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Prospect and key techniques of Global Energy Interconnection Zhangjiakou Innovation Demonstration Zone

Bo Tian [1], Xiaolin Mo [1], Yu Shen [1], Weimin Lei [1], Pengliang Xu [1]
1. State Grid Jibei Electric Power Co.Ltd., Beijing 100054, China

Abstract: In the Background of implementing innovation-driven development strategy and building Global Energy Interconnection, the necessity of building Global Energy Interconnection Zhangjiakou Innovation Demonstration Zone for stimulating economic growth, promoting social development and supporting 2022 Winter Olympics are discussed by analyzing the location advantages of Zhangjiakou and the characteristics of renewable energy in Zhangjiakou. Solutions are put forward in aspects of renewable energy integration in National Wind/Solar/Storage/Transmission Pilot Project, VSC-HVDC transmission of renewable energy and demonstration utilization of renewable energy in the Olympics zone, which could be a reference for problems of large-scale renewable energy in secure integration, outgoing transmission and flexible consumption. And replicable experience for building Global Energy Interconnection will be provided by conducting ±500kV VSC-HVDC Power Grid Demonstration Project, Virtual Synchronous Generator Demonstration Project, Flexible Substation and AC/DC Power Distribution Network Demonstration Project, EV Battery Secondary Utilization Energy Storage Demonstration Project, Smart Grid Demonstration Project of Low Carbon Winter Olympics and other demonstration projects.

Keywords: Global Energy Interconnection, Renewable energy, Innovation demonstration, VSC-HVDC, Low Carbon Winter Olympics.

1 Introduction

With China's economic development has entered a new normal, the mode of economic growth is changing from the extensive growth of scale and speed to the intensive growth of quality efficiency, the economic structure is changing from increments expansion to stock adjustment and increments optimization, the economic growth point is changing from the traditional growth point to a new growth point represented by Internet plus, intelligent manufacturing, clean energy, these changes have gradually become the consensus of all social circles. Implement "national innovation driven development strategy", seize the new round of energy structure adjustment and energy technology change trend, study safe, clean and efficient modern energy technology, building Global Energy Interconnection[1], promote the "electricity centered" energy production and consumption revolution, achieve a green and low carbon development, formulate "China plan" to solve the global energy supply problem, these efforts have aroused widespread concern and positive response from the whole society. Global Energy Interconnection Zhangjiakou Innovation Demonstration Zone has carried out a lot of exploration in the above aspects.

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✉ Yu Shen
shen.yu@jibei.sgcc.com.cn
Wei-min Lei
lei.weimin@jibei.sgcc.com.cn
Bo Tian
tian.bo@jibei.sgcc.com.cn
Pengliang Xu
xu.pengliang@jibei.sgcc.com.cn
Xiaolin Mo
mxl81533@sina.com

2 Characteristics of energy development in Zhangjiakou

Zhangjiakou is located in the Three-North (for northwest China, north China, and northeast China) intersection, which has abundant wind energy resources(annual average wind power density>150W/m^2) and solar energy resources(annual total radiation exposure1400~1750kWh/m^2)[2]. Zhangjiakou is an important node of The Belt and Road Mongolia and Russia economic corridor, it is an important ecological conservation area in Beijing Tianjin Hebei region and one of the 10 million kilowatts level clean energy base planned by the state. By the end of 2017, the installed capacity of wind power in Zhangjiakou reaches 7373MW, and the wind power generation reaches 16.07 billion kWh, Photovoltaic installed capacity reaches 3273MW, Photovoltaic power generation reaches 2604 million kWh, compared with 2012, there are significant improvements(as shown in Fig. 1-4).

Facing the unique resource endowment and regional advantages, in July 2015, National Development and Reform Commission issued the "Hebei Zhangjiakou renewable energy demonstration zone development plan" and put forward the development goal of Zhangjiakou renewable energy development level ranked first in the world[3,4], which aims to better lead the direction of renewable energy innovation and development, promote energy revolution, promote the transformation and upgrading of underdeveloped areas in Zhangjiakou, and promote the construction of ecological civilization in Beijing-Tianjin-Hebei region.

3 Action of State Grid Corporation of China

State Grid Corporation of China (SGCC) responds the national appeal, organizing the expert team to analyze carefully of the characteristics of renewable energy in Zhangjiakou. Starting from the three core elements of construction the Global Energy Interconnection: smart grid + EHV + clear energy. The technical feasibility of large-scale development of renewable energy is discussed in depth, and the plan of "overall planning, demonstration pioneering, standard construction and joint promotion" is finally determined. Through strengthening the integrated design of power grid in the demonstration area, strengthening integration innovation, building demonstration project. In the end, the typical models and standards of renewable energy development, integration, transmission and accommodation will be formed. The plan aims to unite the forces of society, promote the application of new technologies and models, build innovation leading standard and efficient win-win cooperation platform for the development and utilization of renewable energy, and finally service Low Carbon Olympic. State Grid Jibei Electric Power Company Limited as the power grid operator of SGCC in Northern Hebei, undertook the plan of action.

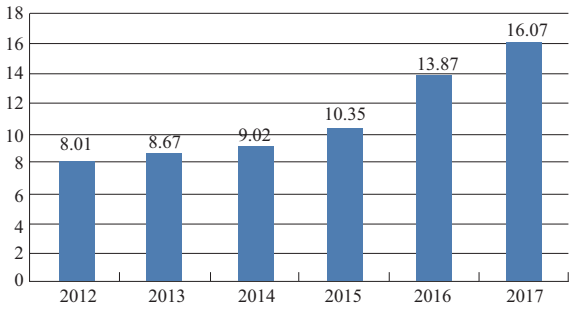

Fig. 1 Wind power generation in Zhangjiakou (billion kWh)

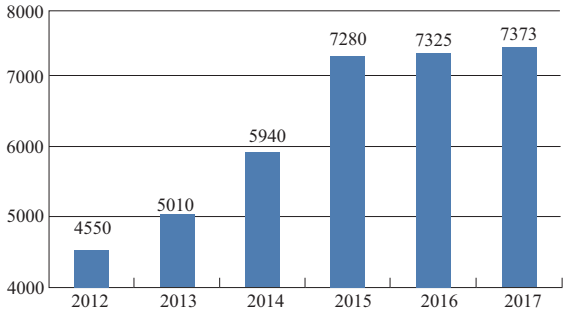

Fig. 2 Installed capacity of wind power in Zhangjiakou (MW)

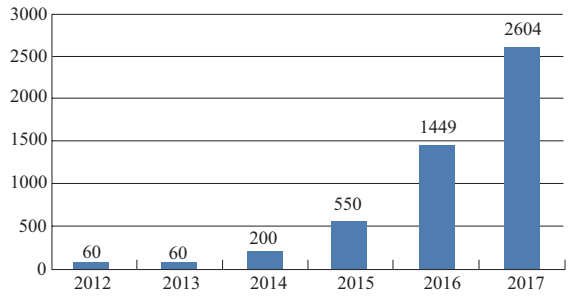

Fig. 3 Photovoltaic power generation in Zhangjiakou (million kWh)

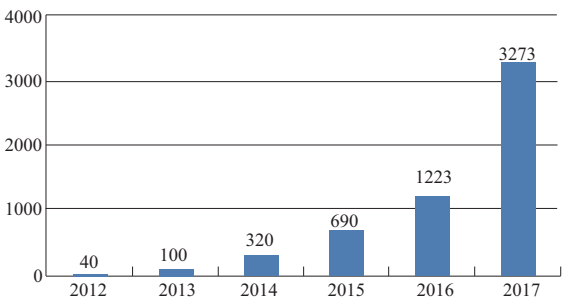

Fig. 4 Photovoltaic installed capacity in Zhangjiakou (MW)

May 2016, State Grid Jibei Electric Power Company Limited issued "white paper on the development of Global Energy Interconneetion Zhangjiakou Innovation Demonstration Zone". Meanwhile, the plan of building a Global Energy Interconnection Innovation Demonstration Zone in Zhangjiakou is determined[5]. The aim is to study and demonstrate advanced electric power production, transmission, storage, usage and operation control technology. Furthermore, a comprehensive and efficient usage of large-scale clean energy will be achieved, the popularization and application of major technologies and equipments will be promoted, innovation template construction for building the Global Energy Interconnection will be provided. Finally, realize the promise of the 2022 "Low Carbon, Green Olympics".

4 Challenges that Zhangjiakou Innovation Demonstration Zone faces

4.1 Integration security and friendliness of large-scale renewable energy should be improved

It is predicted in 2020 that renewable energy power generation capacity scale in Zhangjiakou Innovation Demonstration Zone will be up to 20 million kW and annual energy output will exceed 40 billion kWh[3]. Moreover, Zhangjiakou power grid is relatively weak and has insufficient voltage support capacity. When new energy power generation stations or local power grids take place equipment fault or abnormal fluctuation in voltage or currents, it is necessary to further study the interactive mechanism between high proportion renewable energy and power grid.

4.2 Power grid transportation ability and adaptation of large-scale renewable energy transmission should be improved

Due to the undeveloped economy in Zhangjiakou and lower local load level, it is predicted in 2020 that about 16.5 million kW installed capacity of renewable energy should be focused on transmission and accommodation. At present, a 500kV AC transmission line has been established in Zhangjiakou power grid to transmit conventional thermal power of "west-east power transmission", but it only can meet 5.5 million kW installed capacity of renewable energy transmission, thus it is urgent to apply advanced transmission technologies as EHV AC/DC and flexible DC, upgrade power grid structure, and dramatically improve renewable energy power transmission capacity of Zhangjiakou Innovation Demonstration Zone.

4.3 Elecctric energy substitution capability and energy utilization flexibility of renewable energy high-efficient accommodation should be improved

In order to safeguard ecological stability and promote green sustainable development in Zhangjiakou, it is predicted in 2020 that 55% of electricity consumption in Zhangjiakou may come from renewable energy[3], but the current electricity consumption of renewable energy in Zhangjiakou is less than 20%(about 2.5 billion kWh), showing seriously insufficient accommodation on the spot and huge difference between targeted poverty alleviation, industrial adjustment, and Low Carbon Winter Olympics, thus it is urgent to reinforce in-depth study application of smart power distribution, power utilization and information technology to promote high-efficient accommodation on the spot of renewable energy through electric power replacement and market operation.

5 Key technology and demonstration of Zhangjiakou Innovation Demonstration Zone

According to the construction thoughts of "overall planning, demonstration pioneering, standard construction and joint promotion" in Zhangjiakou Innovation Demonstration Zone, the renewable energy development and utilization cooperation platform with innovation guide, high-efficient standardization, mutual benefits and win-win results is constructed by aiming at development, integration, transmission and accommodation of renewable energy, depending on a number of major science and technology demonstration projects, and integrating with Global Energy Interconnection EHV, smart grid and renewable energy to realize the promotion and application of new energy and new mode and serve for Low Carbon Winter Olympics.

5.1 Renewable energy integration demonstration of National Wind/Solar/Storage/Transmission Pilot Project should be forged

500MW of wind electricity, 100MW of PV and 20MW of energy storage are put into operation in National Wind/Solar/Storage/Transmission Pilot Project that is located in Zhangbei County, Zhangjiakou. It is the integrated exploitation and utilization project of new energy integrating with wind power generation, PV power generation, energy storage and smart transmission. By using wind/solar complementation and energy storage adjustment, the stable and controllable power output can be realized.

During the "13th Five-year Plan", state grid electric

power in Northern Hebei Province should continue creating renewable energy development and innovation platform in National Wind/Solar/Storage/Transmission Pilot Project and focus on carrying out study and demonstration of three key technologies:

1) By studying and demonstrating advanced operation and maintenance technology in wind power plants, reliability and operation and maintenance level of wind power plant equipment can be improved. Based on the national science support plan topic "the Study and Demonstration on the Large-scale Wind Power Plants Smart Operation and Maintenance", technical study on fault prediction, intelligent trouble diagnosis and operation strategy optimization in wind turbine is conducted. The intelligent operation and maintenance system is demonstrated and applied(shown in Fig. 5), improving by 5% of operation hours in demonstration wind power plants, more than 90% of fault forecast accuracy in wind turbine, and increasing by 6% of annual energy output.

2) By studying and demonstrating the unit-style wind power, PV and power plant Virtual Synchronous Generator(shown in Fig. 6-8), P-ω droop control (as in (1)) and other methods are applied to simulate the governor of synchronous generator to realize Primary Frequency Regulation, Q-V droop control (as in (2)) and other methods are applied to simulate the exciter of synchronous generator to realize voltage regulation, integrated effects of renewable energy integration can be improved. On the one hand, based on field measurement and semi-physical simulation, the study on operation properties and control strategies from different parameters of wind power, PV and power plant Virtual Synchronous Generator is conducted. The approximate synchronous source frequency modulation and voltage regulation functions are realized in renewable energy power plants. The effective support of Virtual Synchronous Generator on the power grid also can be realized. On the other hand, under the precondition that renewable energy power plants meet basic technical conditions of integration, equipment functions and control strategies of Virtual

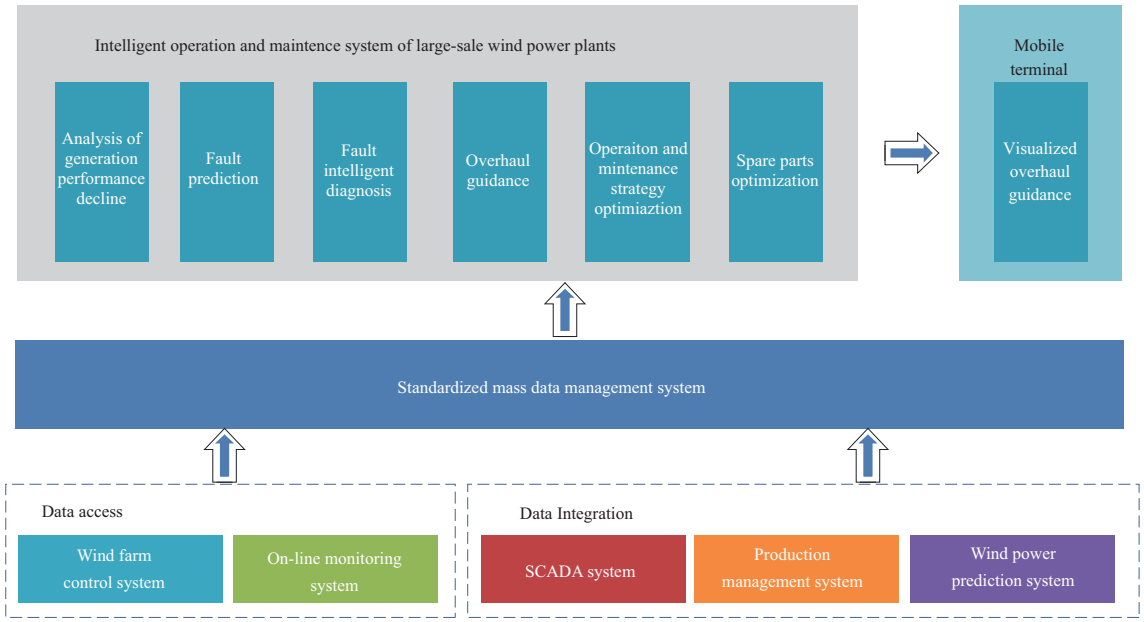

Fig. 5 Intelligent operation and maintenance system function framework of large-scale wind power plants

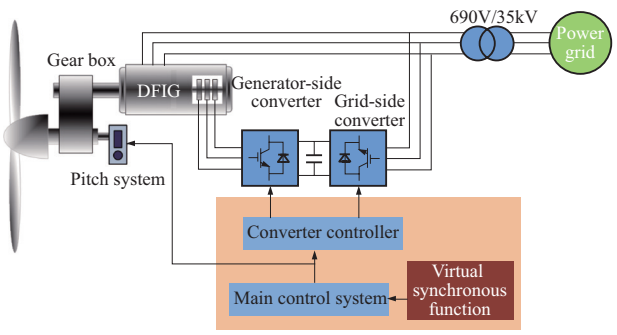

Fig. 6 VSG wind unit

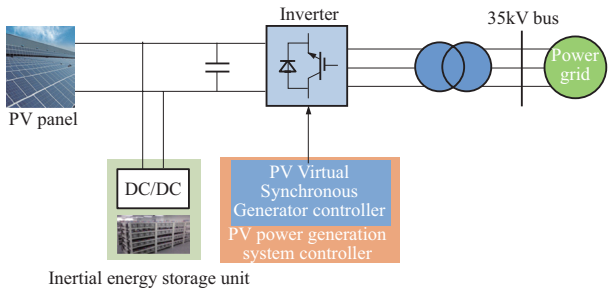

Fig. 7 VSG PV unit

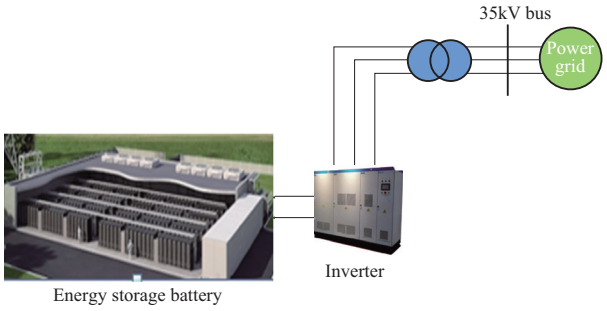

Fig. 8 VSG power plant

Synchronous Generator are optimized. Newly increased costs of virtual synchronous functions are verified in the acceptable range.

$$P_{\mathrm{m}} = P_{\mathrm{ref}} + \frac{1}{D_{\mathrm{p}}}\left(\omega_{\mathrm{ref}} - \omega\right) \tag{1}$$

$$E = E_0 - D_{\mathrm{q}}\left(Q - Q_{\mathrm{ref}}\right) \tag{2}$$

3) By studying and demonstrating large-scale power battery secondary utilization technology, reutilization economy and standardization of retired power batteries are greatly improved. The influence mechanism study of power batteries and system operation parameters on life cycle health status is emphasized, thus rapid selection and reconstruction of power batteries are realized. 10MW power battery secondary utilization and energy storage system is constructed to realize power battery secondary utilization for electricity, heat and safety management. Energy efficiency is not less than 85%. The supporting role of large-scale energy storage on safe and stable power grid operation is developed.

5.2 Demonstration of renewable energy transmission by VSC-HVDC is forged

In order to implement the national atmospheric pollution prevention action plan and serve for renewable energy development, Xiliguole League-Shandong 1000kV AC, Xiliguole League-Jiangsu ±800kV DC, Western Mongolia-Southern Tianjin 1000kV AC, Jarvd-Shandong ±800kV DC have been brought into the national planning and construction[6]. State Grid Corporation of China also speeds up construction feasibility demonstration of Xiliguole League-Zhangbei-Ganzhou 1000kV EHV AC engineering to promote large-scale renewable energy transmission and accommodation in Zhangjiakou.

Meanwhile, with the rapid development of power electronics, VSC-HVDC based on HV and HP IGBT is equipped with the better control ability and flexibility by comparing with the conventional AC/DC power transmission technique[7,8]. As in (3) and (4), U_{s} is voltage fundamental wave vector effective value of AC bus, U_{c} is output voltage fundamental wave vector effective value of converter, δ is the angle that U_{c} lagging behind U_{s}, X is iss inductance between converter and AC bus, P is active power from AC system to converter, Q is reactive power. Active power could be controled by adjusting δ, reactive power could be controled by adjusting U_{c}, realizing decoupling control[9]. Comparison between VSC-HVDC and conventional DC transmission is shown in Table 1, VSC-HVDC can provide excellent solutions for the sake of solving large-scale renewable energy integration, isolated island operation and interconnection of power grid[10].

$$P = \frac{U_{\mathrm{s}}U_{\mathrm{c}}}{X}\sin\delta \tag{3}$$

$$Q = \frac{U_{\mathrm{s}}\left(U_{\mathrm{s}} - U_{\mathrm{c}}\cos\delta\right)}{X} \tag{4}$$

Table 1 Comparison between VSC-HVDC and conventional DC transmission

	Conventional DC	VSC-HVDC
Switching characteristics	Turn-on controllable/turn-off uncontrollable	Both controllable
Commutation failure	Possible	Impossible
Harmonic	More serious	Not serious
Filter capacity	Large	Small
Reactive power compensation device	Need	Don't need
Size	Big	Small
Dependence on AC power system	Can't supply power to passive networks	Can supply power to passive networks
Control flexibility	Slow、inflexible	Fast、flexible
Active/reactive power decoupling control	Can't control reactive power	Active/reactive power decoupling control
DC network interconnection	Difficult	Easy

SGCC summarizes more than 10 years of research experience in VSC-HVDC and VSC-HVDC science and technology demonstration project construction experience in Nanhui Shanghai, Zhoushan Zhejiang and Xiamen Fujian(shown in Table 2). Zhangbei ±500kV/3000MW four-terminal VSC-HVDC demonstration project(shown in Fig. 9) is determined to be constructed by combining with the renewable energy layout in Zhangjiakou, considering enhanced voltage supporting capacity, developing wind/solar/storage complementation performance and enhancing renewable energy integration and accommodation capacity.

Two convertor stations of Zhangbei and Kangbao are used to gather local renewable energy. Fengning convertor station is connected with local pumped storage to restrain renewable energy power fluctuation. Beijing convertor station is connected to Beijing power grid to provide stable clean electric power for Beijing[11].

Table 2 VSC-HVDC constructed by SGCC

location	Shanghai, Nanhui	Zhejiang, Zhoushan	Fujian, Xiamen	Hebei, Zhangbei
Voltage level	±30kV	±200kV	±320kV	±500kV
Rated power	18MW	300MW	1000MW	3000MW
Connection mode	Two-terminal	Five-terminal	Bipolar mode two-terminal	Bipolar mode four-terminal
Power transmission line	DC cable	DC cable	DC cable	Overhead line+ DC cable
HVDC circuit breaker	Not installed	200kV HVDC circuit breaker	Not installed	500kV HVDC circuit breaker
High speed measuring device	Measurement delay 500us	Measurement delay 200us	Measurement delay 200us	Measurement delay <100us
Main uses	Wind power integration	Islanding power supply	City power supply	New energy transmission
Year put into operation	2011	2013	2015	2019

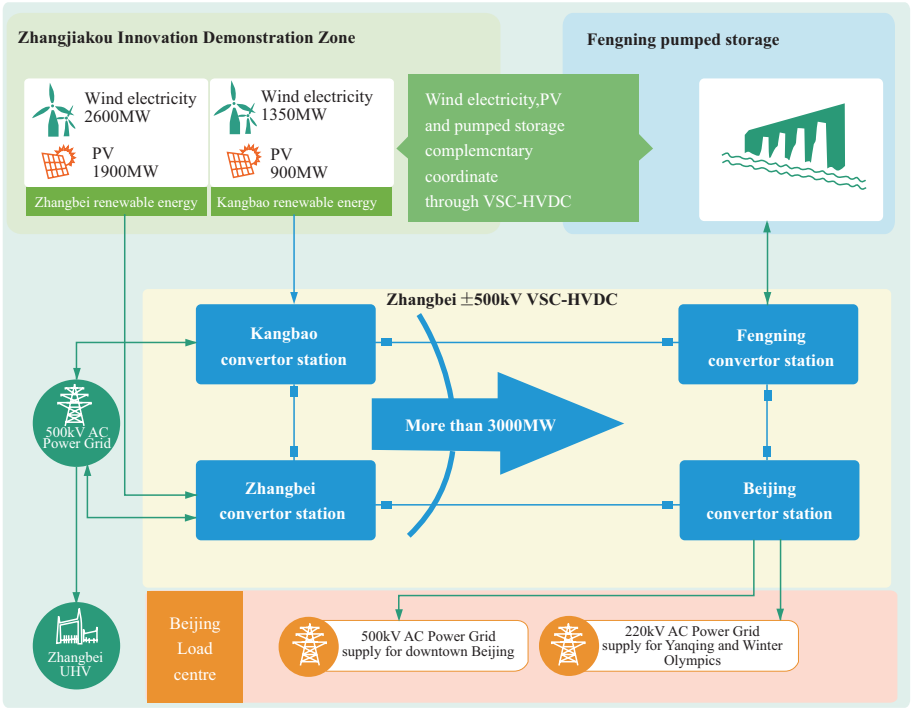

Fig. 9 ±500kV VSC-HVDC power grid demonstration project

Zhangbei ±500kV VSC-HVDC demonstration project is planned by relying on the "Key Technology Study and Application of HV and HP VSC-HVDC" and the "Key Technology Study on the Zhangbei Renewable Energy VSC-HVDV Transmission and Accommodation Demonstration Project Design" research project, and technical breakthrough should be formed from the following aspects:

1) Short-circuit current rise quickly in DC Power Grid, as in (5), i_f is line current after short-circuit of load, U_{dc} is equivalent power source, L_{dc} and R_{dc} is line resistance and line inductance, L_B is current-limiting inductor, R_l is load. IGBT and other key equipments have small performance margin, are easily damaged while short-circuit current

quickly rising. In order to solve this problem, ±500kV half-bridge submodule(H-MMC) converter valves and ±500kV DC circuit breakers are developed and applied to realize rapid fault clearing and fast recovery capacity of VSC-HVDC. ±500kV DC breakers apply high-voltage hybrid and superspeed mechanical technical routes to realize 6ms of break time and 25kA break current.

$$\frac{\mathrm{d}i_{\mathrm{f}}(t)}{\mathrm{d}t}=\frac{U_{\mathrm{dc}}}{L_{\mathrm{B}}+L_{\mathrm{dc}}}\frac{R_{\mathrm{l}}}{R_{\mathrm{dc}}+R_{\mathrm{l}}}\mathrm{e}^{-\mathrm{t}/\tau} \tag{5}$$

2) The overhead transmission line is firstly applied in a large scale to reinforce capacity to prevent from ice, snow, wind and thunder on VSC-HVDC lines, reinforce environmental suitability, and reduce costs. Meanwhile, ±500kV crosslinked polyethylene DC cable technology is simultaneously developed and demonstrated.

3) Bipolar grid structure with metal return is applied. Two poles and each pole are composed of a 6-impulse converter on upper and lower bridge arms. After one pole breaks down, non-fault pole is equipped with the power transfer capacity to improve system reliability and control flexibility of VSC-HVDC. Meanwhile, high-speed measuring equipment with less than 100us of coordination control adapting to VSC-HVDC and rapid protection equipment of 3ms action time should be developed and applied.

5.3 "Low Carbon Winter Olympics" renewable energy demonstration is forged

By focusing on the power utilization demands for renewable energy access, power supply reliability and flexible control in Low Carbon Winter Olympics and depending on integrated advantages of regional resources and geographical position in Zhangjiakou, State Grid Jibei Electric Power Company Limited is speeding up upgrading and rebuilding of smart grid in Zhangjiakou to forge the electric car fast charging network constituted by intercity and urban public fast charging facilities and dedicated fast charging facilities. 3.05 million m^2 of wind power heating project is implemented to promote electricity replacement. The village-level PV anti-poverty project with the total scale of 79000 kW covering 263 villages is accelerating to be impelemnted, so as to create the renewable energy accommodation mode with safety, reliability, flexibility and convenience, and economic practice[5].

During the period of "13th Five-year Plan", State Grid Jibei Electric Power Company Limited fully integrates with the innovative results of previous smart power technology, comprehensively safeguards Low Carbon Winter Olympics by combining with renewable energy accommodation demands in Zhangjiakou. Two demonstrations in smart power distribution technology should be emphasized:

1) Controllable power electronics flexible substation technology is studied and demonstrated to realize the "source-grid-load" flexible coordinative interaction of regional energy, meet power utilization demands of user diversification, verify and demonstrate key equipment for smart distribution grid construction of Low Carbon Winter Olympics. At present, State Grid Jibei Electric Power Company Limited unites Alibaba and Elion to construct AC/DC power distribution network and flexible substation demonstration projects in Zhangbei County(shown in Fig. 10). As constructing a 10kV smart flexible substation, Elion PV anti-poverty station 2.5MW PV power generation should be connected. AC/DC hybrid power distribution mode is used to innovation R&D display center of Alibaba to realize renewable energy accommodation. In the project, flexible transformers are developed. There are 10kV and 380V two sets of AC ports and 10kV and 750kV two sets of DC ports to flexibly control currents in each port and show strong access adaptability for multiple forms of renewable energy and load. With the compact structure, coupling transformers and DC circuit breakers are cancelled to improve equipment economy. The modular equipment modules are applied to improve reliable for convenient maintenance.

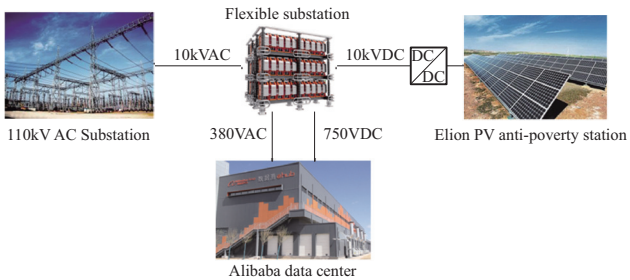

Fig. 10 Flexible substation and AC/DC power distribution network demonstration project

10kV port of flexible transformer applys triangular carrier phase shift PWM method, suppose that frequency of triangular carrier is K_{C} times power frequency, then the electric degress of a cycle of triangular carrier is shown in (6), suppose n is the number of submodules, then equivalent carrier frequency of output SPWM is shown in (7).

$$\theta_{\mathrm{C}}=2\pi/K_{\mathrm{C}} \tag{6}$$

$$K_{\mathrm{eff}}=nK_{\mathrm{C}} \tag{7}$$

2) "Integrated Smart Grid Demonstration Project of Support Low Carbon Winter Olympics"(Shown in Fig. 11), the National Key R&D Program of China, is studied and demonstrated to carry out multi-energy complementary coordinated dispatching and control technology study

by integrating with smart grid technology innovation achievements and focusing on power generation, transmission, distribution, dispatching and utilization. Annual prediction error of regional renewable energy power output is no more than 10%. AC/DC hybrid power distribution technology and multi-functional complementary microgrid technology are applied in the Winter Olympics division, so as to obtain 100% renewable energy for electricity consumption in Winter Olympics Division and no less than 99.99% of power supply reliability. The electric car charging facility network integrated with renewable energy power generation is constructed to realize urban fast charging networking coverage and less than 0.9kM of mean service radius and lay a solid technical foundation on Green and Low Carbon Winter Olympics in 2022.

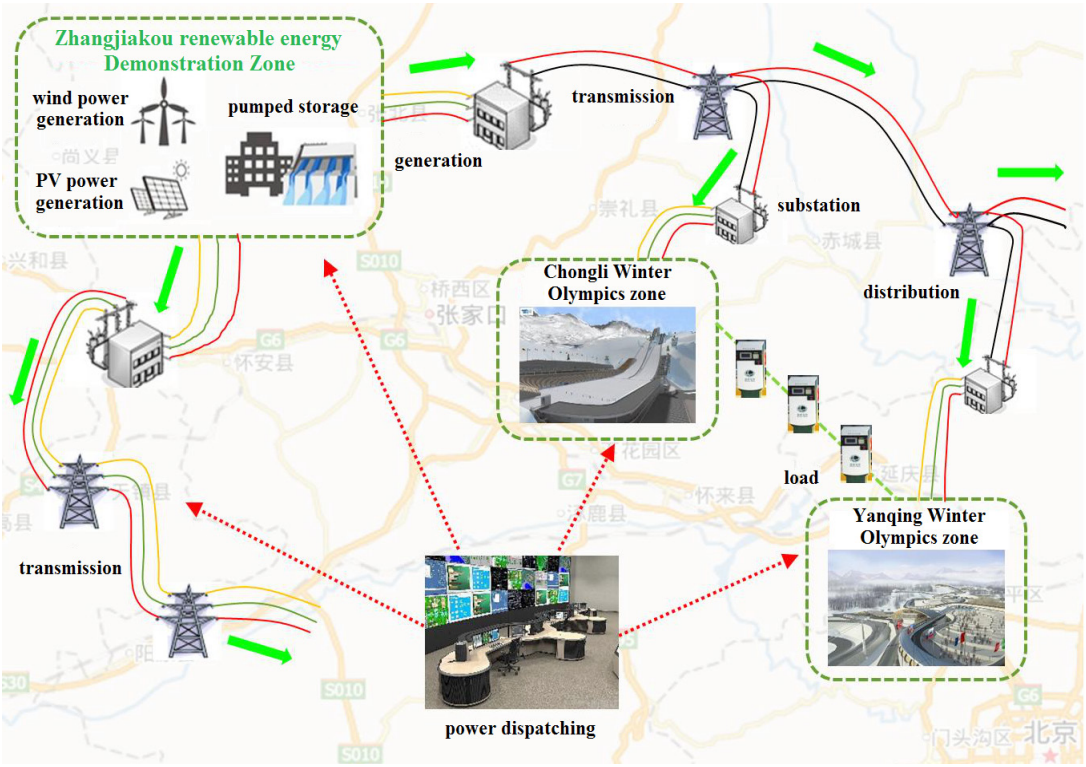

Fig. 11 Smart Grid Demonstration Project of Low Carbon Winter Olympics

6 Prospect of Zhangjiakou Innovation Demonstration Zone

State Grid Jibei Electric Power Company Limited is building the Global Energy Interconnection Zhangjiakou Innovation Demonstration Zone, it got the full support of SGCC and Zhangjiakou government. ±500kV VSC-HVDC Power Grid Demonstration Project, Virtual Synchronous Generator Demonstration Project, Flexible Substation and AC/DC Power Distribution Network Demonstration Project, EV Battery Secondary Utilization Energy Storage Demonstration Project, Smart Grid Demonstration Project of Low Carbon Winter Olympics and other Demonstration Projects is being built as planned, matching equipments and techniques is simultaneously studying.

Electricity consumption of 20 million kW renewable energy generator and 40 billion kWh renewable energy transmission and accommodation on the spot in Zhangjiakou Innovation Demonstration Zone in 2020 comes from renewable energy, 55% of electricity consumption come from renewable energy to replace 14 million t standard coal in fossil energy and reduce carbon dioxide, sulfur dioxide and nitrogen oxide emissions by 36 million t, 350000 t and 60000 t, respectively. China takes full advantage of renewable energy innovation achievements in high-efficient utilization, VSC-HVDC and green power utilization of renewable energy, while practicing “Green and Low Carbon Winter Olympics”, so as to provide the referable successful experience for global energy interconnection around the world.

Acknowledgements

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Biographies

Bo Tian is Chairman of State Grid Jibei Electric Power Company Limited. His research interests are clean energy, smart grid, power grid enterprise management.

Xiaolin Mo received his bachelor degree from Chongqing University. He is deputy director of the science technology and information telecommunication department of State Grid Jibei Electric Power Company Limited. His research interests are smart grid, clean energy, power grid science and technology innovation.

Yu Shen received his master degree from North China Electric Power University. He is division chief of the science technology office of State Grid Jibei Electric Power Company Limited. His research interests are electrical secondary equipment, power grid science and technology innovation.

Weimin Lei received his master degree from North China Electric Power University. He is deputy director of the development and planning department of State Grid Jibei Electric Power Company Limited. His research interests are power system planning, power grid dispatching operation, clean energy development.

Pengliang Xu received his master degree from Tsinghua University. He is division chief of the smart grid office of State Grid Jibei Electric Power Company Limited. His research interests are power grid dispatching operation, clean energy development, power grid science and technology innovation.

(Editor Ya Gao)