroelectric power generations is approximately 47.97 million kW. For long-term energy supply-demand outlook (Best case), targeting installed capacity is approximately 49.25 million kW in 2020. Hydroelectric power generation has features of stable power generation and well-developed technique. Some issues are;

- Greatly limited by the site location.
- The site is being transferred upcountry, which may cause an increase to the generation cost, including electric cable wiring and material transportation, etc.
- Necessary to coordinate water rights.

Current measures to promote installation is RPS system (Hydraulic power of 1,000 kW or less).

(5) Biomass power generation

As of FY 2009, installed capacity is approximately 1.54 million kW (March 24, 2009). For long-term energy supply-demand outlook (Maximum case), targeting installed capacity is approximately 2.17 million kW by 2020.

Features are;

- Unused resources in local areas are available.
- Fuel biomass has a wide range of uses such as heat and material utilization in addition to power generation.
- Cost may greatly vary depending on type and use.
- Supply amount and price may change because biomass is actually a limited resource.

Issues are;

- Competitiveness in terms of material utilization, etc.
- A stable supply of raw materials is required for massive installation.

Current measures to promote installation are tax system, RPS system and research & development, demonstration tests.

III. DISTRIBUTION SYSTEMS IN JAPAN

In this chapter, medium voltage and low voltage distribution lines in Japan are explained.

A. Medium voltage line & low voltage line

Calculation of lightning outage rate of Japanese distribution line is targeted for not single but two- or three-phases spark-over. The single-fault current is low. Accordingly, the fault current does not continue. Fig. 2 shows a typical distribution line connected to a transformer in a substation. The transformer connected to a distribution line in a substation is not grounded. Considering power flow and fault current are low, a distribution line is modeled by capacitance. Single-phase fault current I_F is given by

$$I_F = \frac{V/\sqrt{3}}{R_F + (j\omega 3C)^{-1}} \qquad (1)$$

Where, R_F is the grounding resistance and arc resistance at the fault point

The capacitance is approximately 0.01uF/km. For example, the fault current is less than 1A in case of the distance from the substation to the fault point of 10km. Thus, the fault current is sufficiently lower than the power flow.

Short circuit current becomes several kA. A CB operates to make the current clear. Therefore, the calculation of lightning outage rate is targeted for two-phase line faults.

Insulated cables in the Japanese distribution lines are used to prevent persons from electric shock. Flashover characteristics of insulators depend on the insulator dimension and the cable type. The breakdown voltage of the insulation of the insulated cable is relatively high. Therefore, the flashover characteristics of an insulator on a cross arm to support the insulated cable for lightning impulse voltages are different from those for a bare wire. Surface discharge occurs on the insulated cable. The dispersion of the surface discharge is very large. A pin hole is made due to breakdown of insulation of insulated cable caused by spark-over. This hole is fixed because of the insulation, and arc point does not move. As a result, short-circuit current caused by two-phase spark-over makes melt down at the pin hole.

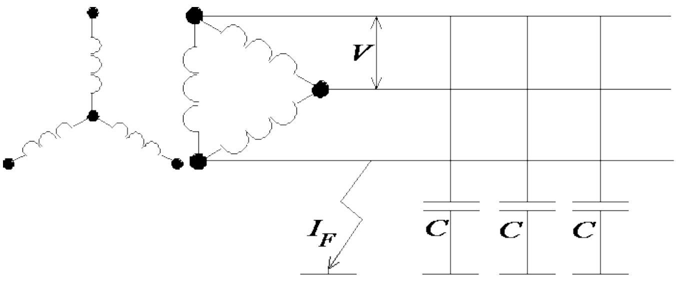

Figure 2. Japanese grounding system in the medium voltage circuit

B. Grounding system in low voltage line

Japanese 6.6 kV medium-voltage line transformers are not grounded. The Japanese low-voltage circuit has no neutral wire, and adopts a TT grounding system as illustrated in Fig. 3. One phase of the drop line is grounded at secondary circuit of a distribution-line transformer. On the other hand, a ground type home appliance of which the case is independently grounded in a house to prevent a person from electric shock.

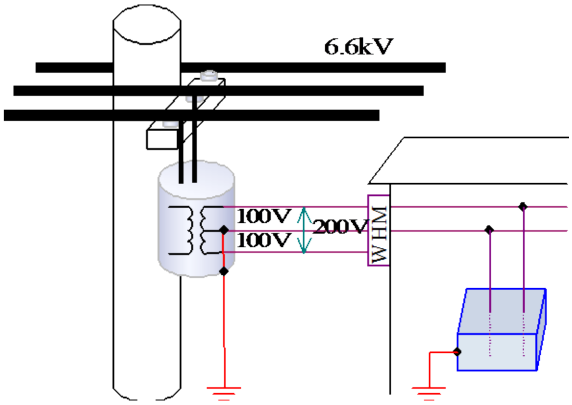

Figure 3. Japanese grounding system in the low-voltage circuit

IV. Lightning Protection of Distribution Systems in Japan

A portion of lightning faults to total faults in 6.6 kV lines is 20-30 %, so it is a challenge for electric utilities. On the other hand, due to rapid progress of advanced information society, minimization of black out faults is needed in electrical power utilities and ensuring reliability is needed in tele-communications companies. Also, in offices and household customers, high performance electrical equipment is widely used, so possibility became higher than before, for these equipment's damage due to small lightning surge. In this chapter, lightning protection of medium voltage and low voltage distributed lines in Japan are explained [5].

A. Lightning protection of 6.6 kV lines

In Japan, main subject of lightning protection in 6.6 kV lines was induced lightning surge and it was studied for a long time. In 1990 decade, it was proposed that direct lightning surge is included as a subject of lightning protection. It was clarified by experimental and theoretical study that countermeasure for direct lightning can be satisfied to a certain extent in the expansion of conventional lightning protection scheme. Recent studies of lightning protections for 6.6 kV lines are mostly targeted to a direct lightning. Conventional lightning protections for 6.6 kV lines was mainly done by lightning arresters and overhead ground wires, recently lightning arresters are typically introduced for the purpose of each electric equipment's lightning protection.

Recently, an estimating method was developed to clarify relationship between types of distribution lines equipment and spark-over occurrence rate i.e. strength against lightning, considering direct lightning and induced lightning. From study results using this method, it was clarified that SO occurrence rate is affected by types of distribution lines equipment. And also it was clarified that almost no SO due to induced lightning surge is occurred when both lightning arresters and overhead ground wires are used.

From now, it will be important to formulate effective and efficient lightning protection schemes, considering number of lightning, distribution lines density and customers density, in addition to SO occurrence rate,

B. Lightning protection of Low voltage lines

Due to rapid progress of advanced information society, lightning damage rate in customer equipment became more than twice compared to 1990s. So, establishment of lightning protection schemes for customer equipment. In study of countermeasure for customer's device, it is not sufficient only studying on each equipment and it is important to totally studying one circuit, i.e. low voltage distribution system including power apparatus and communication equipment. There are many parameters for low voltage distribution systems, so it is difficult to find one method that is effective for all cases. It will be efficient to estimate lightning risk and find a suitable protection method for each circuit configuration.

Smart meters will be widely used due to wide spread of smart houses. As a smart meter includes an equipment working at low voltages, it is an urgent challenge to estimate lightning performance and establish measures for lightning for it. A smart meter consists of metering section, communication unit and opening/closing function unit. At this time not so many studies on estimating lightning performance and establishing measures against lightning for details about smart meters.

V. Lightning Protection of Renewable Distributed Generations [2]

Top of a blade of a wind turbine with a couple of MW capacity is more than one hundred meters high. In general, the lightning tends to strike a higher structure. Accordingly, the lightning often strikes a wind tower or a blade. Most of lightning currents have high amplitude and high frequency, and sometimes have large energy. Such the current generates high voltage in power apparatuses and measurement and control systems in a wind turbine generation system, and causes damages to the apparatuses and malfunctions of the systems. Distributed energy resources in outside of a house or a building take a risk of lightning damages.

Lightning surges come into a wind turbine generation system consisting of single wind turbine and an overhead line as illustrated in Fig.4. The lightning surges come from an overhead line such as a distribution/transmission line or a telecommunication line, direct lightning stroke to a wind tower or a blade, and ground potential rise caused by lightning hit to the ground or the tower.

The mechanisms to cause lightning damages are classified as follows.

- Lightning overvoltage: high current with high frequency generates high voltage, and causes breakdown.
- Energy: lightning current with long duration has large energy, and causes meltdown or burnout of conductors and a blade.
- Lightning electromagnetic impulse: lightning current with high frequency generates impulse voltages.

Wind turbine blades sometimes explode and scatter due to the lightning flash. Serious damage of a wind turbine blade causes serious economic loss due to long term loss of service and its cost to repair the blade. Abnormal lightning such as winter lightning, which is frequently observed along the coast of the Sea of Japan, causes serious damages to wind power generation. Many utilities in Japan gave up maintaining the wind power generation because some lightning damages in winter seasons needed long time and much money to repair the blade during the winter. Therefore, the rational lightning protection design for wind turbine is very important to stably generate.

Home photovoltaic panels are set on a roof of a house or top of a building. Considering lightning sometimes strikes an antenna on a roof, lightning might strike a photovoltaic panel on a roof. Air-termination system such as a lightning rod or a shielding wire is used to prevent photovoltaic panels from damages caused by direct lightning flashes. The insulation level of photovoltaic system is very low in comparison with that of distribution line. Therefore, the lightning protection design for photovoltaic system is targeted for lightning-induced voltages.

However, lightning flash with low lightning current might strike a photovoltaic panel on a roof of a house based on an electro-geometric model even if an antenna stands beside the panel. Direct lightning flash causes serious damages in photovoltaic system. If low lightning current cause no damage in the system, direct lightning hit should be considered in lightning protection design of photovoltaic system. Photovoltaic generation needs large area to generate MWs electric power. The height of the system is low, but the probability of the lightning striking a photovoltaic panel is not small.

Wind turbine and photovoltaic systems related to the lightning protection should be designed on the basis of the IEC international standards 62305 series and 61400-24. Lightning current parameters exceeding the values used in the IEC standards are sometimes observed. Thus, lightning phenomena are not well known. Moreover utilities want to make the cost for lightning protection as low as possible. Therefore, it is very important to know lightning protection methods for distributed energy resources, and to improve them.

The lightning protection of electrical equipment and signal transmission systems should be carried out by the following methods.

- Shielding: air termination system such as a shielding wire or a lightning rod catches a lightning discharge. Overhead lines, buildings and structures can be protected from direct lightning stroke using the air termination system.
- Reduction: lightning overvoltage becomes lower by reducing impedance. Equipotential bonding method is a kind of reduction methods because the equipotential bonding reduces voltage differences in grounding system.
- Suppression: surge arrester and surge protective device (SPD) suppress lightning overvoltage.

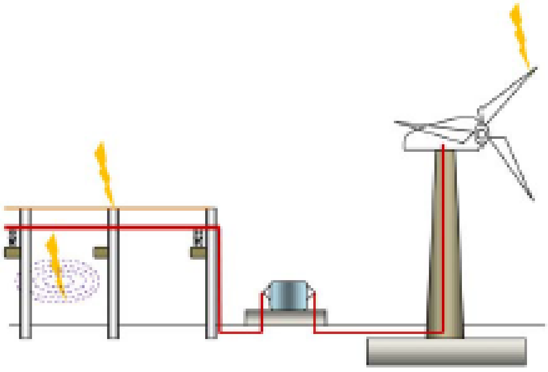

Figure 4. Lightning surges come into a wind turbine generation system

VI. Conclusions

This paper studies roles of power distribution systems in Japanese Smart Grids and their protection from lightning. Also, philosophies and differences between our country and others. Existing lightning protection technologies and predicted changes after large penetration of distributed generations are stated.

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