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Article

Discussions on the Architecture and Operation Mode of Future Power Grids

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Abstract: The new energy revolution, of which the primary energy will be based on renewable energy sources and the terminal energy will be based on electric power, will have a revolutionary impact on the future power grids. In order to develop the corresponding power grid for the future energy system, first of all, the architecture and mode of operation of the future power grid must be investigated. In this paper, we suggest that the DC—dominant operation mode for transmission system, distribution network and distributed power system should be developed, and a MP-MC dominated transmission architecture (multiple powers to multiple consumers) and the two-way power exchange control (TPEC) should be employed to build "wide-area super virtual power plants" (WASVPPs) which cover all the major power plants in a wide range, allowing the consumers to obtain a stable and reliable supply of electricity from the "cloud powering" created by WASVPP and the distributed power system which is connected to the grid.

Keywords: renewable energy; DC power grid; distributed power system; charging station for electric vehicles; complementarities of energy resources; virtual power plant; cloud powering

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1. Introduction

With the increasing depletion of fossil fuels and growing environmental pressure, mankind has recognized the need to vigorously develop renewable energy sources [1], and make a significant change by progressively substituting fossil energy with renewable energy. The renewable energy sources will be mainly utilized to generate electricity. Then, it would be expected that the terminal energy will be based on electric power in the future. This significant change on the energy structure will have a revolutionary impact on the future power grid, mainly reflected in the following areas [2]:

Firstly, the grid will experience a massive growth of power generation compared to the current one, and long-distance power transmission and grid interconnection will still exist for quite a long time as a result of the fact that the renewable energy sources distribution is usually far from the load centers. We all know that the larger the interconnected power grid backboned with the alternating current (AC) is, the stricter the demanding be on the operating conditions of the power system and the more prominent the issues of unpredictability, safety and stability will be [3]. It can be clearly seen that it will be a great challenge to solve the safety and stability concerns of the future large power grid.

Secondly, the renewable energy resources have intermittent and unstable characteristics, which leads to intermittent and unstable power generation output.In addition, the solar photovoltaic power generation systems do not have the mechanical inertia the traditional hydraulic turbines or steam turbines do, and wind turbines are very different from the traditional generators. So with the large-scale access to renewable energy power, how to guarantee the real-time dynamic power balance, stability of the grid and efficient dispatch of electricity becomes another major challenge faced by future power grids.

Thirdly, the dispersion characteristics of the renewable energy sources make the distributed power generation which generates power locally close to the load side an important type. It means that the electricity consumer could be at the same time the power supplier. The large power grid will develop in parallel with the distributed electricity network in the future power grid. Therefore, it will be the new challenge on the future grid to effectively implement the positive interactions between the large grid and distributed power network, as well as achieve the optimal utilization of both distributed and centralized power sources.

Fourthly, with the renewable energy gradually replacing the fossil energy, the current energy consumption system based on the fossil energy, especially the fuel transport system (such as cars, motorcycles and so on) will use electricity, which means that a large number of the mobile loads (*i.e.*, electric motorcycles) and batteries that is used on the widely distributed electric vehicles within a wide range will become the one of the main loads of the grid. It makes the load characteristics of the future power grid very different from those of the current grid, so how to adapt to such a great change in the load will also be a very important task.

Fifthly, the primary energy in the future grid will be diverse (such as hydro power, wind power, photovoltaic power, biomass and ocean energy power generation, *etc.*), and their spatial and temporal distribution and dynamic power features also vary, so how to realize the positive interactions among these different power generation systems and achieve the comprehensive optimal utilization of each energy source should be taken into consideration in building the future power grid.

As aforesaid, these significant changes in the energy structure will bring a series of great challenges for the future power grid, and it is worthy to study deeply on how to solve these problems in the future grid development by starting from changing its network structure and operation mode. This paper presents a preliminary investigation on this issue, for reference and further discussion.

2. Complementarities of Various Power Resources in the Future Power Grid

It is very useful to analyze the complementarities of various power resources in the future power grid before we explore its structure and operation mode. The power generated from a single renewable energy power station is difficult to adjust and control to satisfy our needs because the power from wind, solar, ocean energy and so on are unstable, irregular and intermittent. However, if we "package" these multiple power resources together, the complementarities of resources can make the "power package" a relatively stable and controllable resource. The complementarities of various power resources in the future power grid are mainly reflected in the following areas:

2.1. The Complementarity of the Energy Resources in the Time Coordinate

Some resources are available only in a certain period, while other resources seem to be more adequate in some other time. For instance, the solar power can only be used during the daytime, while wind and waves energy can be even more robust at night; the hydro power resources are more abundant in the summer, and solar and wind resources are more abundant in the winter. Because of the time difference, the solar resources in the eastern and western regions also have complementarity in the time coordinate. The solar or wind energy variability can be compensated for by adjusting the power generation and reservoir capacity of hydro power stations because hydro power has certain controllability. For example, within a day, we can appropriately decrease the hydro power (the available hydro power in China is estimated to be 540 million kilowatts) and increase the reservoir capacity when the wind and solar energy are adequate; Otherwise, we can increase the hydro power when the solar and wind are insufficient. Compared to other renewable energy sources, biomass (it is estimated to be 5 million kilowatts in China) is much better in complementarity in the coordinates of time because it can be stored in large quantities. The biomass power generation can be started to supplement other sources when there is a shortage of solar and wind power.

2.2. The Complementarity of the Energy Resources in the Space Coordinate

The energy resources at different places are complementary at the same time. A recently published paper from researchers at the University of Delaware and Stony Brook University studied the data on wind power output at different locations [4]. The 5-year wind data from 11 meteorological stations, distributed over a 2500 km expanse along the U.S. East Coast shows each individual wind power generation site exhibited the expected power ups and downs, but when they simulate a power line connecting them, called in the paper the Atlantic Transmission Grid, the output from the entire set of generators rarely reaches either low or full power, and power changes slowly. Notably, during the 5-year study period, the amount of power shifted up and down but never stopped. The results of the some other studies [5–9] also showed that the total power output of dispersed wind farms is smoother.

Thus, the power output will have significant complementarity if we connect the wind farms within a wide range into a group. Similarly, we assume that wave energy and solar energy are also complementary in the coordinates of space.

2.3. The Complementarity of Different Power Generations

Different renewable energy power generations are different in terms of output response, which can be reflected in the form of complementarity. For example, the photovoltaic power generation fluctuates in real-time as the light intensity changes, while the solar thermal power generation does not have such real-time fluctuation on power output with the change of solar radiation intensity because its thermodynamic system has a large inertia time constant; apart from that, the solar thermal power generation is capable of adjusting the power output through the short-term adjustment of heat exchange power because the thermodynamic system can store some thermal energy. Likewise, different types of wind generators are not the same in start-stop wind speed as well as the output performance. Therefore, the whole power plant will have more smooth output if different types of renewable energy power generation are used in the same power plant with unified coordination and control.

2.4. The Regulatory Role of Electric Vehicle Charging Systems

The power batteries of electric vehicles (EVs) will be one of the major loads in the future grid. For instance, the total electric power capacity in China should reach 2500 GW in 2050, and the charging power for EV could reach 500 GW at that time, as explained below. In fact, this load can also be seen as power resources. We can increase the charging power when the solar and wind energy is abundant, and decrease the charging power when they're insufficient or even feedback some electricity to the grid. In this sense the charging system can play a role in smoothing the power output. Assuming the car ownership in China reaches 400 million by 2050, half of which are electric vehicles (that is 200 million), and that vehicle batteries can on average last for 4 days after charging, then there will be about 50 million cars that need to be charged every day, which roughly equals 500 million kilowatts of charging power. Here we think battery replacement will be the main charging mode of the future electric vehicles for the following reasons: first, as the more unstable and uncontrollable renewable energies will be the dominant energies, if we use the energy storage system to compensate the variability of the renewable energies, and the EVs are charged in plug-in mode, then the efficiency of the energy system (partly as the efficiency of energy storage times the efficiency of EV batteries) would be lower than the replacement mode; secondly, if the EVs are charged in plug-in mode, then a large amount of random loads or even pulse loads which are not controllable will be connected to the grid, leading to difficulties in achieving the power balance of the grid; thirdly, if the plug-in mode would be used, the required retrofit of the distribution network would be very difficult and expensive. Therefore, if the battery charging system for electric vehicles would be charged according to the actual situation of the power grid by employing the replacement mode, the efficiency and economy would be higher than for the plug-in mode.

In summary, although the renewable energy resources such as the solar, wind and wave energy are intermittent and unstable, we can also make the power supply more smooth, stable and controllable so as to meet the consumers' demands on electricity if we make full use of the complementarities of time,

space and power generation style of these resources and the regulatory roles of the hydro power, biomass power and charging system of the electric vehicles even without installing large number of energy storage systems.

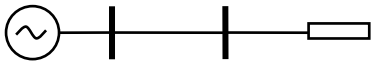
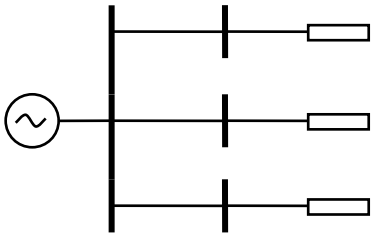
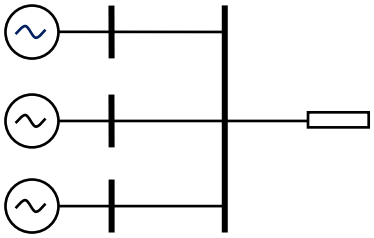
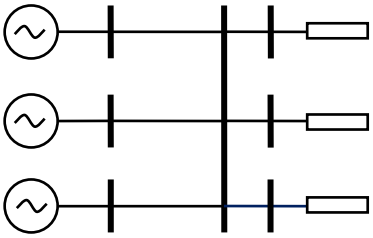
3. The Possible Architecture and Operation Mode of the Future Power Grid

When trying to answer the questions such as how to package all the resources organically into the future grid that is dominated by renewable energy power, how to transport a large amount of electricity over a long distance and how to effectively guarantee the safety and stability of the grid and reliability of electricity supply we may start from the study of grid architecture and operation mode.

3.1. The Architecture of Future Power Transmission Grid

The future power grid will mainly include the transmission and distribution system and distributed network for the end user. Of these, the transmission network will play a key role in the wholesale electricity market, because most of the renewable energy sources are far from the load centers. Therefore, this paper will emphasize the structure of the future transmission network.

Table 1. Four basic transmission modes in current grid.

	C	**MC**
P	 **Single Plant to Single Consumer Mode**	 **Single Plant to multiple Consumers Mode**
MP	 **Multiple Plants to Single Consumer Mode**	 **Multiple Plants to Multiple Consumers Mode**

In the early stages of grid development, the capacity of generating units is relatively small as well as the demands on electricity, so the architecture of the grid is basically from a power plant to the receiving end (here the receiving end refers to one load center or power supply area), which is defined here as power to consumer transmission mode (P-C mode). Later, with the continuous expansion of the capacity of generating units and power plants, power to multiple consumers mode (referred as the P-MC mode) has been developed, that is from power plant to multiple receiving ends. With the increasing demand on electricity, the consumer begins to have higher and higher demands of the reliability of the power supply. One power plant is unable to meet the need of the consumer any more,

which leads to the build-on of multiple power sources to the consumer transmission mode (referred to as the MP-C mode) that supplies one receiving end from multiple power sources. In addition, with the multifaceted requests on power supply reliability, power grid interconnection and operational management, the architecture of the grid become increasingly complex, which brings about the transmission mode of multiple receiving ends supplied with multiple powers through load-center substations (that is multiple powers to multiple consumers, referred as MP-MC mode). Table 1 shows the four basic transmission modes in the current grid. From the point of view of grid architecture, the current grid is basically the combination of P-C, P-MC, MP-C, MP-MC transmission modes, but currently the MP-MC mode hasn't been the dominant mode of transmission system, besides there is no obvious coordination and complementarity among the various power plants because the plants are operated independently, therefore the MP cannot be completely taken as an organically combined "power package".

It would be an inevitable choice to upgrade the MP-MC mode to be the leading mode of the transmission network in the future grid if the receiving ends are supplied with stable and reliable electricity. The justifications are as follows: first, it is very difficult to supply stable and reliable electricity to the consumer whether using P-C mode or P-MC mode because a single power plant is incapable of providing sufficient and stable power, unless high-power and high-capacity energy storage systems were built. However, these energy storage systems are not only very high in cost and low in efficiency, but the technology is still immature (except for the pumped storage, but it is very difficult or even impossible to build a large number of pumped storage stations in many solar and wind-rich areas or load centers). Secondly, MP-C mode might be able to provide a more stable and reliable electricity supply to the consumer if the power structure is reasonably designed, but it actually breaks down the power grid into multiple independent electricity networks, which makes it difficult to bring into play the comprehensive advantages of optimal allocation of resources, economy and reliability of interconnected power grid within a wide range. It is hard for the MP-C mode to become the dominant mode, especially considering the diversity of energy resources in the future, as well as the mismatch between the spatial and temporal distribution of resources and load centers.

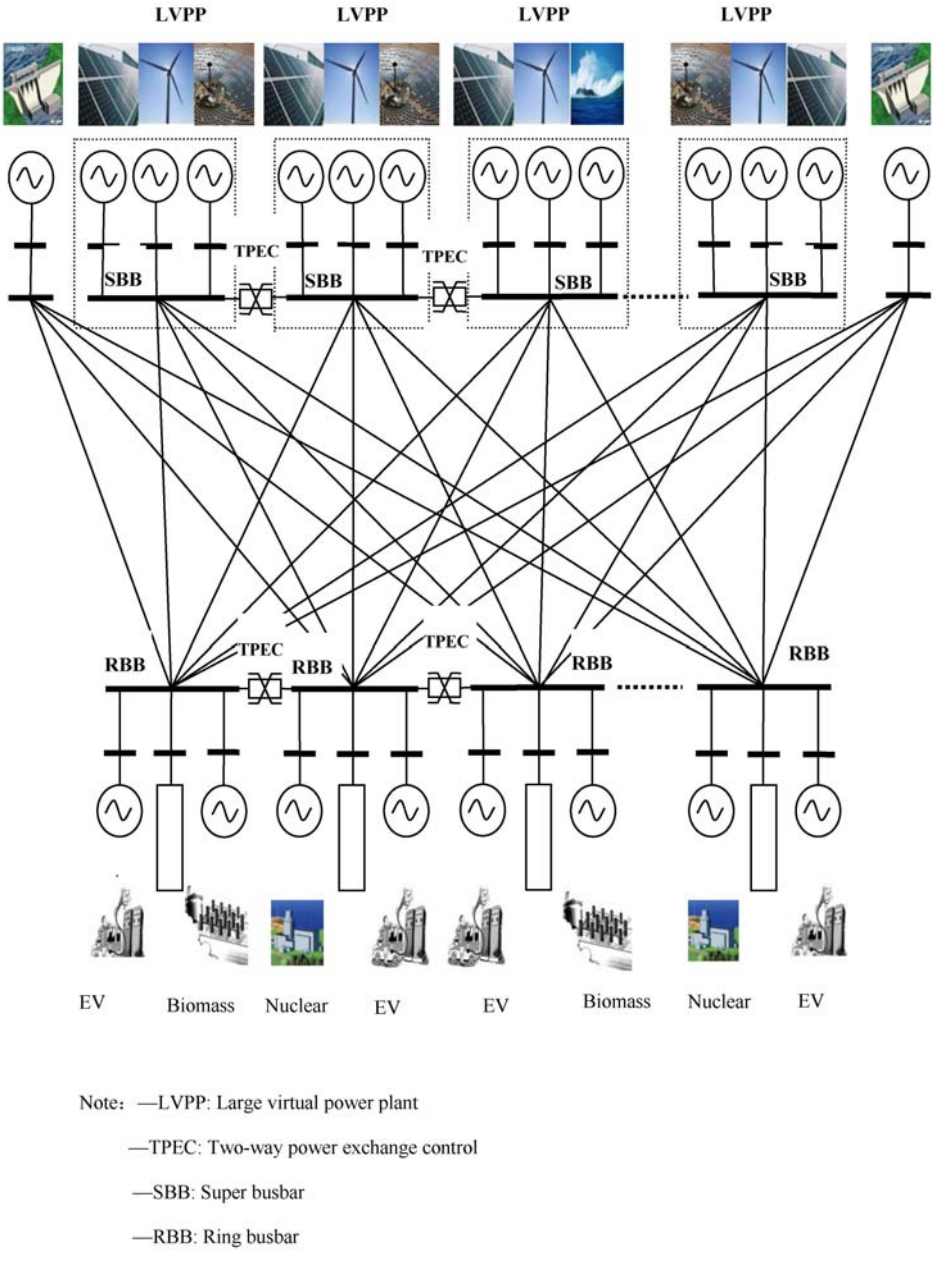
Based on the above understandings, we propose that the basic structure of the future transmission network will be more realistic and superior if the modes shown in Figure 1 are used.

First, we make full use of the complementarities of various centralized power plants (solar photovoltaic power, solar thermal power, wind power and ocean energy power generation, *etc.*) in a given region and link these plants together using the "super busbar" (referred as SBB, which can be achieved by using superconducting power cable) through a unified coordination and control technology so as to package them into a large virtual power plant (LVPP). For instance in China, we can build many LVPPs via different combinations in the areas of Xinjiang Province, Gansu Province, western and eastern Inner Mongolia, northeast of China and coastal areas relying on a variety of resources and power generation modes. The purpose of the portfolio is to make the power output of LVPP smoother, predictable and controllable to some extent compared to one single power plant. Then the electricity can be transported from SBB to the consumer by the high-voltage transmission.

Secondly, here the receiving end refers to a load center (such as Bohai Sea area, Yangtze River Delta area, *etc.*) or a power supply area (such as Hunan Province or central China, Chongqing city or Sichuan Province, *etc.*). The receiving end can receive power from multiple LVPPs, which is

connected to the ring busbar (RBB) of the receiving end. As the LVPPs located in different regions also have good resource complementarities, the receiving end can obtain relatively stable and reliable electricity via the RBB. The biomass power generation, nuclear power and electric vehicle charging stations can be accessed to the RBB of the receiving end according to the local conditions to regulate the power. Thus, each user within the receiving end can be supplied with relatively stable and reliable electricity from the RBB. Thirdly, we can increase the connection line and install the two-way power exchange control device (TPEC) among the SBBs of each LVPP and the RBBs of each receiving end, by this way, not only the power sources of each receiving end are effectively interconnected, but it can be connected together with a number of LVPPs to build a "wide-area super virtual power plants" (WASVPP) [2].

Figure 1. Basic structure of the transmission network in the future.



With the above transmission modes, the consumers may access stable and reliable supplies of electricity from the "cloud powering" generated by WASVPP (and the distributed power system as discussed below), rather than from one or several central plants, which just like the users in the Internet can access Cloud Computing. In this case, even if a few lines are removed because of failures, there will be no large scale blackouts. Fourthly, it can be connected to the transnational power grid via SBB of LVPPs or RBB of the receiving ends, thereby making it possible to balance the power of the system using the complementarity of resources within a wider context and to achieve international energy trade.

The features mentioned above are just the basic architectural structure of the transmission network in the future. For a specific transmission network, it can be reasonably designed and built based on this basic mode according to the distribution of power and load.

3.2. Operation Mode of the Future Power Grid—DC-Dominated Mode

3.2.1. The Future Transmission Power Grid—A DC-Dominant Grid

The current transmission system dominated by the alternating current (AC) has prominent stability problems. Power system stability refers the overall attributes of the power, network and load. There are many reasons that result in power system stability problems, among which imbalance of instantaneous power is a very important factor. With the continuous expansion of the modern transmission network, the dangers of large scale power blackouts caused by the accidents are increasing [10]. The collapse of the large power grids and large scale blackouts caused by the great disturbances has caused great losses of production and services. The stability issue has become a constraint bottleneck in the development of modern power systems. In the future, the capacity and scale of the transmission network will be further expanded, but renewable-energy-based power, especially wind energy, has intermittent and instability characteristics, which bring enormous challenges to the large power system dominated by AC. In response to this challenge, therefore, the dominant operation mode of the future transmission network also needs new ideas.

As we all know, compared with the AC transmission, DC transmission has many advantages, mainly as follows: (1) DC transmission is not subject to the stability problem that is inherent for AC transmission, and its transmission distance and power are not restricted by the synchronous operation of the power system; (2) There is no capacitance current, no reactance drop when the DC line is operated in a steady-state, and the voltage distribution along the line is relatively stable, and no reactive compensation is needed; (3) It is easier and quick to regulate and control the power and current of DC transmission lines; (4) When transporting the same power, the DC lines are low cost, relatively simple in the tower structure of overhead lines, and compact in corridors, and the cable with the same insulation level can be run at a higher voltage; (5) It is not required to run synchronously for the AC system that is linked by DC transmission lines so as to achieve the asynchronous connection between different AC systems; (6) In addition, the DC transmission also has low line loss and small disturbance of the communication. Therefore, DC transmission has been receiving more and more widespread attention, and has been applied in many areas in the power system.

The power transmitted in the future transmission system will be much higher than that of the modern power grid, then the DC transmission can not only improve the transmission capacity, but also

avoid the stability problem caused by the AC transmission, and thus help to improve safety and reliability of power transmission network. With the continuous technology improvement, cost reduction and reliability increase of the power electronics with high-voltage and high-power as well as the increase of availability of converter stations, the DC transmission technology will play a more important role in future grid. Presently, the R&D of high voltage direct current (HVDC) circuit breaker, multi-terminal HVDC systems and its operation and control have been receiving increasingly widespread attention. It is foreseeable that constructing the future DC-driven transmission network using the DC transmission will be a very reasonable choice.

3.2.2. The Future Distribution Network—A DC-Dominant Network

At present, the structure of load in the power grid is approximately as follows: motors account for 65%, lighting about 15%, information devices about 10% and others (mainly electrochemical, electrolytic plating and heating equipment) 10%. Of these loads, the information devices, electrochemical, electrolytic plating, and a small number of light sources need DC power, but due to the fact that the current distribution system is the AC network, we often use rectification to obtain DC power. With the significant adjustment of energy structure and the continuous development of information technology and new materials technology, the demands of loads to the power will also change dramatically in the future grid, and DC systems with more and more requirements will be present. First of all, electric vehicles will become one of the main loads in the future. As mentioned earlier, the charging load of electric vehicles in China will reach about 500 million kilowatts by 2050, and the charging load of electric vehicles is DC power; Second, with the continuous development and penetration of information technology, information devices (such as computers and microprocessors, communications equipment, intelligent terminals, sensors and sensor networks, *etc*.) will consume more power, and this equipment also needs DC power; Third, with the growing development of semiconductor lighting technology, it can be predicted that lighting systems in the future will all use LED lighting that is also a DC load; Fourth, the prices of power electronic devices are getting lower and lower, and motors in the future will be driven more and more by a variety of power electronic converters. Currently, the power electronic devices used to drive motors generally use AC-DC-AC power conversion mode, which first converts the AC to DC, and then converts the DC into AC with variable frequency and amplitude to drive motors, thereby to gain better drive performance and higher operation efficiency of the motor systems. It can be seen that the DC power supply can not only eliminate the conversion from AC to DC and reduce the cost of the motor drive systems, but further improve the overall efficiency of the motor drive system. Using DC power, the braking energy of motor systems can directly be feed-backed to the DC power grid without any transformation, which can greatly save power. In addition, when the motor system is driven by DC power, what the motors get from and feedback to the DC power grid is only active power, instead of occurring additional reactive power when supplied by AC power. This can further reduce the network losses and improve the power supply efficiency. Therefore, the motor load in the future will also be put more and more demands on the DC power supply.

It can be seen that the DC power will account for an increasing proportion in the future distribution network. In particular, the DC load will take a dominant role in office areas, residential areas and schools, and other non-industrial load areas. It becomes an inevitable requirement to develop the

DC power distribution technology with the changes of load demand on the power. Therefore, the future distribution system will develop gradually towards a DC-based network.

3.2.3. Distributed Power System—DC Mode has Significant Advantages

Renewable energy is one kind of distributed resource, and using this dispersed resource locally will be one of the important features of future energy systems. Therefore, the end user would not only get power from the "Cloud Powering", but produce electricity to meet their own needs, and sell the power back to the grid when the power production is more than what they need or when the grid has the demand. In the future the electricity network of the end users will be the distributed power system that highly mixes its own distribution network with distributed power generation. The distributed power systems will have even broader applications among non-industrial users due to their rather lower demand on the power.

In a distributed power network, solar photovoltaic power generation will be one of the most common applications, and the electricity from the photovoltaic power generation is DC. Meanwhile, it will be an inevitable choice to apply the distributed energy storage system in order to greatly improve the reliability of power supply and power quality, and most of the energy storage systems need DC power for electricity storage. Considering that the future distribution network tends to develop towards the direction of DC-based system and the proportion of non-industrial consumers using the DC power will reach a very high level, it becomes obvious to apply the DC mode in the distributed power systems. In summary, we believe that the transmission system, distribution network and distributed power system will gradually develop with the DC-based operation mode.

4. Summary

The new energy revolution, characterized by renewable energy-based primary energy and electric power-based terminal energy needs the development of a corresponding power grid. Based on the characteristics of future energy resources, the stability problem of AC network and the future users' demands on DC power, we propose that the DC-based transmission and distribution network and distributed power system should be developed in the future. The complementarities of energy resources should be made full use in the wide area in order to solve the energy supply problems caused by the intermittent and unstable renewable energy resources. A "wide-area super virtual power plants" (WASVPP) should be built through the MP-MC (multiple powers to multiple consumers)-dominated transmission mode and the two-way power exchange control (TPEC) equipment. The WASVPP covers all the major power plants in a wide range and allows the consumers to get stable and reliable supply of electricity from the "cloud powering" created by it and the distributed power system which is connected to the grid.

It is proposed that the survey and assessment of spatial and temporal distributions of energy resources and evolution of load distribution in the coming decades should be carried out according to the circumstances of different countries and area, and then the researches on the evolution and road map of the current grid to future grid should be conducted, and the way should be paved for the key technology innovation and system and mechanism innovation to lay a solid foundation for meeting the major changes on the future energy and power grid.

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