DC Micro Grid System

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A DC micro grid system has been proposed as a power network that enables the introduction of a large amount of solar energy using distributed photovoltaic generation units. To test the feasibility of the system, we have developed a demonstration facility consisting of silicon photovoltaic (Si-PV) units, copper indium gallium (di)selenide photovoltaic (CIGS-PV) units, concentrator photovoltaic (CPV) units, an aerogenerator, and a redox flow battery. The redox flow battery, a key component for supply-demand adjustment in the micro grid system, successfully balanced supply and demand in the grid by its rapid charge-discharge ability even under the fluctuating condition of power generation and consumption.

Keywords: micro grid, DC distribution network, redox flow battery

1. Introduction

How can we increase the amount of photovoltaic (PV) generation? From this viewpoint, we are overviewing electric facilities from power plants to electric appliances in demand sites. PV modules generate DC electric power. The power should be converted to AC that is synchronized with commercial grids to be transmitted and distributed to demand sites. To reduce energy dissipation through the transmission, the power is sent near the demand site after being raised the electric voltage to 66 kV or higher. The power is transformed to 100 V and provided to residential outlets after multi-processed reduction in voltage at substations and pole-mounted transformers. Therefore, we should consider how we can establish efficient transmission and distribution systems for PV generation in addition to cost, efficiency and lifetime for generation facilities, if we utilize the power source as infrastructure.

Transmission facilities for PV generation often stay idle as well as generation facilities themselves, because they do not yield electricity during night and poor weather. If contribution from solar power were much smaller than transfer capability, existing facilities could take care of it. To understand this problem easily, we assume a huge PV farm comparable to a nuclear power plant with a giga wattage class output. PV generation, which has poor yield for its footprint, needs vast ground to generate such a big power. Consequently, the generation facilities must be set up in sites far from consuming regions. Transmission facilities must have enough large capacity for maximum current which can be generated under the best weather condition. They do not work during off-generating time such as at night and under poor sunshine. If PV plants supplied constant huge power as dam type hydraulic or nuclear plants, we would make choice of a far-reaching transmission system that connects distant sources and a consuming center.

Electric power storage devices, such as batteries, can absorb fluctuation of PV generation and equalize power transmission. However, this scheme reduces capacity of transmission facilities and requires rather huge additional cost for the huge accumulators. Therefore, until drastically reduced cost is available for storage devices, we cannot adopt this method. Then, put gas turbines together, with which we are able to adjust output power rather rapidly. The combined plant can absorb the fluctuation of PV generation, and consequently, improve the operation ratio for transmissions. However, it requires a parallel established thermal power plant comparable to the PV, which is a roundabout way for our initial goal, the introduction of a large amount of PV.

As mentioned above, large scale PV plants in remote sites have a serious problem on economic efficiency. We need a new power system that enables the introduction of a massive amount of distributed PV units in demand sites. This article proposes DC micro grid systems as an option for such a purpose.

2. Purpose and Architecture of the DC Micro Grid System

Following three terms are briefly summarized purposes of the DC micro grid system.

(1) Increase the introduction of distributed PV units.

(2) Reduce energy dissipation and facility costs resulting from AC/DC conversion by integrating the junction between a commercial grid and DC bus which connects PV units and accumulators.

(3) Supply power to loads via regular distribution lines (not exclusive lines for emergency) even during the blackout of commercial grids.

Figure 1 shows a schematic view of the DC micro grid system. This system utilizes a DC bus as its backbone and distributes power to a community that consists of several dozens or a hundred of households in a residential area. A 350 V DC bus is installed instead of 200 V / 100 V lines in conventional AC distribution systems and connected with a high voltage commercial grid through the intermediary of a bidirectional AC/DC converter. All the PV units in the community are linked with the DC bus through DC/DC

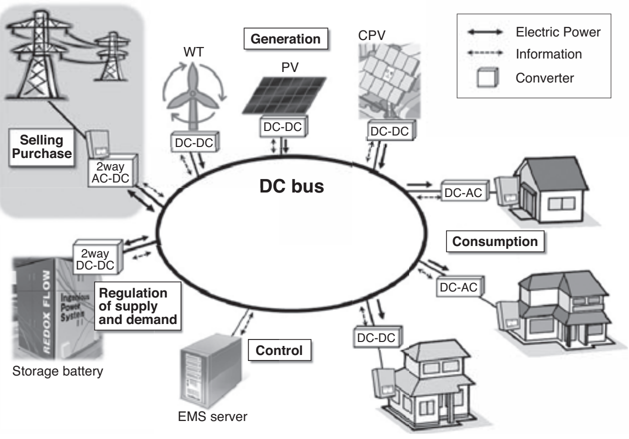

Fig. 1. Schematic diagram of a DC micro grid system

converters. These converters always track the maximum power point of the DC power sources which fluctuates depending on the intensity of solar radiation. Conventional appliances can be used as they are if an inverter is installed in each house to change the DC power into 200 V / 100 V AC power, but DC power feeding will spread widely because of its high efficiency, once safe and compact gears, such as breakers and outlets, are standardized in the future. Storage batteries of the community are also linked to the DC bus. The DC-based distribution system reduces facility costs and energy dissipation associated with AC/DC conversion because the PV units and battery are DC connected and most of the current energy-saving appliances operate on DC due to the progress of inverter technology. This is why we should push ahead with the DC system.

The system doesn't require long transmission lines to convey solar power from remote areas because the PV units have been distributed in the demand area. Power sources and loads are closely located to each other in a community. The excess and deficiency of power are variable factors which should be compensated for a good balance between supply and demand. The compensation system, which consists of storage batteries and a bidirectional power converter, keeps a good power balance in the community by absorbing short term power fluctuations. Since long term fluctuations, such as those between day and night, are also smoothed by the battery system, the micro grid system seems to be a small source or load for the outer wide-area grid. Consequently, this scheme reduces the cost for the stabilization of commercial grids.

The state of charge (SOC) of the storage battery always indicates the time integral of difference between supply and demand in the DC micro grid system. The SOC becomes full with excess power, whereas it reaches the lower limit in deficiency. The amount and direction of the power flow from a commercial grid is controlled according to the SOC, and power supply is maintained in the micro grid. However, power supply to the micro grid might be regulated to stabilize the power flow of the commercial grid. Therefore, information about the situation of the commercial grid is essential for the operation of the micro grid system. The current regulation on grid connection requires protective relays that decouple the inverter at the link point when they detect abnormal voltage or frequency[1]. In addition to this function, the inverter should be equipped with a power flow regulator that controls the purchasing and sales of currents according to the control signal from the commercial grid. This scheme requires bidirectional communication between micro girds and the commercial grid, which also enables the automatic calculation by exchanging information on purchased and sold power between the micro grid and the commercial grid. We can set the rate for purchasing and selling power in detail by utilizing the bidirectional communication. When power supply is tight in the commercial grid, power consumption is suppressed by raising both purchasing and selling rates. On the other hand, when power supply is sufficient, power consumption is encouraged by abating the rate. Thus, the automatic calculation system of the electric rate functions as a huge power trading market. The operation of the commercial grid is committed to a free market process except for the tight situation that needs central control.

For the above mentioned cooperative control with the commercial grid, the DC micro grid needs to have a good autonomous adjustability. A storage battery with a large capacity can easily respond to changes in supply and demand but requires large footprint and high cost. For example, think of the situation where the SOC of the storage battery is full but the excessive power cannot be sold to the outer grid, and we have no choice but to suppress the generation of PV. To avoid such an unfavorable situation, we should use loads before the SOC becomes full, while suspending the use of the loads that can wait during low SOC. Targets for the demand control are air conditioners, lights, boilers, laundry machines, dishwashers, EV chargers, elevators, and water supply pumps of buildings and condominiums.

The DC micro grid is also resistant to disasters. Even under conditions where electric power and fuel are not supplied from outside, we can have electric power sources. At the time of the power failure of the commercial grid, the DC micro grid works as an independent power source that is disconnected from the commercial grid. Since power is fed to loads via regular distribution lines, exclusive lines for emergency are unnecessary. In such a situation, power supply needs to be regulated in order to continue the independent operation; however, people who live in the same community would cooperate to make the best use of the limited power.

A school is one of the best sites to install the PV system because it consumes electric power during daytime hours. By installing the DC micro grid in a school, the students can observe their own energy consumption and generation, thereby enhancing their awareness of energy saving through hands-on experience. Furthermore, as many schools are designated as emergency evacuation centers, the DC micro grid's independent operation is useful as an emergency power source.

3. Supply and Demand Control by Storage Batteries

The above mentioned DC micro grid requires storage batteries and control units as its key components. To respond to short term power surplus or deficiency, the storage batteries have to repeat charge and discharge operation frequently under the condition where the current varies rapidly. The DC micro grid requires batteries that quickly respond to changes in the current and ensures high durability in such demanding operation. Large capacity (from several hundred kWh to a few MWh) should be available for a community that consists of several dozens or hundreds of households. Furthermore, precise detection of the SOC during the frequent change in operation is also indispensable to manage the power load and control the amount of power purchased from or sold to the commercial grid.

A redox flow battery (RF battery) satisfies the above mentioned four conditions: quick response, high durability, large capacity, and precise SOC detection. **Figure 2** shows the basic concept of the RF battery. The battery works by a reduction-oxidation reaction in the electrolytic solution which circulates between cells and tanks. The cells, where ions exchange electrons, are separated from the tanks, where the solution is stored. While most batteries are named after their active materials, the RF battery is so called because of its special architecture. "Redox" is an abbreviated word of reduction and oxidation. "Flow" phrases the circulation of an electrolytic solution. The active materials of both the positive and the negative electrodes are vanadium ions. Battery reaction proceeds as the ions change their valence in the solution without any solid deposit on electrodes. Therefore, the cell reaction is very fast. There is no degradation by the charge-discharge cycle, too. A large scale battery is also easily built due to its simple architecture. In fact, a 6 MWh RF battery system used to be utilized for smoothing the output fluctuation of a wind farm where many aerogenerators were installed[2]. Another significant advantage of the RF is the precise and simultaneous detection of the SOC while current flows in cells.

The above mentioned features of the RF battery are best suited for DC micro grid systems, but the energy density of the RF battery is lower than that of other secondary batteries, and consequently, it requires large footprint[2]. Among the secondary batteries in use, NaS battery and Lithium ion battery are promising for DC micro grid systems. Although these batteries are inferior to the RF battery in terms of responsive control and service life, these challenges will be overcome by combination use with electric double layer capacitors which have shown significant advancement in performance.

The battery is connected with a DC bus via a DC-DC converter to control charge and discharge. Electric power flows from the generator to the DC bus, and flows out to loads. When the former is larger than the latter, the voltage of the bus increases. Contrary, when the latter is larger, the voltage decreases. The bidirectional DC-DC converter monitors the voltage of the DC bus at any time to keep it constant by charging, when it is higher than a target, or discharging, when it is lower. This simple control maintains a good balance between supply and demand. However, the voltage at a point far from the battery is different from the target value since the bus voltage as a reference value for the control is detected at the connection point of the battery. When power generation is greater than power consumption, the voltage at the distant point is higher than the target since the current flows toward the battery, while the voltage is lower during discharge. Therefore, when we design a DC micro grid, the cable size must be chosen carefully so that the voltage falls within the allowed band from the end to the end in view of the length and maximum current of the bus. In the case that the bus length is too long to equalize the voltage, multiple batteries need to be installed separately in the DC micro grid.

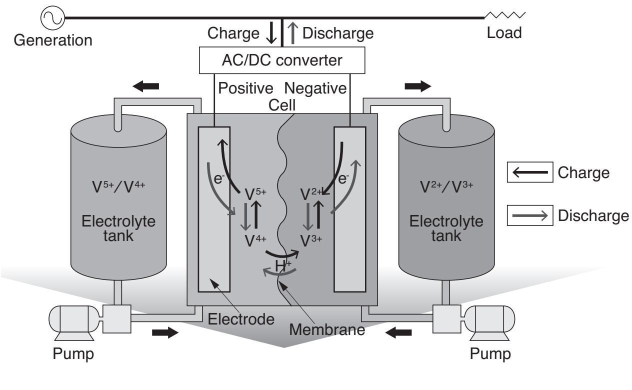

Fig. 2. Conceptual diagram of redox flow battery

4. Supply-Demand Balance Test for RF Battery

An experimental facility was constructed to demonstrate balanced operation between supply and demand in the DC micro grid. **Table 1**, **Fig. 3**, and **Photos 1-3** show the specification of the experimental facility, composition, and appearances of main devices, respectively. Since the purpose of this experiment is to demonstrate the balanced operation between supply and demand, the facility was disconnected from outer power sources.

Table 1. Specifications of the DC micro grid experimental facility

DC bus	350 V/1 km
Redox flow battery	4 kW/10 kWh
PV generation	
Polycrystalline silicon	4 kW
CIGS compound	2 kW
Concentrator photovoltaic	1 kW
Aerogenerator	1 kW
Inverter	4 kW
Loads	
Appliances	2 kW
EV charging station	2 kW

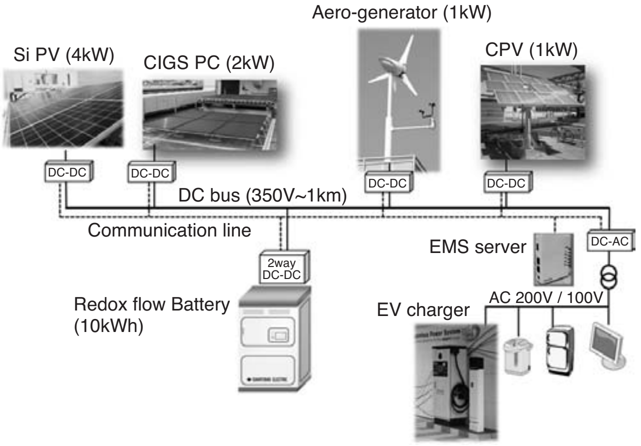

Fig. 3. Composition the DC micro grid experimental facility

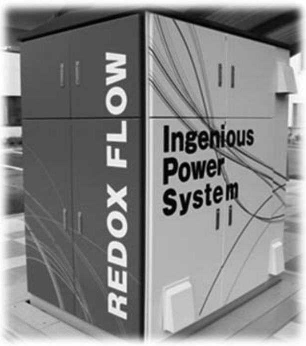

Photo 1. Redox flow battery

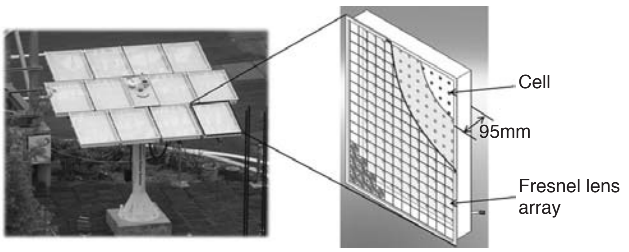

Photo 2. Concentrator photovoltaic

Photo 3. Inverter and loads

In comparison with actual cases, the experimental facility uses the same length of lines but deals with 1% to 10% of electric power. In the DC bus, the target voltage is 350 V, and the total length is 1 km. The exclusive RF battery has been developed for this experiment, and it has 4 kW of maximum output and 10 kWh of accumulating capacity. The battery was connected at the center of the DC bus through a bidirectional DC-DC converter. The PV units and an aerogenerator were distributed on the DC bus. The total output of these generators is about 8 kW.

The PV system consists of three different types of modules: polycrystalline silicon modules and CIGS compound modules, both of which are commonly used, and concentrator photovoltaic (CPV) modules that we have developed. The CPV module collects strong sunlight with lenses by precisely tracking the sun and generates electric power with multi-junction cells with extremely high conversion efficiency, thereby yielding about twice the power generated by a general polycrystalline silicon module on a sunny day. Although conventional CPV modules are thick and heavy, we have realized thin and light modules. The aerogenerator is a 1 kW device that is commercially available and compact enough to be installed in a residential area. DC-DC converters are installed between generating units and the DC bus in order to maximize power generation according to insolation or wind conditions.

All loads were placed at the terminal of the DC bus and fed by 60 Hz one-phase three line AC power that was converted from DC by a 4 kW inverter. The AC power goes through a smart distribution board and intelligent power tap, which are able to measure the power flow and send the data wirelessly to a management server. The loads consist of an air conditioner, TV, lighting, refrigerator, EV charger, and so on.

All the six power converters (four DC-DC converters for generating units, a bidirectional DC-DC converter for the RF battery, and an inverter for AC supply to loads) were developed for this experiment by us. Since these converters are connected to a LAN network, information on current flows and voltage detected in the converters is transmitted to the management server, which enables the remote operation of the system.

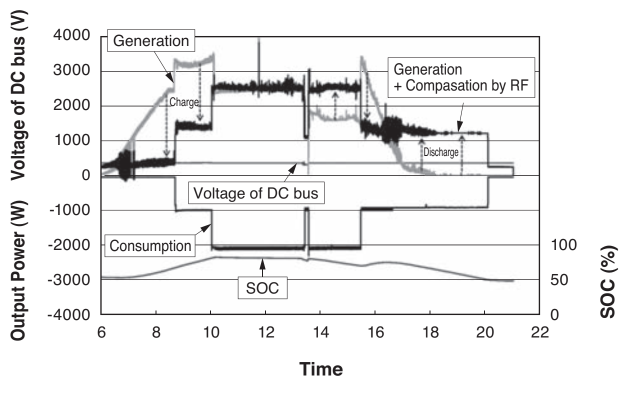

Fig. 4. Operational status of the DC micro grid experimental facility

Figure 4 shows the shifts in power generation and consumption in the experimental DC micro grid system throughout the day. In response to the fluctuation of generation and consumption, the RF battery successfully continues the compensation and keeps the voltage of the DC bus constant. This experimental facility has operated for more than six months. The result has demonstrated that the RF battery has a great potential for balancing power supply and demand.

5. Conclusion

In view of the economic efficiency of the entire electric power system including power transmission and distribution, PV generation that has intrinsically low working rates should be installed dispersedly in the demand area. Based on this idea, we have proposed the DC micro grid system as a solution for the major installation of PV generation and stabilization of power flows in the commercial grids. To demonstrate the key technique of the system, balancing power supply and demand, we have conducted an experiment using the DC micro grid system utilizing a RF battery. This experiment has demonstrated the technical feasibility of the DC micro grid system. In response to social needs and trends, we are going to develop this system into practical application and improve its economic efficiency.

Technical Terms

*1 Micro grid: An electric power system which supplies power to a local area by utilizing small scale generating units, such as gas turbines, photovoltaic generators, aerogenerators, and fuel cells. Its facility costs and energy dissipation associated with power transmission are lower than those of a large centralized power generation system that is constructed in a remote site. Since the power generation units are built in the demand site, a cogeneration system can be easily established, which enhances energy efficiency by utilizing heat and steam resulting from electric generation.

*2 DC-DC converter: An electric power conversion unit that changes a source of DC from one voltage level to another.

*3 Energy management system (EMS): A system that manages the operation of electric power for stable power supply and effective saving.

*4 Electric double-layer capacitor (EDLC): An electrochemical capacitor with relatively high energy density resulting from a physical phenomenon called electric double layer.

References

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