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Full-length article

Engineering practices for the integration of large-scale renewable energy VSC-HVDC systems

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Abstract: With the continuous development of power electronic devices, intelligent control systems, and other technologies, the voltage level and transmission capacity of voltage source converter (VSC)-high-voltage direct current (HVDC) technology will continue to increase, while the system losses and costs will gradually decrease. Therefore, it can be foreseen that VSC-HVDC transmission technology will be more widely applied in future large-scale renewable energy development projects. Adopting VSC-HVDC transmission technology can be used to overcome issues encountered by large-scale renewable energy transmission and integration projects, such as a weak local power grid, lack of support for synchronous power supply, and insufficient accommodation capacity. However, this solution also faces many technical challenges because of the differences between renewable energy and traditional synchronous power generation systems. Based on actual engineering practices that are used worldwide, this article analyzes the technical challenges encountered by integrating large-scale renewable energy systems that adopt the use of VSC-HVDC technology, while aiming to provide support for future research and engineering projects related to VSC-HVDC-based large-scale renewable energy integration projects.

Keywords: VSC-HVDC, Renewable energy integration, DC grid, Engineering practice.

1 Introduction

High-voltage direct current (HVDC) transmission technologies are mainly divided into traditional line-commutated converter (LCC)-based HVDC (LCC-HVDC) and voltage source converter (VSC)-based HVDC (VSC-HVDC) technologies. Considering areas where the power grid structure is weak, local conditions are unavailable for constructing supporting thermal power units, and large-scale renewable energy connections can not be withstood, the implementation of LCC-HVDC systems is very difficult and expensive, especially for offshore wind farms. Therefore, VSC-HVDC, multi-terminal VSC-HVDC, and VSC-based DC grids are the most reasonable and effective solutions for the long-distance transmission of large-scale renewable energy and for constructing grid connections. Countries that optimally utilize renewable energy contain developed regions with good resource development conditions owing to two decades of rapid development in this field.

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The development and utilization of renewable energy has gradually advanced to include remote onshore areas and the deep-water sea. Considering the abundance of various renewable resources and the surrounding environment, these areas typically do not have the capacity to construct supporting synchronous power supplies such that they cannot adopt high-voltage AC (HVAC) and LCC-HVDC systems. However, with the continuous development of power electronics, intelligent control systems, and other technologies, the voltage level and transmission capacity of VSC-HVDC systems will continue to increase, while the system losses and costs will gradually decrease. Therefore, it can be foreseen that VSC-HVDC technology will be more widely applied in future large-scale renewable energy development projects [1-3].

Developed countries have been actively exploring the integration of renewable energy via VSC-HVDC transmission. In recent years, many such engineering project shave been put into operation or are under construction around the world. Among them, Germany has commissioned many offshore wind farms in the North Sea. China is a world leader position in the field of integrating large-scale renewable energy systems via multi-terminal VSC-HVDC and VSC-based DC grids. To achieve the goal of reducing carbon and greenhouse gas emissions by 80% by 2050, the EU and its member states proposed an ambitious plan denoted as the ‘Super-grid’ in 2008, planning to establish a pan-European smart DC grid based on VSC-HVDC technology [4-6]. The purpose of this plan was to promote the development of large-scale renewable energy in remote areas of Europe, achieve efficient access to renewable energy over a wide area, suppress power fluctuations, activate cross-border power transactions, ensure the safe and stable operation of power grids, and improve the coordination of the development of renewable energy and power systems, etc. VSC-based DC grids are also an important solution that China may use to overcome issues associated with collecting and transmitting renewable energy in areas with abundant resources in the northwest and coastal areas that possess weak power networks, as well as issues associated with large-scale renewable energy transmission and nationwide accommodation of these technologies [7-9].

The use of VSC-HVDC transmission technology can overcome the issues encountered by the transmission and integration of large-scale renewable energy systems, including weak local power grids, lack of support for synchronous power supply, and insufficient accommodation capacities. However, this solution also faces many technical challenges because of the differences between renewable energy and traditional synchronous power generation. Based on actual engineering practices used worldwide, this article analyzes the technical challenges encountered by integrating large-scale renewable energy systems that adopt VSC-HVDC technology, and aims to provide support for future research and engineering projects related to VSC-HVDC-based large-scale renewable energy integration [10, 11].

2 Capacity optimizations for a renewable energy VSC-HVDC integration system

When a renewable energy system is connected to the power grid via VSC-HVDC, the capacity of the VSC-HVDC converter station, installed capacity of the renewable energy system, and operation mode of the renewable energy plant are the main factors that affect the grid-connection capacity of the renewable energy system. If the ratio of the converter station capacity to the installed capacity of renewable energy sources is incorrect, this will result in the excessive curtailment of the renewable energy or a low converter station utilization [12, 13]. Therefore, to fully understand and accurately simulate the characteristics of renewable power generation units, it is necessary to optimize this ratio to determine the maximum renewable energy grid-connection capacity. The Tjaereborg project in Denmark and the Shanghai Nanhui VSC-HVDC project have attempted to achieve such an optimization.

2.1 Tjaereborg project in Denmark [14]

The Tjaereborg project in Denmark is an experimental project. Its main purpose was to study the effectiveness of the optimization and controllability of wind energy transmission when using VSC-HVDC converters to provide an overall frequency conversion for wind turbines. Construction of the project began in March 1999 and a trial operation began in December 2000. This project not only made further attempts towards the application of VSC-HVDC transmission in the grid connections of offshore wind farms, but also provided a useful reference for the grid connections of large-scale offshore wind farms. The wind farm of the Tjaereborg project has 4 different types of wind turbines with a total capacity of 6.5 MW. The rated capacity of the VSC-HVDC converter is 8 MVA/7.2 MW, and the DC voltage and length of the DC line are ±9 kV and 4.3 km, respectively. The HVDC converters of this project use ABB’s first-generation two-level converter.

In this project, the wind power can be transmitted to the inland AC network via only an AC feeder, only a DC feeder, or AC and DC feeders in parallel. The AC feeder is used when the wind power is below 500 kW, and the DC feeder is used when the wind power is above 700 kW. The AC and DC transmission transition serves to minimize the losses at low wind power and is conducted automatically The VSC converter can change the voltage frequency within 30~65 Hz, which makes it possible to optimize the power output from the wind turbines by adjusting the frequency in relation to the wind speed. The experiences gained from this project demonstrate that VSC-HVDC is a promising technique for connecting large-scale wind farms to AC networks.

2.2 Shanghai Nanhui VSC-HVDC Project [15]

The Shanghai Nanhui Wind Farm is located on the coastal reclamation region on the north side of the Dazhi River Estuary in the Binhai Township, Nanhui District. There is a total of eleven 1.5 MW wind turbines with a total installed capacity of 16.5 MW. This system is connected to the 220 kV Nanhui Station via the 35 kV Dazhi Station using two 35 kV lines. The Nanhui VSC-HVDC transmission demonstration project is located between the Nanhui wind farm and Dazhi station. One of the two AC lines that were originally operated in parallel was transformed into a DC line via the hybrid transmission of cables and overhead lines. This project has a rated transmission power of 20 MVA, a DC voltage level of ±30 kV, and a DC cable length of 8 km. It uses modular multilevel converter (MMC) technology and was put into operation in 2011.

The Nanhui project is the first VSC-HVDC demonstration project that was independently developed and constructed by China. The VSC stations in this project have two main operation modes: the STATCOM mode and the HVDC transmission mode. In the STATCOM mode, the DC feeder is on standby and the VSC stations are only used to participate in the voltage-reactive power regulation process instead of in active power transmission. In the HVDC transmission mode, the DC feeder performs in parallel with the AC feeder. This project can effectively improve the under-voltage ride-through capability of the wind farm by more than 50%.

The Tjaereborg project in Denmark aimed to use DC transmission as a backup for the AC system. The main purpose of this project is to use the flexibility of VSC-HVDC to support the AC system. Therefore, this project is not concerned with the issue of capacity optimization for VSC-HVDC-based renewable energy grid-connections; however, the development of this project provides a good reference for the transmission power optimization of an AC/DC hybrid system. Considering the Shanghai Nanhui VSC-HVDC project, it is a significant achievement for China in terms of the engineering and construction of a VSC-HVDC system. Additionally, it also provides a reference for the optimization of the installed capacity of a renewable energy grid connected via VSC-HVDC. This project reflects the idea of allowing for sufficient margin in the design of early renewable energy transmission systems. With the development of renewable power generation systems and VSC-HVDC technology, the capacity optimization of grid-connected renewable energy systems has become increasingly popular owing to its potential for economic efficiency.

3 Frequency support of renewable energy VSC-HVDC integration systems

As the utilization of renewable energy in the power grid increases, synchronous power generation units are gradually rendered inoperative, causing the inertia and reserve capacity of the entire system to be reduced. This result in challenges associated with the frequency stability of the power grid. By adopting measures such as de-loading operations and virtual synchronous generator technology [16, 17], the renewable power generation unit can provide a certain inertia response and capacity for frequency regulation; however, it will be unable to efficiently detect changes in the power grid frequency over time due to the isolation of the VSC-HVDC transmissions. As a result, it can hardly participate in the regulation of the system frequency. Therefore, coordinating the control of the renewable power generation units and VSC-HVDC system such that they can participate in grid frequency regulation in a timely and effective manner must be investigated. The Swedish Gotland project and the Nan'ao multi-terminal VSC-HVDC project have made useful attempts to achieve this goal.

3.1 Gotland project in Sweden [18]

Gotland is Sweden's largest island, and it has very rich wind resources. The rapid development of wind power on the island had caused its capacity for wind power generation to increase from 15 MW in 1994 to 48 MW in 1997. However, the island itself uses less electricity than is generated, and the excess electricity must be sent elsewhere. Therefore, a VSC-HVDC transmission system with a rated capacity of 65 MVA and a DC voltage level of ±80 kV was constructed with a transmission distance of 70 km.

The Gotland project was put into operation in the fall of 1999 and is the world's first commercial VSC-HVDC system. This project not only transfers Gotland's electricity to the mainland of Sweden, but also provides the dynamic reactive power support required by wind farms, which overcomes the issues of power flow fluctuations, voltage flicker, and frequency instability. Moreover, it effectively improves the stability of the connected AC system and fully reflects the excellent performance of the VSC-HVDC transmission system. The project's converter stations use ABB's first-generation two-level converter with a switching frequency of 1,950 Hz and a converter loss of up to 3%. The control and protection system of the VSC-HVDC was to be upgraded in 2017 to enable increased renewable energy integration, as well as to improve the grid reliability and stability on Gotland island.

3.2 Nan'ao multi-terminal VSC-HVDC project [19, 20]

Nan'ao is located in the eastern sea of Guangdong Province. Wind power generation is one of the three pillar industries associated with the county's economic development. The total installed capacity of wind power on the island is about 143.28 MW, of which the three larger wind farms are the Niutouling Wind Farm (52.5 MW), Yun'ao Wind Farm (29.25 MW), and Qing'ao Wind Farm (45.05 MW). A large offshore wind farm, the Tayu Wind Farm (50 MW), is also planned for construction. The main purpose of the multi-terminal VSC-HVDC demonstration project in Nan'ao Island is to realize the safe distribution and connection of nearly 200 MW of power derived from wind farms on and near Nan'ao Island to the Nan'ao Power Grid and Shantou's main power network via a VSC-HVDC system. The project was also designed to safeguard the electricity supply of the island and lower the impact of wind power fluctuations on the local weak power grid.

The project involves a three-terminal VSC-HVDC transmission system, where in two sending terminals and one receiving terminal are used. The sending end converter stations are the Qing'ao Station and Jinniu Station, and the receiving end converter station is the Sucheng Station. The capacities are 50 MVA, 100 MVA, and 200 MVA, respectively, and the DC voltage level is ±160 kV. Modular multilevel converter (MMC) technology was used in this project. This project was formally put into operation at the end of 2013 and is the world's first commercial multi-terminal VSC-HVDC project [21-23]. Moreover, a 50-MW offshore wind farm is also planned to be connected via the Tayu Station in the future. Fig. 1 shows a schematic diagram of this multi-terminal VSC-HVDC demonstration project.

The Nan'ao multi-terminal VSC-HVDC has three main operation modes: an AC feeder and DC feeder in parallel, DC feeder only, and STATCOM. However, the lack of DC circuit breakers poses risks to the operation of the DC-feeder-only mode.

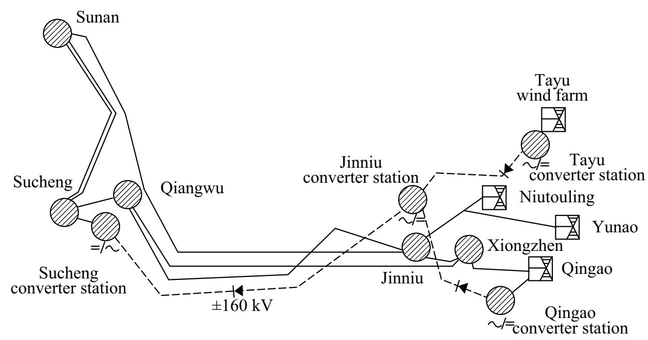

Fig. 1 Schematic of the structure of the Nan'ao VSC-MTDC project [19]

Both the Gotland project in Sweden and the multi-terminal VSC-HVDC project in Nan'ao are very significant. The former represents the first VSC-HVDC transmission system to be put into commercial operation, while the latter represents the world's first multi-terminal VSC-HVDC system. Before the project was put into operation, the power grid in the Nan'ao area was very weak, and the fluctuations of the grid-connected wind power system had a large impact on the local power grid. After this project was put into operation, the flexible control capabilities of VSC-HVDC were used to provide not only support for the wind power integration, but also effective support for the stability of the local power grid.

4 Fault control of renewable energy VSC-HVDC integration systems

Considering islanded large-scale renewable energy grid connections via a VSC-based DC grid, a power surplus in the DC grid will occur and the voltage of the grid will increase. These phenomena will occur if the generation of renewable power cannot be reduced within a sufficient amount of time (especially under the condition of full-power operation), the AC system at the receiving end experiences large disturbances, or the receiving-end converter is blocked due to failure. Consequently, the entire DC grid may shut down, and all of the renewable power generation units could be tripped due to the rapid increase in the voltage of the AC system at the sending ends [24]. Therefore, the coordinated control of the VSC-based DC grid and renewable power plants to achieve fault ride-through must be considered [25-27], as well as the achievement of the over-voltage ride-through of the renewable power generation units without the support of a reference power source (VSC station). Attempts to achieve these feats have been made by the Zhoushan multi-terminal VSC-HVDC project and Zhangbei four-terminal VSC-based DC grid project.

4.1 Zhoushan multi-terminal VSC-HVDC project [28, 29]

The Zhoushan Islands have abundant wind resources. The construction of wind farms in the Zhoushan Islands began in 1993. By 2010, the installed capacity of onshore wind farms was 97.8 MW. By 2015, the total installed capacity of Zhoushan wind farms was approximately 870 MW, of which the near shore wind farms were 600 MW. By 2020, the total installed capacity of the Zhoushan wind farms will be approximately 1,820 MW, of which near shore wind farms will provide approximately 1,500 MW. However, the power grid of Zhoushan has a small capacity, low power quality, and low power supply reliability. The current power grid also cannot withstand the integration of a large amount of fluctuating renewable power sources. Therefore, multi-terminal VSC-HVDC technology becomes a good solution to overcome these issues.

The Zhoushan multi-terminal VSC-HVDC demonstration project has a DC voltage level of ±200 kV. Converter stations were constructed on Zhoushan island, Daishan island, Qushan island, Yangshan island, and Sijiao island, which were interconnected using submarine cables. The capacities of the converter stations at each end are 400 MW, 300 MW, 100 MW, 100 MW, and 100 MW, respectively. The total length of the DC cables is141 km, including 129 km of submarine cables. The length of the 220 kV AC transmission lines is 22.5 km, and the length of the 110-kV AC transmission lines is 15.2 km. A schematic diagram of the grid structure of the Zhoushan multi-terminal VSC-HVDC project is shown in Fig. 2.

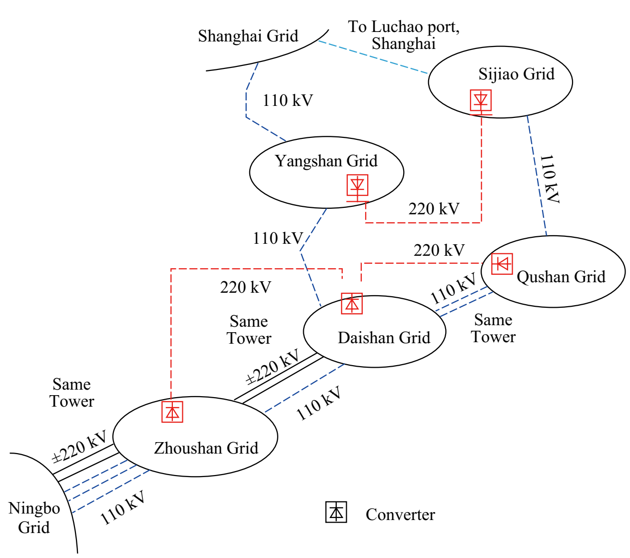

Fig. 2 Schematic diagram of the structure of the Zhoushan multi-terminal VSC-MTDC project [29]

The VSC stations of this project have 25 operation modes with various terminal combinations. During normal operation, the multi-terminal VSC-HVDC runs in parallel with HVAC transmission. However, when the connection of the VSC AC-side network to the main AC system is cut off, the VSC AC-side network can be supported by a single VSC station and a couple of VSC stations.

Zhoushan's multi-terminal VSC-HVDC project enables multiple wind farms to supply power to multiple islands, and utilizes multiple power sources to supply power to multiple load centers. The project involved the construction of a DC transmission network between the main islands in northern Zhoushan; strengthened the network structure and the electrical connections of the islands under its jurisdiction; improved the reliability of the power supply in this region; and provided a basis for the development of clean energy systems such as wind and solar. The project was completed and put into operation in 2014. It is the world's first five-terminal VSC-HVDC project equipped with a ±200 kV cascade full-bridge hybrid DC circuit breaker.

4.2 Zhangbei four-terminal VSC-based DC grid project [30, 31]

The Zhangjiakou area is rich in renewable energy resources. The installed capacity of renewable energy that has been developed and planned for development in this region is very large. Wind power, photovoltaic (PV), and energy storage systems may be installed in this area, which makes it an ideal region for the construction of multi-energy systems. At the same time, the energy consumption in the area is small, but it is adjacent to the Beijing-Tianjin and Jibei load centers, which is a typical scenario for large-scale renewable energy development and delivery systems [32].

Because the Zhangjiakou power grid is located at the end of the main AC grid, the voltage support capability of synchronous power supply systems is insufficient, and the connection of large-scale renewable energy sources could result in safety issues. Moreover, due to the weak 500 kV AC power grid installed in this area, it is difficult to distribute large quantities of renewable energy considering the stability constraints of this system. The construction of a VSC-based DC grid in the Zhangbei area can directly realize flexible energy interactions between renewable energy, energy storage systems, and loads at the sending ends. It can effectively achieve the complementary daytime and night time regulation of large-scale PV and wind power systems, and overcome the peak regulation issues of the system involving large-scale renewable energy sources. The active power imbalance is preferentially processed in the DC grid, which reduces the impact of intermittent energy on the receiving AC grids and improves the utilization efficiency of the renewable energy [32]. A schematic structure of the Zhangbei four-terminal VSC-based DC grid is shown in Fig. 3.

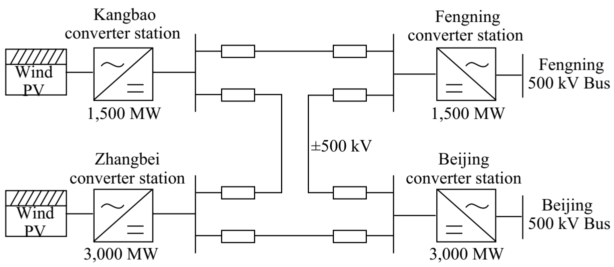

Fig. 3 Schematic diagram of the structure ofthe Zhangbei VSC-based DC grid

The Zhangbei VSC-based DC grid incorporates overhead transmission lines to construct a four-terminal ring structure with a voltage level of ±500 kV, and itis equipped with essential equipment such as DC circuit breakers and ultra-high-speed line protection devices. The two converter stations at the sending end are located in the Zhangbei county and Kangbao county in Hebei Province, with capacities of 3,000 MW and 1,500 MW, respectively. The receiving-end converter station is located in the Yanqing District, Beijing, with a capacity of 3,000 MW, and power is supplied to the nearby Winter Olympic venues. The regulating terminal converter station is located in Fengning county, Hebei Province, and it is connected to the Fengning pumped storage station as a regulating power source with a capacity of 1,500 MW. The DC transmission line passes through Hebei and Beijing with a total length of about 648 km.

The planned renewable energy capacity connected to the Zhangbei converter station is 4,698.5 MW, of which 2,298.5 MW results from wind power and 2,400 MW from PV power. The planned renewable energy capacity at the Kangbao converter station is 1,599.5 MW, including 1,249.5 MW of wind power and 350 MW of PV power. The Zhangbei and Kangbao converter stations have no synchronous generators and local loads on site. Under the normal operational mode, the Zhangbei and Kangbao converter stations use an island operation mode, but they can also operate in parallel with AC transmission in a fault mode. The Zhangbei VSC-based DC grid demonstration project began in March 2018. The Zhangbei and Beijing converter stations were scheduled to be operational by the end of 2019, and the remaining projects are scheduled to be operational in 2020. Upon completion, it will become the world's first ring-shaped VSC-based DC power grid [33].

Zhoushan's multi-terminal VSC-HVDC project and Zhangbei's four-terminal VSC-based DC grid project are also very significant. The former represents the world's first multi-terminal VSC-HVDC grid equipped with a 220 kV DC circuit breaker, while the latter is the world's first ring-shaped four-terminal VSC-based DC grid [34, 35]. VSC-HVDC technology can not be used to realize the rapid removal of DC faults. Therefore, considering the large-scale transmission of renewable energy, the development and wide application of VSC-HVDC technology is restricted. In the Zhoushan multi-terminal VSC-HVDC project, the Zhouding converter station uses a high-voltage DC circuit breaker that adopts a ±200 kV cascaded full-bridge hybrid structure, which improves the control of the DC grid faults. Zhangbei's four-terminal VSC-based DC grid project configures energy dissipation resistors on the AC side of the sending-terminal converter stations, which provides an example of an engineering application for the fault control involved with the connection of islanded large-scale renewable energy sources into a VSC-based DC grid.

5 Oscillation of renewable energy VSC-HVDC integration systems

In a VSC-HVDC-based large-scale renewable energy integration system, a large number of power electronic converters, DC lines, and smoothing reactors, among other components, are involved. Therefore, resonance frequencies will inevitably occur within the system, and the system may undergo system oscillation, which threatens the overall safety and stability of the system [36, 37]. For example, in 2013, the German BorWin1 offshore wind power system and its VSC-HVDC experienced harmonic oscillations, which resulted in a system outage [38]. Therefore, sub- and super-synchronous oscillation must be considered when planning and operating VSC-HVDC-based large-scale renewable energy delivery systems.

The BorWin1project [39] is a German project using a VSC-HVDC system to connect the BARD Offshore 1 offshore wind farm and other offshore wind farms near Borkum, Germany to the European power grid, as shown in Fig. 4. The project started in 2007 and was put into operation in 2009. The BARD Offshore 1 wind farm includes eighty 5 MW wind turbines located in the North Sea that are 130 km away from the coast. The rated capacity of the converter station is 400 MW, the DC voltage level is ±150 kV, and the total length of the DC line is 200 km, including 125 km of submarine cables and 75 km of underground cables.

The project's converter station uses ABB's third-generation two-level converter. Since the BorWin1 project, Germany has developed a series of offshore wind farm projects based on VSC-HVDC systems in the North Sea, as shown in Table 1. The VSC-HVDC transmissions of these systems, except that of BorWin1, are based on modular multi-level technology, and the highest voltage level reaches ±320 kV.

Table 1 VSC-HVDC-based offshore wind projects in operation and in construction in Germany

Project	Transmission Capability	Length	Operation Time
BorWin1	±150 kV, 400 MW	200 km	2010
BorWin2	±300 kV, 800 MW	200 km	2015
BorWin3	±320 kV, 900 MW	160 km	2019
DolWin1	±320 kV, 800 MW	165 km	2015
DolWin2	±320 kV, 900 MW	135 km	2016
DolWin3	±320 kV, 900 MW	160 km	2018
HelWin1	±250 kV, 576 MW	130 km	2015
HelWin2	±320 kV, 690 MW	130 km	2015
SylWin1	±320 kV, 864 MW	205 km	2015
DolWin6	±320 kV, 900 MW	90 km	2023
DolWin5	±320 kV, 900 MW	130 km	2024

Fig. 4 Illustration of the BorWin1Project [39]

This series of German VSC-HVDC projects have strongly supported the development of VSC-HVDC-based offshore wind farm grid connections. However, the renewable power generation plants and VSC-HVDC systems realize power conversion and transmission based on the fast controllability of the power electronic converters. Therefore, under some operating conditions, oscillation phenomena may occur when the two systems are jointly operated [40, 41]. The relevant suppression measures for these phenomena focus on designing additional damping control systems for the generation units and improving the control strategy of the VSC-HVDC converters.

6 Conclusions

With the increase of VSC-HVDC-based renewable energy grid-connection projects, especially the accelerated development of offshore wind farms, many challenges related to large-scale renewable energy integration technologies based on VSC-HVDC transmission have been encountered. These challenges include capacity optimization, frequency support, fault control, and oscillation. The developed projects presented in this study have made successful attempts to overcome these issues. With the further development of renewable energy sources, a large number of thermal, nuclear, and other traditional power generation systems will be replaced with renewable power generation systems. Accordingly, risks associated with the accommodation of renewable energy sources, as well as the security and stability of the existing power grid, will be encountered. As VSC-based DC grid technology can reduce the fluctuation and randomness of renewable energy over a wide area [42], it has attracted increased attention and provides an important solution for large-scale renewable energy integration and smart grid development.

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