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Technology Trends and Development Recommendations for High-Efficiency Wind Power Utilization in China

Shi Wenhui[1], Baihong[1], Qu Jixian[1], Wang Weisheng[1], Huang Qili[2]

1. State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems (China Electric Power Research Institute), Beijing 100192, China
2. State Grid Corporation of China, Beijing 100031, China

Abstract: The development of wind power in China has obtained remarkable achievements during the past several years. Today, the installation scale and generation capacity of wind power in China are only slightly less than those of coal power and hydropower. Wind power has been changing from a supplementary power source to an alternative power source, and it is expected to play a leading role in energy development in the future. To achieve a high proportion of renewable energy use and to promote sustainable development of wind power, this study focused on improving wind power utilization efficiency in China and analyzed the current situation and problems with wind power utilization in China. From the aspects of clustering control and optimal dispatch of large-scale wind power, comprehensive wind power utilization, complementary multi-energy utilization, and distributed integration and control, this paper proposes the trends in technology development of wind power in China and provides recommendations for wind power and large energy power system development. Market mechanism establishment, industry management, and technical standard formulation are proposed.
Keywords: efficient wind power utilization; optimal dispatch and control; complementary multi-energy system; comprehensive wind power utilization; distributed integration and control

1 Introduction

During recent years, wind power has undergone rapid development in China [1,2], and its installed capacity has increased. Up to 2017, the cumulative installed capacity of wind power was the highest in the world for 8 years; the cumulative capacity reached 1.64×10^8 kW, which was an increase of 30 times from 2007. During 2017, the wind power on-grid electricity quantity reached 3.057×10^{11} kWh, which accounted for 4.8% of the total amount generated [3]. Wind power has become the third largest power source in China. The development and utilization of wind energy are important issues for China's energy transformation, and are an important means to address climate change.

The power structure of an area with excellent wind resources is usually dominated by thermal power. Restricted by the local load level and peak-load regulation capability of conventional generators [4], wind power accommodation space is limited. With the rapid development of wind power, an accommodation problem has appeared. During 2011, wind power curtailment in Gansu Province reached 1.04×10^9 kWh, and the curtailment rate was 17.1% [5], which attracted wide attention. Thereafter, China's government introduced a series of policies and measures to promote the efficient accommodation of wind power, and its curtailment was reduced. During 2017, the total wind power curtailment was 4.19×10^{10} kWh and the rate was 12%, which was a reduction of 5% compared to that of 2016. Nevertheless, the accommodation problem is still among the important factors that restrict the sustainable and sound development of China's wind power industry.

The government of China has promised that the proportion of

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Corresponding author: Shi Wenhui, State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems (China Electric Power Research Institute), Senior Engineer. Major research fields include wind power generation and photovoltaic power generation integration on power grid technology. E-mail: whshi@epri.sgcc.com.cn
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non-fossil energy consumption to primary energy consumption during 2020 and 2030 will reach 15% and 20%, respectively. The *13th Five-Year Plan for Wind Power Development* released by the National Energy Administration in November of 2016 noted that by the end of 2020 [6], the cumulative installed capacity of wind power will reach more than 2.1×10^8 kW, and the annual generation will reach 420 billion kWh, thereby accounting for 6% of the total power generation of the country. In addition, according to the *China Wind Roadmap 2050* issued by the China National Renewable Energy Centre, the installed capacity of wind power during 2050 will reach 1×10^9 kW, thereby satisfying 17% of the country's demand. In the future, China's wind power industry will continue to develop at a relatively rapid rate. Because of the fluctuation in wind energy resources, weak support for the power grid, and the low disturbance resistance of its generation equipment, the highly efficient use of wind power and the safe and stable operation of power systems will face greater challenges with an increasing proportion of wind power in the future power system.

To promote and ensure the sustainable and sound development of the wind power industry in China, realize the high-proportion wind power development goals in the future, and ensure that wind power becomes an important renewable energy that is useful for energy structure adjustment and addressing climate change, it is important to study the problems of high-efficiency wind power utilization.

2 Current technology and existing problems in wind power utilization

To promote the high-efficiency utilization of wind power, during the past several years China has implemented many measures, and certain achievements have been made. However, some problems from the aspects of wind power integration and operation, multiple uses of wind power, multi-energy complementation, and distribution, among others, remain.

2.1 Wind power integration

In terms of wind power forecasting, domestic universities and research institutes have conducted extensive research. Considering the development status and characteristics of wind power in China, a relatively complete wind power forecasting system was established considering multiple time scales, such as ultra-short-term, short-term, medium-term, and long-term. The forecasting model includes a statistical method based on multiple data sources [7], a physical method based on micro-scale meteorology, and computational fluid dynamics [8]. An adaptively dynamic forecasting method [9] that can make full use of fragmented multivariate historical data and adaptively choose the optimal mode under multi-sample space by considering local climatic characteristics was implemented. As a result, the accuracy and universality of forecasting were effectively improved. Currently, China has independently developed a wind power forecasting system on both the grid side and the wind power station side, which have been applied by most provinces with wind power integration. However, in complex terrain, extreme weather, and offshore wind power forecasting, power forecasting is also based on deterministic prediction. Thus, the prediction technology and method need to be improved.

In terms of wind power clustering control, an integrated reactive power control system was developed to target the voltage stability of points of common connection. The active coordinated control system of wind farms was developed and successfully applied on the Gansu power grid, which is of great significance in improving the management and control level as well as the utilization efficiency of wind power for the system dispatching centers of the area. Based on IEC 61850, China's research institutes have conducted research on integrated wind farm monitoring technology inside IEC 61400-25. Based on mature substation automation platform system technology, an integrated wind farm monitoring platform system with high extensibility was developed. Overall, China has conducted some research on wind power stations' active and reactive power control technology, and has developed a control system that has been applied. Research on active power control is mainly concentrated on a control strategy and control method evaluation. However, there is limited research on large-scale wind power station adaptive frequency modulation control under multiple conditions and active power hierarchical control technology for large-scale wind power stations based on multi-source data interaction. Research on reactive power control mainly concentrates on the wind turbine's control strategy, the optimal reactive power location, and the wind farm's local control strategy. The developed application system has problems in that the different wind power manufacturer's interface is not identical and the on-line control and response is coincident. In addition, the performance of the wind farm/clustering that initially supports the grid operation and control needs to be improved.

In terms of optimal dispatching of wind power, the most commonly used scheduling models and methods include the following: an optimal scheduling method considering the AGC reserve, one considering the spinning reserve capacity with wind power integration, and one based on stochastic renewable energy constrained by risk probability [10,11]. An optimal dispatching support system for renewable energy has been developed and applied to 23 provincial (regional) power-dispatching control centers in China. However, it is still necessary to strengthen the dispatching and operational technology to meet the needs of large-scale wind power integration, the power market, and ancillary service technology to promote wind power accommodation.

Compared to onshore wind power, research on offshore wind power has been delayed. Research on the influence of offshore wind power integration, HVDC transmission, and remote clustering control remain in the primary stage, and the relevant technical standards and codes remain in formulation.

2.2 Multiple uses of wind power

In terms of hydrogen production via wind power, many foreign countries have invested considerable funds in research and related demonstration projects. For example, research on the Wind2H2 project conducted by the US Department of Energy includes renewable energy power control, hydrogen energy storage technology, an optimal capacity configuration of a wind-hydrogen system, power allocation for on-grid wind power and hydrogen production via electrolysis, economic and benefit analysis, and the influence of electrolysis technology on a wind-hydrogen system and its large scale and industrialization. In China, research on key technologies remains at the initial stage. A wind hydrogen coupling system and the feasibility of offshore wind hydrogen have been studied, and a few demonstration projects have been established. Wind-generated hydrogen provides a possible means for the comprehensive utilization of wind power. The influence of wind fluctuation on the hydrogen system, clustering control, and optimal operation of the wind-hydrogen coupling system and hydrogen storage technology must be overcome [12]. In addition, the economic benefit should be continually analyzed.

In terms of wind power heating, some small-scale demonstration projects have been established by several wind development enterprises in China; if its theory is to be fulfilled, then the main technical obstacles are the optimal dispatching of heat and electricity. The existing operation mode mostly adopts a binding settlement mode without considering its coordinated optimization and scheduling control. Wang [13] proposed a real-time operation measure that considers the coordination of heat storage and curtailment. It was based on historical operation and curtailment data, and optimal electric heating power and storage capacity could be obtained. Dispatching centers can obtain a day-ahead and real-time curtailment curve as well as a scheduling wind and heat storage output based on the wind power forecasting and real-time power system operational state. During settlement, using real-time recording curtailment and heat storage data ensured that the heating storage was supplied by wind curtailment. A pilot project was established for coordination optimization and a scheduling strategy for wind curtailment heating.

In terms of a heat-electricity operation monitoring system considering wind accommodation, some software has been applied, such as the on-line real-time monitoring system for heating units in the Jilin power grid and the adjustable output monitoring system for heating units in the Jiangsu power grid. However, its development and application remains in the initial stage, and most of the monitoring remains in the research and validation stage.

2.3 Complementary multi-energy utilization

Considering different resource conditions and energy consumption objectives, multi-energy complementarity can alleviate the contradiction of energy supply and demand by supplementing different energy types. It is helpful for protecting and utilizing natural resources and can achieve better environment benefits [14,15]. Different power sources, such as wind, water, gas, thermal, and storage, are complementary in a different time and space. The *13th Five-Year Plan for Electric Power Development* notes that multi-energy complementarity is an important measure for improving wind power accommodation, which mainly includes two modes, namely small-scale and system-level multi-energy complementarity.

At present, wind-water and wind-solar complementarity is the most commonly used means for small-scale hybrid systems in China. The existing system includes a village-level wind-solar hybrid generation station and a wind-solar hybrid generation station for meteorological stations. The energy and power supply in remote areas can be satisfied by these systems.

In terms of system-level multi-energy complementarity, several works have been completed. For example, a power system flexibility index was proposed based on system reliability and equipment control capability [16]. A multi-point distribution planning method concentrating on wind-solar complementarity was proposed based on deterministic planning criteria [17], in which the reliability and economy of hybrid operation of wind and other power sources were analyzed. In addition, some projects for multi-complementarity of wind-solar-storage-transmission were conducted. However, use of the power system flexibility analysis method in considering the complex performance of various power sources is still lacking. Power system scheduling and control did not fully consider the global optimization and real-time control of a multi-power supply of different time scales. The existing control system cannot fully use the dynamic peak load regulation capability to realize the maximal renewable energy accommodation.

2.4 Distribution development and utilization

Distribution development and utilization is another means in addition to large-scale centralized wind power development and long-distance transmission. It is usually near consumption users and integrated into a 35 kV power grid or less, and is dominated by local accommodation, multi-point integration, and unified monitoring. It is in the demonstration stage in China. Although demonstration projects have been established, most of them follow the experience of centralized wind farms or do not fully consider the accommodation capability of a local grid, thereby resulting in a large investment and deteriorating power quality.

The main technologies suitable for distributed wind power utilization include wind resource assessment, optimization planning, wind power forecasting, and related information collection and monitoring. Regarding resource assessment, because the distributed wind power is near the consumption user, the impact of shading objectives should be considered at the same time because it is a dispersive distribution and a wind tower cannot be installed at every wind site. It can provide a firm support for distributed development during the early planning stage based on analyzing the inherent operational characteristics of the distributed wind power and studying the resource assessment method considering long-distance wind tower data and satellite meteorological data. Regarding wind power forecasting, most research has focused on large-scale centralized wind forecasting. Further research on distributed wind power forecasting and its forecasting accuracy needs to be conducted. In addition, there are few research studies on grid integration planning technology, information collection, and monitoring technology for wind power distribution development in China [18].

A micro-grid is among the effective forms of distributed wind power application. During recent years, several distributed micro-grid systems sourced by wind power or multi-energy complementarity have been established in China. For example, a distributed smart micro-grid demonstration project based on large wind turbines, namely the Jiangsu Dafeng commercial park distribution project, provides 37% of the power supply for the park. The Zhoushan East Fushan Island micro-grid systems sourced by wind, solar, storage, and diesel generators supply nearly all the renewable energy for the island. Today, the power quality of the independent power supply system can meet the requirements of international standards under different operational modes, thereby providing a new means for power supply in remote areas.

3 Future trends in high-efficiency wind power utilization in China

Developing renewable energy is the only means to construct China's clean, low-carbon, safe, and efficient energy system. To support large-scale development and highly efficient utilization of wind power in the future, several technologies should be improved, namely large-scale wind power integration and operation, multi-energy complementation and distribution development under market mechanisms, and comprehensive utilization of wind power. In addition, in accordance with the Internet Plus trend, a study on wind power operational management technology is needed, as well as a related platform based on big data technology.

3.1 Safe and reliable operation of large-scale wind power integration

3.1.1 Large-scale wind power clustering control and optimal scheduling technology

The reverse distribution of wind energy resources and load centers in China means that long-distance transmission for wind power in China is needed. Large-scale wind power clustering control technology will be developed toward intellectualization and automation. By establishing a clustering control supporting system, initiation of hierarchical control of large renewable stations based on multi-source data interaction can be achieved, as well as intellectualization and automation, thereby further improving the operation and control level of a large-scale wind power base. Via the development of wind power initiative support and coordinated control technology, the integration of wind power from passive adaptation to initiative support can be realized.

Wind power forecasting is the basis for its optimal dispatch; thus, its probability prediction and error evaluation system needs to be improved. A numerical meteorological forecasting model and resource assessment software suitable for the climate and terrain characteristics of China will be established, and a new forecasting method based on multi time-step and multiple spaces as well as multi-prediction objects will be developed; thus, the resolution and accuracy of the resource assessment and power forecasting will be further enhanced. The optimal dispatching of wind power will be toward uncertain scheduling, online risk warning, and initiative defense. An optimized dispatching system suitable for various energy applications based on power market mechanisms will be established via optimization of power storage types such as wind power, electrochemistry, pumped storage, heat storage, and oil and gas, and via combination of operation and dispatching technology and key technologies on UHV cross-regional dispatching and operation of wind power bases. Then, the accommodation of wind power can be maximized, wind power utilization efficiency can be improved, and the total operation cost can be reduced.

3.1.2 Large-scale offshore wind power integration technology

The simultaneous development of onshore and offshore wind power is a definite trend in China. With the increase in future offshore wind power, the problem of integration will gradually appear, and it will become the focus of future research. DC clustering and integration technology will be among the main choices for future offshore wind power integration because of its unique technical superiority.

Through research on the key technologies of offshore wind power planning, resource assessment, and power forecasting suitable for the large offshore wind power base clustering and integration's DC grid topology optimization, operation and control, and fault protection, an operation and control and protection system for integrating large-scale offshore wind power into the DC power grid can be established. The bottleneck of the AC/DC hybrid power grid interface technology can be overcome, and the integration and efficient utilization of large-scale offshore wind power can be promoted.

3.2 Comprehensive high-efficiency and low-cost utilization

3.2.1 Economic and efficient wind hydrogen technology

In the future, with the decreasing cost of hydrogen storage materials and progress in large-scale hydrogen storage technology, long-distance storage and transmission of hydrogen is expected to be realized and the wind hydrogen cost is expected to increasingly decrease, thereby making it possible to industrialize.

Through research on the coordinated control technology of a hydrogen storage system of high voltage and high power, a hydrogen storage system integrating mechanism, a jointly optimal operation control and scheduling system of wind and hydrogen storage, and an energy management strategy and coordinated optimization control strategy used for wind power integration, the difficulty of wind hydrogen technology can be alleviated, and wind power hydrogen can become an important direction in wind power development and utilization to realize large-scale application. In addition, wind power accommodation can be enhanced.

3.2.2 Wind heating technology under a market mechanism

The key issues in the development of wind heating are to realize the coordinated operational strategy and control technology of heat and electricity through full consideration of the structure, operational characteristics, integrated design principles and optimization methods, and optimization configurations and operational mechanisms of large-capacity heat storage units to maximize the peak load regulation capability of urban heating systems and overcome the bottleneck of the combined operational strategy and control technology of wind heating systems. In turn, large-scale development of wind power can be promoted and wind power utilization efficiency can be improved.

3.3 Multi-energy complementarity technology under energy interconnection

Under a background of future energy interconnection, multi-energy complementarity technology provides a reasonable means for wind power efficiency utilization. Making full use of the complementary characteristics of different energy resources under different temporal and spatial criteria and establishing its coordinated planning and coordinated optimization scheduling and control system, a multi-energy complementarity system can be realized.

Through the analysis of different operational characteristics of different complementary modes, such as wind and solar, wind and water, wind and thermal, and micro-grid complementarity, research on the utilization mode and optimization planning technology of multi-energy complementarity technology, including distributed wind power, was conducted. By taking full consideration of the reverse distribution of China's resource centers and load centers, as well as the energy structure, and by studying the architectural configuration technology and energy management and control technology of the multi-energy complementarity system, the system peak regulating capability can be maximized and dynamic optimal generation groups of the multi-energy complementarity system can be realized. Finally, the system operation cost can be reduced and the efficiency of the whole energy system can be improved.

3.4 Distributed integration and control technology

Ordered integration, coordinated control, and optimal energy management are the key issues for the future utilization of distributed wind power. Through research on distributed generation, centralized monitoring, operation control technology, energy management technology of virtual power plants based on regional distributed generation and the cluster coordination control technology of a multi-micro grid, the future distributed power supply and micro-grid will develop toward plug and play, highly efficient operation, and flexible interaction.

Studying the centralized monitoring and control technology of distributed generation, the corresponding centralized monitoring platform and operational management system were established, as well as stable communication between the distributed generation and the monitoring center. On the basis of remote monitoring of distributed generation, through the technologies of bidirectional adaptive protection and the control technology of multi-distributed generation integration, rapid reconstruction technology of a power supply network based on multi-distributed generation/storage and micro-grids, coordinated control and intelligent scheduling technology based on multi-energy type generation, and clustering control technology and multi-user interaction technology of distributed generation and micro-energy networks, safe integration and micro-grid control of multi-distributed generation and flexible and efficient utilization of distributed energy can be realized, thereby finally supporting the development of distributed energy.

3.5 Wind power-supporting technology based on big data

In the future, with the rapid development of cloud computing, Internet plus, and Internet of Things, attracting increasing attention from society, the wind power industry should be accorded with the future trend and take full advantage of the rapid growth in data in the design, operation, and scheduling of wind farms. A complete wind power big data structure including meteorological influence, wind turbine types, wind farm operation, dispatching, and other information can be established.

Based on big data technology and through the establishment of a wind power accommodation support platform, an analysis platform of wind energy resource assessment and wind power forecasting, an analysis platform of wind power influence on environmental ecology, and an operation and maintenance management platform, it can be shared with the whole of society in wind power development and operational information resources, provide the services of a large wind farm data online assessment, and display a real-time wind power accommodation curve and detailed statistics of wind curtailment so as to optimize the operation of wind power and promote energy marketization reform and the safe, reliable, and efficient operation of a high proportion of wind power.

4 Recommendations

To realize high-efficiency wind power utilization, other than technological improvements, coordinated planning with other energies, related encouragement of policies, power markets for accommodation, and standards and codes need to be fulfilled step by step. Four recommendations are put forward as follows:

4.1 Promote the win-win development of wind power and a large energy power system

Coordinated development on the generation side should be concentrated on by developing a large centralized wind power base while simultaneously focusing on the distributed wind power. With the increasing generation of wind power speed, the power source structure adjustment and development of storage energy technology should be increased. Power consumption industry planning should consider the energy distribution characteristics. To support the aforementioned works, attention should be paid to the coordinated planning of the energy industry to strengthen regional energy planning, coordinate the unified and coordinated planning of renewable energies and conventional energies, and realize the coordinated development of power generation and the power grid.

4.2 Establish an incentive policy system for the coordinated development of renewable energy

Establishing an incentive policy system covering generation, integration, and consumption is key. On the generation side, enhancing the peak load regulation capability of conventional generators and accelerating the perfection of thermal unit flexibility reconstruction and its peak load compensation policy are important. On the power grid side, on the basis of breaking through the large-scale wind farm clustering control ability and accelerating the construction of provincial transmission lines, the accommodation scope will be enlarged and the power distribution and balance capability of a large power grid can be realized. On the consumption side, by promoting electric power substitution while encouraging distributed development, users can be guided to participate in peak load regulation and frequency modulation and initiatively respond to renewable energy output changes, thereby improving the electricity price policy to encourage users to purchase renewable energy.

4.3 Accelerate the establishment of a market mechanism for renewable energy accommodation

Reinforcing the priority accommodation of renewable energy is important. Within a province, priority scheduling of renewable energy should be implemented, the provincial accommodation barriers should be overcome, and provincial ancillary services should be implemented. The construction of a unified national power market should be accelerated. A trading system dominated by medium- and long-term transactions and supplemented by temporary transactions should be established. A provincial and regional spot market should be started. Users' choice of purchasing renewable energy across provinces or across regions should be encouraged. The improvement of market rules and renewable energy trading mechanisms should be accelerated. A compensation mechanism for renewable energy imports and exports should be established. Users should be encouraged to participate in demand-side response and market transactions. The time-of-use tariff mechanism should be improved. Renewable tariffs should be separated from government subsidies: electricity tariffs should be priced through the market, and subsidies should be priced by the government.

4.4 Improve the management and technical standard system of the wind power industry

A unified management system for the development of wind power should be established by making full use of all national resources to conduct the design of a wind power development strategy and planning and supporting policies. A comprehensive coordination mechanism to coordinate different departments of the power grid, power generation, meteorological and technological research and development, standards, equipment manufacturing, etc., can help to coordinate the allocation of funds and technical forces, as well as be responsible for the organization and implementation of important projects. Then, a favorable environment for the development of wind power can be created.

Wind power standards should be improved using a testing and certification system. First, standards should be continuously improved as well as the testing and certification systems for wind turbines and wind farms. Second, current IEC standards should be revised to conform to China's wind resources and environmental conditions. At the same time, with the diversification of wind power utilization, the corresponding standards need to be updated and matched in time. The corresponding guidelines should be formulated as complementary to the implementation of standards and provide detailed implementation methods for wind power equipment research, development, and testing. Finally, a testing and validation system in accordance with international standards should be established, the necessary infrastructure construction should be completed, and mandatory testing and validation of the wind power equipment and its main parts should be gradually conducted.

5 Conclusions

This paper presented the current situation and obstacles of wind power utilization in China, and put forward some key technologies for high-efficiency wind power utilization in the future, namely clustering control and optimal scheduling for large-scale wind power integration, large-scale offshore wind power integration, comprehensive wind power utilization, multi-energy complementarity technology under energy interconnection, and distributed integration with flexible control strategy, among others. Finally, related recommendations to promote high-efficiency utilization were proposed, such as the coordinated development of wind power with a large energy power system, power market establishment, industry management, and technical standard formulation.

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