Special Contribution Article

The Digital Grid: The Convergence of Power and Information, and Its Application

The large scale deployment of wind-generated power, solar power and other power from renewable energy sources cannot be achieved without overcoming fundamental issues with the existing electric power grid and the urgent development of new power supply systems. This special article will introduce the reader to the Digital Grid concept - the convergence of power and information in a next-generation network architecture that holds the potential to revolutionize power transmission networks. In this architecture, IP addressed digital grid routers mutually interconnect a “cell grid” of distributed asynchronous power networks, while digital grid controllers enable inter-cell power transfers. Through the adoption of this architecture, the large-scale deployment of a renewable energy-based power system can be a reality.

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1 Introduction

In recent years, the impact of issues such as changes in the global climate and soaring fossil fuel prices has accelerated a shift to renewable energy sources such as wind and solar energy. The government has set solar power targets of 28 million kilowatts by 2020 and 53 million kilowatts by 2030; however, according to the “Low Carbon Power Supply System Workshop Report” [1] issued by METI in July 2009, the current power grid will be able to deploy only 13 million kilowatts by 2020, even if a system capable of producing the solar-generated output target is achieved.

Because grid voltage ceilings due to the reverse power flow created by solar power generation located at the terminal points of the power distribution network become a limiting factor, the greater the penetration of solar power generation systems, the more pronounced issues such as excess power generation and insufficient frequency regulation become [2] [3] . Also there are the basic problems of the large fluctuations in the power generated by solar, wind and other renewable energy sources and the inability to forecast supply in addition to the inability to achieve fundamental grid power source synchronization. With the added consideration of its relative incompatibility with the existing backbone power grid, renewable energy could be described as a power source with many problems.

In order to overcome these problems and enable the large-scale deployment of renewable energy, the development of a new power supply system is urgently needed, and a variety of approaches are receiving intense study [4] [5] [6] . While there are proposals for measures to reinforce grid interconnection, there is also much criticism pointing to the frailty and inefficiencies of a giant grid system.

On the other hand, the “smart grid” and similar proposals [7] [8] principally in the USA are driving the advance of more efficient power grid operation that uses digital information networks to secure an interactive grasp of power flows with a focus on the power consumption side. However, even with the digitalization of information and smart management of the supply and demand of power, it is difficult to exchange power as dictated by a digital information system because of the stepless analog nature of electrical power itself provided by synchronized rotation devices. For this reason in Europe where there is increasing renewable energy deployment, the concept of subdividing a power grid into multiple cells and regulated supply-demand balance within each cell is being adopted. Also in rising and developing nations, distributed asynchronous power grids (hereinafter referred to as “cell grids”) are common; however, it is forecast that their future procurement of fossil fuels will grow increasingly difficult. In light of this situation, if large-scale deployment of renewable energy is promoted as a solution, the introduction of energy storage devices for maintenance of cell frequency and voltage will be inevitable. For this reason, there is the difficult issue of synchronization of the interconnection of such cells.

This article introduces the concept of the Digital Grid (DG) that serves as a solution to the above issues and can take into consideration the power exchange between autonomous power devices and power grids.

2 Digital Grid

2.1 Example of the DG Architecture

The DG divides the existing power grid into cells with assignment of IP addresses to power converters, storage, generators and other power equipment and devices. With the freedom of inter-cell power management that exploits the synchronized operation of these multiple elements, the result is a power infrastructure that enables the handling of power in a way analogous to the handling of information on the Internet. As shown in **Fig. 1** , DG is composed of the Digital Grid Router (DGR) and the Digital Grid Controller (DGC). The DGR is a self-commutated multileg AC/DC/AC converter that can provide asynchronous connections/coordination between the backbone grid and the cells as well as between cells, mutual exchange of active power, and the supply of reactive power when required. The DGC is a device for management of power. The cell as defined by the DG concept means the minimum grid unit that possesses a distributed-type power source, storage and load and can be operated in a stand-alone mode, ranging in scale from an individual household or commercial facility to a building, village, town or city. As examples of large cells, Japan has the Hokkaido, East Japan and West Japan regions. In the USA, peak demand is 800GW, but as shown in **Fig. 2** , it can be subdivided into about 8 to 130 large-capacity cells and interconnected with DGRs.

The DGR appends IP addresses to each power converter and transmits converter operation data to the designated address, and transmits subsequent operation initiation data. In other words,

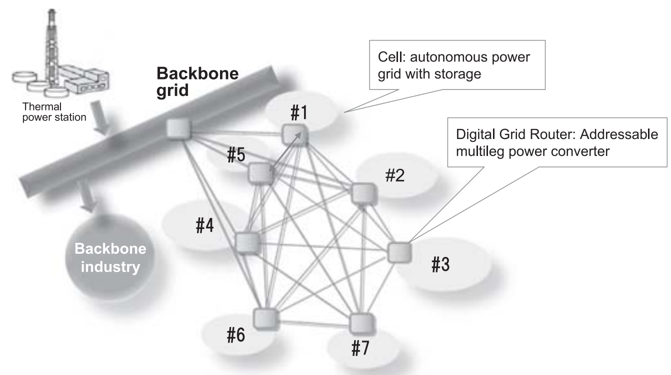

Fig. 1 Example of Digital Grid architecture.

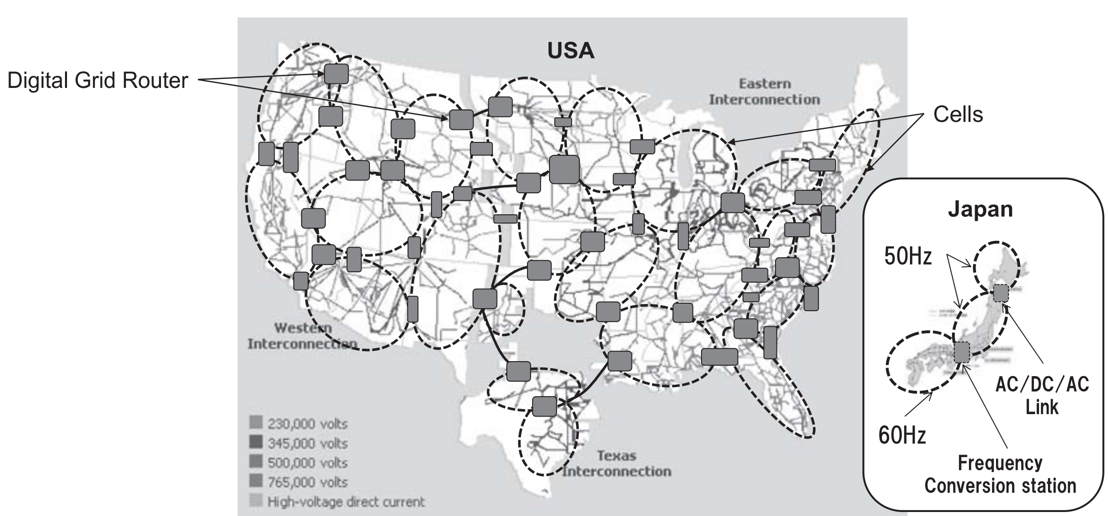

Fig. 2 Large-capacity cell example.

it unifies the interchange of information and power in a single device. This capability will make the large-scale deployment of renewable energy in each cell possible. Also the DGC has an IP communications function, enabling it to manage power exchange in coordination with the DGRs located within the cell.

2.2 Features of the Digital Grid

The DG has the following characteristics:

1) Cells in the DG have various types of distributed power generation and loads, and by using energy storage devices, they can absorb power fluctuations arising from solar and wind power generation and maintain frequency within a specified range in the corresponding cells. In other words, the cells are autonomous.
2) Autonomous cells with different frequencies and phases are connected by DGR and coordinated power line routing, enabling selective interchange of power.
3) In each synchronized system within a cell, instead of the communication of central power supply instructions, power supply-demand management is performed by the DGR. In detail, power generators, energy storage devices and other power equipment are managed/regulated by external DGCs which supply/demand control is performed within the cell based on DGR instructions.
4) DG creates "digital electric power"- virtual unification of information and power, enabling freedom to interchange power within the grid. By assigning fixed IP addresses to DGRs and DGCs and utilizing Power Line Communications (PLC) and/or external data communications networks, IP communications is enabled. Referring to the routing information, which includes the originating address and destination address, digital power can be transmitted to the destination via the designated DGR at will. The needed quantity of power exchange can be divided among several power units, and sent via different routes if separate routing data are appended. The routing information includes various profile data such as the size of the digital electric power and the length of supply (time) while footer information can be used to record the confirmation of termination of power transmission and evidence of an energy transaction.

2.3 DGR

The DGR may have both a connection terminal that has a power converter with a self-commutated power conversion device for AC/DC/AC power conversion and/or a connection terminal without a power converter and possessing only a circuit breaker/isolating circuit. The terminal without a power converter is the counterpart to the terminal with a power converter on the other end of the connection, resulting in a configuration that avoids the double conversion of power (**Fig. 3**). At the connection terminal where power conversion takes place, power from connected cell is rectified to DC. The voltage, phase and frequency are synchronized with that of the remote cell to which this DGR terminal is connected, and then power is inverted and transmitted, enabling the total power of all inputs and outs to each DGR is controlled so as to be net zero. As a result of the adoption of a self-commutated power converter and because of independent control of power and phase in the grid coordination mode, DGR can transmit the desired active

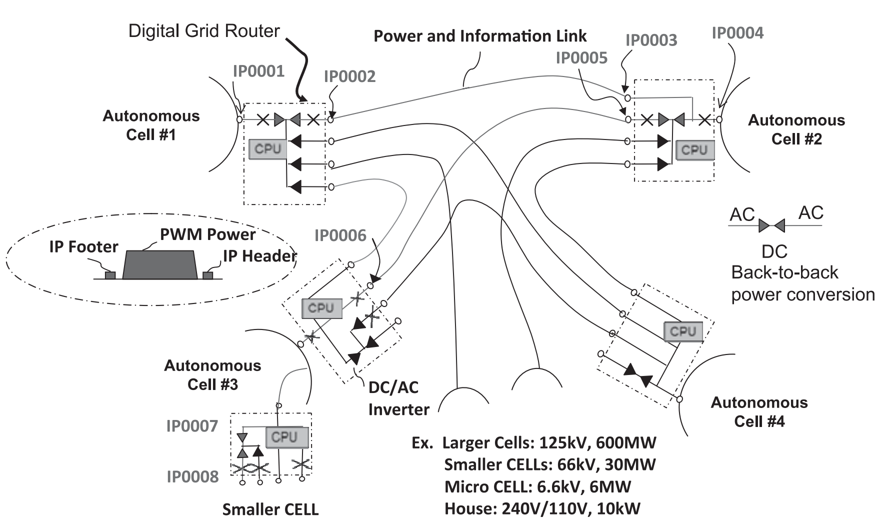

Fig. 3 Image of interconnection of cells with DGRs and how power is routed.

power in a desired direction at will and independently generate the desired reactive power at the desired size, thereby enabling voltage regulation. Also because this is a self-commutated device, in the case of null voltage status of the connected power grid, it can also become a voltage source and supply power.

As shown in Fig. 3 illustrating an example of DGR interconnection, the positioning of DGR enables the construction of an asynchronous network in which two freely selected cells can be connected without power line route divergence and with a power converter at only one terminal of the connecting power line route.

2.4 DGC

DGC can meter the quantity of power generated from solar, wind and other power sources that have relatively severe fluctuations; exchange data through external telecommunications circuits; control increases/decreases in the output of diesel-fueled generators, gas-engine generators, and other power generators who output is relatively easy to adjust; monitor the State of Charge (SOC) of energy storage devices and control charge/discharge quantity; and monitor the power consumption of various equipment and appliances. Through this method of controlling power equipment, the DGC can forecast power exchange-related information and "reserve" power transactions. Based on the information provided at that point and after a certain period of time, the cell autonomously validates the reservation for a power exchange. As a method of controlling power forecasts, a variety of approaches can be considered according to the characteristics of each cell, but it is considered best to have a forecast management system that maintains the SOC of the energy storage device at around 50% for general conditions, lowers SOC below 50% to absorb the output of a forecast increase in solar or wind power is forecast, and raising the SOC above 50% in anticipation of a forecast of decreased output from renewable energy sources and increased output from the battery.

3 DG Benefits

The 7 main benefits of the above-described Digital Grid are as follows:

(1) Large-scale deployment of renewable energy

In the conventional power grid, the power flows of different sizes and directions take place within the grid to compensate local supply-demand imbalance and to maintain the synchronization. When large-scale renewable energy sources with their inherent characteristic of output fluctuations are connected to the power grid, even larger changes in the direction and size of power flows become unavoidable.

In the case of the DG, those fluctuations are absorbed by frequency changes within each cell, and power flows for the maintenance of synchronization become unnecessary due to ability to have differing frequencies maintained in each cell in stable coexistence. Moreover, power loss will be minimized. Therefore, stable DG operation will be maintained even if the dissemination of renewable energy is progressed.

(2) Grid with high redundancy and robustness

In the case of the conventional grid, a power line routing accident or other incident can make usage of the grid impossible, resulting in downstream power outages and instantaneous voltage drops. With DG, it is possible to square the number of cells with a proportional increase in power interchange routing, enabling the exchange of power via an alternate route even if multiple routes are not available for service. The result is remarkably higher redundancy for power interchange and the superior robustness of the overall DG.

(3) Sharing of energy storage devices

In the case of independent cells that have no interconnection with other cells, the higher volatility of the supply-demand imbalance necessitates sufficiently larger capacity energy storage to compensate. The free interchange of power among multiple cells in the DG model results in a decrease in the volatility of the supply-demand imbalance since the overall DG is essentially the same as a single cell. The result is that an energy storage facility can be shared by multiple cells, the amount of energy storage capacity that needs to be installed for the DG is reduced compared with amount that would be required if each cell independently provided its own storage.

(4) Load sharing

If the remaining charge in the storage devices of a cell is low and it is determined that it poses a barrier to frequency maintenance, it is possible to request a power exchange with nearby cells and receive the power gradually from multiple cells via multiple routes. On the other hand, if the SOC of the storage device is high when wind power generation commences, it is possible to gradually send the excess power to nearby cells. The result is a smaller load on individual cells and connecting power lines.

(5) Power trading

In order to secure the supply-demand balance in the case of a conventional synchronized grid, the "30-minute same time, same quantity" rule is applied to electrical power utilities of a specified scale. In the case of the DG, each cell is asynchronous, therefore, short cycle imbalances are met by energy storage devices, longer cycle imbalances are compensated by distributed fossil fuel power sources, and the portion that cannot be borne is discharged as the rotational energy of a turbine or other rotating machine. In other words, it is possible to bear the burden of frequency increases and decreases. Accordingly, when trading power, restrictions on emergency exchanges and the "30 minute same time, same quantity rule" are largely mitigated, and adoption of familiar transaction model consisting of pre-negotiation, reservation, confirmation and delivery can be adopted. The result is the formation of a new business platform for power trading.

(6) Coexistence with the backbone grid

In pursuit of economical performance to respond to industrial demand, the conventional power grid has sought to achieve economies of scale through its development as wide-area interconnected grid with large-scale centralized power sources. For private citizens, it is also vital infrastructure that supports medical, food and other lifelines.

DG adds Internet-like flexibility and robustness to this key infrastructure, enhancing the security of private civilian demand.

The hybrid configuration of the existing backbone grid and the DG will tap the potential offered by a new power grid.

(7) Security

Because cells are premised on an autonomous power system, they can ensure their own power security. For example, if another cell suffers an incident, the gate blocking of the interconnection point is swiftly performed.

4 Conclusion

The concept of convergence of power and information has been proposed in the past, but it has come with the technological difficulty of being unable to differentiate between individual power flows in a synchronized grid. The DG introduced in this article uses DGR and DGC to append information to power flows, enabling their differentiation and identification. This holds the potential to dramatically revolutionize the existing power system. In the future, if distributed-type renewable energy generation and energy storage devices are sufficiently deployed, cells will have the capability to be autonomous, and it is believed that even if multiple power exchange transactions take place, only the final demand that is a compressed offset of the transactions is transacted. These execution algorithms resemble financial transactions, and while within the cell is a conventional synchronized grid, the connected power line routes will transform into a network for economic transactions.

The process for transition to the DG will consist of deployment of DGCs only in the existing transformer substations, transformer equipment and other principal power equipment of the power grid equipment, and the maintenance of other equipment in their current state as autonomous cells; positioning of DGRs between the conventional power transmission lines, that connect substations, and the substation bus; and the asynchronous interconnection with other cells and with the backbone grid. In the developed countries, these steps could be described as both a flexible and realistic approach to deployment. Also in developing nations, DG deployment enables construction of a flexible grid that allows the asynchronous interconnection of adjoining grids depending on the degree of necessity.

*Digital Grid is a registered trademark of the Digital Grid Consortium, a non-profit corporation.

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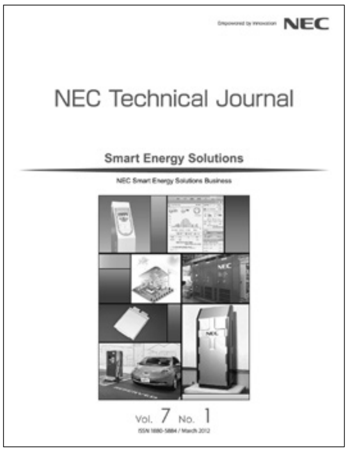

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