Views & Comments

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Basic Ideas of the Smart Grid

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Electrical power grids have encountered many challenges in recent years, including global warming, the quest for energy security, increasing cultural conservation, and the stringent power reliability and quality requirements of the digital age. Many studies have been conducted on the development and implementation of the smart grid (SG) to address these issues.

In terms of power grids, the development of the SG is aimed at achieving at least four major objectives: ① the secure operation of large power grids under disturbances, the minimization of the risk of blackouts, and enhanced resilience; ② the seamless accommodation and efficient utilization of vast amounts of distributed energy resources (DERs); ③ the facilitation of an advanced electric power market and demand response; and ④ the provision of electric power with high reliability, high quality, and high efficiency for a digital society.

From a broader perspective, considering that the implementation of the SG draws on many technical and business fields, the key goal is to encourage the innovation of relevant technologies and business models in order to create an industrial revolution.

Considering the many ideas that underlie the SG, their clarification will facilitate the scientific and efficient implementation of SG projects. This article elaborates on some basic ideas.

1 Essential technical characteristics of the SG

The essential technical characteristics of the SG are: the two-way flow of electricity and information in order to establish a highly automatic and widely distributed energy exchange network; and the utilization of distributed computation, communication, and Internet within power grids in order to realize the real-time exchange of information and a near-instantaneous balance between power demand and supply at the device level. The following four features are important in this regard.

1.1 Flexible network topology and integrated energy and communication system architecture (IECSA)

Because of the wide integration of DERs, the power flow of each line of the power grid (including the transmission and distribution grids) is likely to be bidirectional and time-varying. Hence, to maximize the potential benefit of the SG, the topology of the distribution grid should be flexible and reconfigurable. In addition, it should use flexible alternating current (AC) and direct current (DC) power transmission and distribution devices, as well as other electronic power devices such as the intelligent universal transformer (IUT), which is a type of energy router that is regarded as the cornerstone of smart distribution grids. Furthermore, where there is electricity, there is a reliable two-way communication network. From the sensors and intelligent agents in the basic layer, the energy grid and the information and communication network are deeply integrated.

1.2 Huge quantities of DERs

DERs include distributed generation, distributed energy storage, and demand response. Among these, solar power, wind power, and demand response are distributed according to natural geography. With regard to demand response, the electricity consumption of end-users may change with the retail price of electricity, or decrease when the electricity price in the retail electricity market is high or the power grid is insecure. The following observations are thus worthy of note.

(1) As distributed generation is close to the power load, power and energy can be balanced on-site in order to reduce the investment requirement, network loss, and operation and maintenance cost of the grid. In addition, with the increasing price of traditional power, the cost of photovoltaic (PV) devices decreases rapidly, and is accompanied by a gradual reduction of the cost of distributed energy storage. At the same time, the utilization efficiency of the distributed energy system, such as the combined heat and power (CHP), may increase to higher than 80%. All these factors indicate that parity between the cost of distributed generation and the retail price is within sight. At the same time, distributed generation can be used to improve the reliability of consumer service and strengthen the security of the power grid. Consequently, the vast majority of studies on the development and implementation of the SG worldwide have focused on the "distributed."

Indeed, studies conducted at Tianjin University have shown that in present-day China, the total social cost of a "distributed PV + active distribution" scheme (i.e., distributed PV stations without energy storage, locally integrated

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into an active distribution grid) has fallen below the total social cost of a "large-scale base of centralized renewable generation + long-distance transmission" scheme (i.e., a large-scale base with a combination of wind power and thermal power, integrated into a bulk power system at a load center through a ±800 kV ultra high voltage (UHV) DC 2000 km long-distance transmission line).

Hence, the development of a future power grid is faced with the challenge of dealing with tens of millions of distributed power resources with intermittency, variability, and uncertainty, while ensuring the security and reliability of the power grid, human and equipment safety, and market viability.

(2) Studies have revealed the presence of a significant shiftable load in the time coordinate in a power grid, and that such a load, like a virtual power resource, is a favorable measure for reducing the peak load and filling the valley load in order to improve asset utilization and power generation efficiency, and reduce grid losses. This measure enables the achievement of a near-instantaneous balance between power supply and demand at the device level. For example, demand response and load control can be used to compensate for the intermittency, variability, and uncertainty of solar and wind power. This represents a revolutionary change compared to the constraints of a traditional power grid, which requires strictly imposed generation to meet the load demand at any time. In facilitating demand response and load control, the SG would employ advanced metering infrastructure (AMI), plug-and-play technology, and an advanced power market. The control and management of the load and power distribution would be comprehensively taken into account.

(3) Plug-in hybrid electric vehicles (PHEVs) and vehicle-to-grid (V2G) technology have the double attributes of being both a load and a source, and their charging power and energy storage are very large. In addition, compared with distributed PV and wind power, the location and capacity of these electric vehicles have a higher uncertainty. On one hand, as a new type of load, the integration of many electric vehicles significantly increases the load and complicates the load characteristics of distribution grids, thus presenting challenges to the planning and operation of the future power grid. On the other hand, as a type of energy storage device, electric vehicles are important potential control measures for reducing the peak load and filling the valley load, for frequency regulation, and so on. For this purpose, the SG should provide electric vehicles with a plug-and-play platform, including advanced market and novel technology support.

In addition to electric vehicles, distributed energy storage can be used in many aspects of distribution grids, for increasing operation reliability, improving power quality, enhancing the ability to accommodate renewable resources, and so on. The SG will provide the basic platform for the interaction and coordinated control between distributed energy storage and distribution grids.

It is gratifying that the innovative process of the new distributed energy storage technology is developing rapidly in recent years, and is expected to break through the bottleneck of the high cost of energy storage.

1.3 Distributed intelligent infrastructure

(1) Power infrastructures that were built before the age of the microprocessor were based on centralized planning and control, which significantly limited the flexibility of the power grid, and also reduced the efficiency, security, and reliability. Furthermore, because the number of DERs will be huge and DER outputs are difficult to forecast, the traditional centralized control mode will be unable to adapt. Consequently, the smart distribution grid will be a distributed intelligent infrastructure.

As shown in Figure 1, a smart distribution grid is divided into several cells. The exchange power in the normal operation between two cells can be scheduled according to the schedule. Each cell incorporates several intelligent network agents (INAs) such as relay protection devices and DERs, which are interconnected through the cell communication network. The INAs collect and exchange system information, make independent decisions regarding local control such as relay protection by themselves, and coordinate decisions such as voltage control, reactive power optimization by itself, and network reconfiguration through the distribution fast simulation and modeling (DFSM) of each cell. There are also communication links among cells, thus each cell can make independent decisions and the operation center of the distribution grid with DFSM coordinates the decision-making between cells. Furthermore, the dispatching center of a transmission grid and the operation centers of distribution grids supplied by the transmission grid are linked through the communication network. The dispatching center of the transmission grid with transmission fast simulation and modeling (TFSM) enables coordinated decision-making based on the regional system requirements, and hence smart control across organizational and geographical boundaries. The entire grid is thus self-healing and resilient.

(2) The resilience of the system includes the ability to withstand and recover from

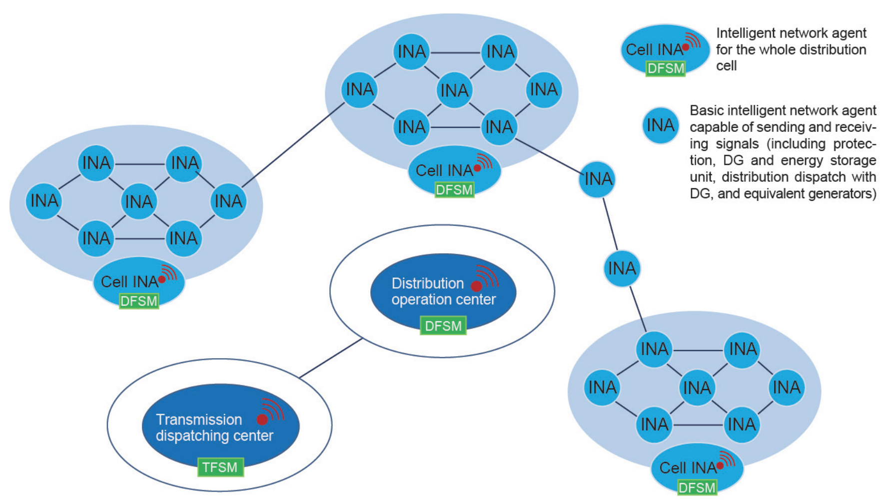

Figure 1. Distributed intelligent infrastructure.

deliberate attacks, accidents, or naturally occurring threats or incidents. This requires a major change in our perspective on the system, as well as in how it is structured and how complex interactive networks are operated. The distributed intelligence infrastructure shown in Figure 1 can be used to adequately deal with the disturbances mentioned above. For example, in an emergency, the infrastructure enables the adaptive isolated island operation of the corresponding cell, and the rapid restoration of the entire grid to normal operation. This can enhance grid resilience and minimize the impact of power failure.

(3) The structures and control strategies of smart distribution grids must satisfy the following two basic requirements, which are beyond the capability of the traditional grids used today:

- Comprehensively considerate both end-user control and overall control of the distribution grid. The end-user system comprises distributed generation, distributed energy storage, power conditioning equipment, reactive power compensation devices, and energy management systems. The control of all these devices and processes must be incorporated into the control of distribution grids in order to systematically achieve the best possible performance, security, and power quality.
- Support access of the high penetration of DERs.

(4) A cell, as shown in Figure 1, may become a so-called "smart microgrid" or involve many smart microgrids. The smart microgrid is an integrated system that is used to meet the energy demand of a group of users (such as a small community or town) or a single user (such as a university, building, or enterprise). The key difference between a microgrid and distributed generation is that the former is capable of coordinated control in an island containing several energy sources. Under normal operation, the intermittency, variability, and uncertainty of renewable energy sources in a microgrid can be internally compensated. Thus, the power flow through the tieline between a microgrid and a bulk grid can be maintained at almost a constant level, which is helpful for the secure operation of the whole power grid. Therefore, the microgrid is regarded as a "good citizen" and more and more microgrids are expected to appear in future grids. Research should pay more attention to the cost reduction of microgrids.

1.4 Real-time exchange and sharing of information

The information technology used for the operation of a smart transmission grid is the same as that used for the operation of a smart distribution grid. In essence, the lifeblood of any SG is the data and information used by its applications, enabling the development of new and improved operation strategies. The data collected from any layer of the power system, including user consumption, distribution, transmission, generation, and power market, may be linked and used to improve the operation of another layer. The real-time and timely exchange of data among stakeholders is thus the basic feature of the SG.

2 Basic functions and relevant technologies of the SG

The SG is an enabler and a well-designed SG should enable the following key functions.

(1) Wider participation:

- Motivation of end-users: Customers should be provided with detailed information about their energy consumption in a timely manner, as well as the various available rate schemes, including options such as time-of-use pricing and real-time pricing;
- Capability to easily and transparently accept any form of energy;
- Capability to complement centralized generation with large quantities of plug-and-play DERs.

(2) Efficiency improvement:

- Capability to allow customers to actively participate in a mature, healthy, and integrated power market;
- Provision of high-quality power and appropriate rate schemes for different power quality levels;
- Asset optimization and resource utilization for efficient system operation.

(3) Reliability and resilience enhancement:

- Self-healing in the event of an outage in order to minimize service interruptions;
- Resilience to attacks and natural disasters;

and so on.

In order to enable above functions, innovation is required to induce novel technologies and business models. Relevant SG technologies include the following three classes.

(1) **SG technologies.** These include wide-area measurement (wide area measurement system/phasor measurement units (WAMS/PMUs) and situational awareness) and control systems, the integration of information and communications technology (ICT), the integration of renewable and distributed generation, the application of transmission expansion, flexible network topology of the distribution grid, advanced distribution network management, AMI, consumer-side management systems, and so on.

(2) **Technologies promoted by the SG.** These include wind turbines, PV power generation devices, plug-in electric vehicles, green and energy-efficient buildings, and smart household appliances. Electric vehicles and green buildings may become the killer applications of the SG.

(3) **Technologies building platforms for the SG.** These include integrated communication technology, sensing and measurement technology, energy storage technology, power electronics, diagnosis technology, superconducting technology, and so on.

To accelerate the implementation of the SG, the best technologies and ideas, such as open architecture, Internet protocol, plug-and-play technology, common technical standards, non-specialization, and interoperability, will be applied. In fact, many of these technologies have already been applied in power grids; however, the potential of these technologies can only fully exploited in a case involving two-way digital communication and plug-and-play capabilities.

3 Other considerations

3.1 The benefits of the SG are extensive and enormous

According to the report published by the US Electric Power Research Institute in 2011, the estimated investment needed to realize the envisioned power delivery system from 2010 to 2030 is between $338 billion and $476 billion. While the total benefit is between $1294 billion and $2028 billion. The benefit-to-cost ratio is between 2.8 and 6. In China, the SG development strategy not only enables us to obtain electricity with high security, high reliability, high quality, high efficiency, and reasonable price, but also improves the country's energy security and environment, promotes sustainable development, and stimulates the market and innovation, thus enhances the international competitiveness of China.

3.2 Enormous challenges facing the SG

The SG is facing extensive challenges, involving many technological, systemic, and social issues; and the transition of power grids will change business models entirely. Figuring out the critical barriers will facilitate the maximization of the SG's potential.

3.3 The necessary condition for the development of the SG is to build an overall favorable environment

(1) Laws, policies, standards, and roadmaps. According to the nature of the SG, stockholders not only include power companies and electrical equipment manufacturers, but also include consumers and other industries. Furthermore, the organization, R&D, and implementation of the SG will be extremely complicated. Corresponding laws, policies, standards, and roadmaps should be scientifically made in order to motivate, support, and guide the participation of more enterprises and the public.

(2) An advanced power market. To motivate innovations in the SG, it is essential to build up a mature, healthy, and integrated power market. This process should address issues such as time-of-use price and real-time price that reasonably reflect the market value of electricity as a commodity. Policies should be developed that encourage the owners of distributed power and energy to sell electricity to the grid, promote the supply of clean energy (feed-in tariff), and ensure returns on the investments of the power companies and other investors.

(3) The SG and the Internet. Actually, the SG is an interdisciplinary product, born with the thoughts of the Internet. From 1925 to 1950, the idea of the interconnected power grid has been established and was greatly expanded in the world. In fact, it possesses four basic properties of the Internet known as interconnection, openness, peer to peer, and sharing. Novel technologies and ideas in the area of the Internet should be brought for the realization of the vision of the SG. To further promote the innovation of the SG, close cooperation is required among scientists and engineers in the fields of energy and information and communication. The use of common languages and protocols is imperative in order to fully maximize the potential of the SG and to deliver its broad range of social and economic benefits.

3.4 Short-term and long-term objectives of the SG

The SG will change the way people live and work, just as the Internet has done. Due to the need for sustainable R&D and disruptive technological breakthroughs, the realization of the SG will require a long-term transition and the coexistence of multiple technologies, which can be understood by reviewing the history of the Internet. In the short term, the focus can be placed on achieving a smarter grid that utilizes existing or near-ready technologies in order to improve the efficiency of power grids, provide power with higher quality, and create important social benefits such as environmental improvement.

3.5 Benefit orientation

The ongoing development of the SG requires continual research to predict varying needs and evaluate varying benefits and cost. During the process of implementing the SG, the following question should always be considered: Does the work match the market, motivate consumers, optimally utilize assets, and operate effectively? Power enterprises and regulators should continually show consumers that the benefits of the SG will eventually exceed its cost.

Compliance with ethics guidelines

Yixin Yu, Yanli Liu, and Chao Qin declare that they have no conflict of interest or financial conflicts to disclose.