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Grid connection of offshore wind via VSC-HVDC systems

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Grid connection of offshore wind via VSC-HVDC systems

INTERNATIONAL
ELECTROTECHNICAL
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GRID CONNECTION OF OFFSHORE WIND VIA VSC-HVDC SYSTEMS

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Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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INTRODUCTION

New technical solutions to meet the engineering development of grid integration of offshore wind generation via HVDC are the content of this document. The new solutions include new technologies, methods and practices to provide more flexibility and improve the efficiency of power systems, constantly balancing generation and load.

The development of offshore wind is progressing steadily, and VSC-HVDC systems are commonly adopted to link long distance offshore wind farms with the onshore bulk power grid. According to this fact, the purpose of this Technical Report (TR) specifically focuses on the planning, interaction and coordinated control between offshore wind farms and VSC-HVDC systems.

For various stakeholders, including transmission system operators, offshore wind farm owners, research institutes and so on, this Technical Report is to collect information from regulatory contents including relevant issues in different countries and regions, and work out a TR for offshore wind farm Integration via DC Technology, which mainly addresses the technology development tendency, best practices, and the future standardization activities.

The aim of this document is to draft a strategic, but nevertheless technically oriented and referenced TR, which represents the core and key issues of offshore wind integration via VSC-HVDC systems. Offshore wind farm developers and owners, transmission system operators have a common understanding about the key issues based on practices and challenges between offshore wind farms and VSC-HVDC systems.

GRID CONNECTION OF OFFSHORE WIND VIA VSC-HVDC SYSTEMS

1 Scope

The voltage source converter based on high-voltage direct current (VSC-HVDC) transmission technology has attracted increasing attention because of its advantages such as flexible control, supply to passive systems, and black start capability, which has been widely used in offshore wind farm integration. Although offshore wind farms generate electricity just like any other power plants on a system-wide level, such offshore wind generation has quite distinctive characteristics to be considered in terms of capacity optimization, voltage and power control, fault response, multi-frequency oscillation, power DC collection, etc., when compared to conventional generation integration via HVDC. Understanding these distinctive characteristics and their interaction with the other parts of the power system is the basis for integrating large-scale offshore wind farms via VSC-HVDC.

This document discusses the challenges of connecting offshore wind farms via VSC-HVDC, key technical issues and emerging technologies. The potential solutions include new technologies, methods and practices to provide more flexibility and improve the efficiency of power systems. The primary objective of this document is to provide a comprehensive overview of challenges, potential solutions, and emerging technologies for grid integration of large-scale offshore wind farms via VSC-HVDC. It is expected that this document can also provide guidance for further standardization on relevant issues. The purpose of this document is not intended to hinder any further development of state-of-art technologies in this field.

This Technical report is not an exhaustive document in itself to specify any scope of work or similar, between a purchaser and a supplier, for any contractual delivery of a HVDC project/equipment. It is expected that this document is used for pre-study and then to make studies, specification for delivery of specific HVDC project, as applicable.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TR 62001-5, *High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters – Part 5: AC side harmonics and appropriate harmonic limits for HVDC systems with voltage sourced converters (VSC)*

IEC 62747, *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*

IEC 62934, *Grid integration of renewable energy generation – Terms and definitions*

IEC TR 63401-1, *Dynamic characteristics of inverter-based resources in bulk power systems – Part 1: Interconnecting inverter-based resources to low short circuit ratio AC networks*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TR 62001-5, IEC 62747, IEC 62934, IEC TR 63401-1 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

4 Practices and challenges

4.1 Practices

4.1.1 General

The number of projects using HVDC to integrate renewable energy (RE) is growing, mainly due to the significant acceleration of offshore wind development. These projects are, to date, mainly based on point-to-point HVDC systems.

4.1.2 Projects in North Sea, Germany

BorWin1 is the world's first HVDC system connecting an offshore wind farm. It connects the BARD Offshore 1 wind farm and other offshore wind farms near Borkum, Germany to the European power grid by VSC-HVDC. 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 connection is 200 km, including 125 km of submarine cables and 75 km of underground cables.

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 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

These projects have strongly supported the development of VSC-HVDC-based offshore wind farm grid connections. The renewable power generation farms and VSC-HVDC systems achieve power conversion and transmission based on the fast controllability of power electronic converters. Under operating conditions, in case some oscillation phenomenon occurs when the two systems are jointly operated, 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.

4.1.3 Nan'ao project, China

Nan'ao is located in the eastern sea of Guangdong Province in China. This project is the world's first multi-terminal HVDC system for offshore wind farms. It involves a three-terminal VSC-HVDC transmission system including two sending terminals and one receiving terminal. 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. The Tayu converter station was planned, but hasn't been constructed yet.

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 demonstration multi-terminal VSC-HVDC project. Figure 1 shows the 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.

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.

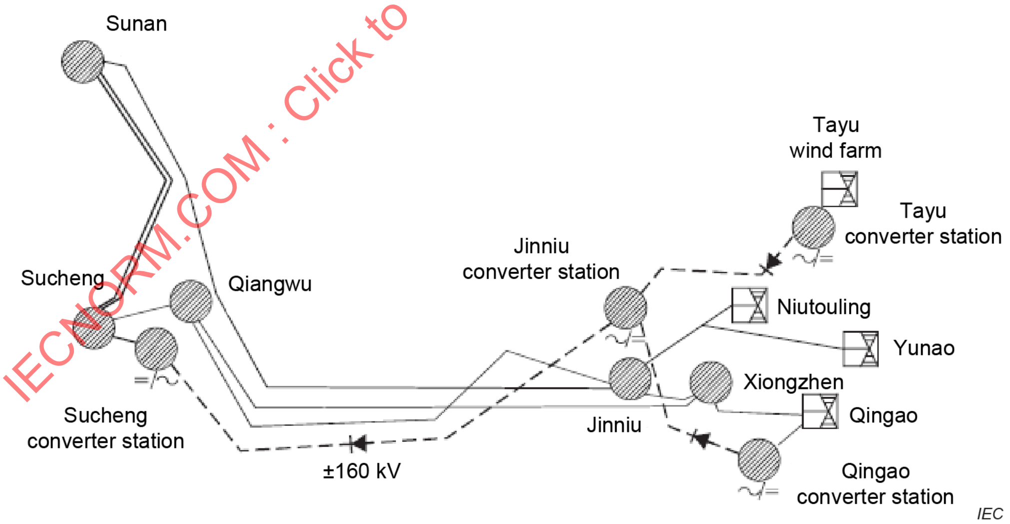


Figure 1 – Schematic structure of the Nan'ao VSC-MTDC project

4.1.4 Hybrid Interconnector project, Belgium and Denmark

European Electricity Transmission System operators Elia (Belgium) and Energinet (Denmark) have announced in February 2021 to set up a working group to examine the feasibility of a subsea cable between Belgium and Denmark that links the high-voltage grids of both countries over a distance of more than 600 km. A 'hybrid' design, which means that it brings wind energy from offshore wind farms to onshore power grids and can also be used as an interconnector between different electricity grids, is being examined. On the Danish side, the interconnector connects to a new 'energy island' to be built 80 km off the Danish coast and to which a large 10 GW wind farm is eventually connected.

When the interconnector between Belgium and Denmark is completed, the cable run through the territorial waters of four countries: Belgium, the Netherlands, Germany and Denmark. This gives Belgium direct integration to the renewable bulk generation in order to decarbonizes its energy-intensive industry and achieve the European climate targets. The start of the feasibility study follows the political cooperation agreement signed by the Belgian and Danish Energy Ministers. The project dovetails with the implementation of the European Green Deal, which aims for Europe to become the first carbon-neutral continent by 2050 by increasing the current capacity of offshore wind from 25 GW to 300 GW.

It is the first time Belgium is connected to a new electricity market that is further away than neighbouring countries. Hybrid technology also enables Belgium to gain direct integration to large wind farms in the far northern part of the North Sea where the meteorological conditions are different from those off the coast of Belgium. This provides greater security of supply and helps the Belgian energy-intensive industry to continue decarbonising.

4.2 Challenges

When large-scale offshore wind farms are connected to the VSC-HVDC system over long-distance transmission, the operation characteristics of offshore wind farms and the VSC-HVDC system affect each other. The adaptability of offshore wind farms connected to the VSC-HVDC system becomes an important issue affecting grid operation. In particular, the complex interaction between offshore wind farms and the power grid brings new challenges to the offshore wind farms and VSC-HVDC system.

1) Planning optimization. The planning of offshore wind farms and its integration is significantly important considering the relatively high investment of offshore wind farms and the VSC-HVDC system. When the capacity of offshore wind farms is larger than the VSC-HVDC capacity, wind curtailment is inevitable. Also, if the VSC-HVDC capacity is larger than offshore, the overall investment becomes excessive.
2) Voltage control. At present, the study on hierarchical voltage control for aggregated wind farms focuses on the AC grid. As the islanded aggregated offshore wind farms connected via VSC-HVDC are decoupled from the AC network, the optimization target and mode of which is quite different from the traditional connection. New voltage control strategies combined with its characteristics are developed.
3) Active power control. As the utilization of offshore wind farm in the power grid increases, synchronous power generation units are gradually decommissioned, causing the inertia and active power reserve capacity of the entire system to be reduced. This brings challenges to the frequency stability of the power grid. Developments of enhanced frequency regulation methods are required.
4) Fault control. When large-scale offshore wind farms are connected to a VSC-HVDC system, the operational characteristics of offshore wind farms and VSC-HVDC grid interact with each other. Various methods of fault ride-through inevitably have a certain impact on the offshore wind turbine, and even have impacts on the regulations and standards for offshore wind farms with interconnection to power system via DC.

5) Multi-frequency oscillation. In a VSC-HVDC-based large-scale offshore wind farm integration system, a large number of power electronic converters, DC lines, and smoothing reactors are involved. The resonant frequencies usually occur within the system. In case the system undergo system oscillation, the overall safety and stability of the system are threatened. Therefore, sub- and super-synchronous oscillation problems caused by the interaction of the VSC-HVDC and wind power control are considered when planning and operating VSC-HVDC-based large-scale offshore wind farm systems.

6) Function verification. It is the mainstream practice of offshore wind farms via VSC-HVDC transmission system to build the simulation verification system with actual control and protection devices and to verify the effectiveness of various functions of HVDC control and protection system and offshore wind together. Compared with the conventional VSC-HVDC projects or wind power projects connected to the grid using AC transmission mode, the control and protection system simulation verification of wind power projects connected to the grid using VSC-HVDC transmission has different simulation models, different composition for verification system and different characteristics, such as different charging modes of offshore converter station, different control modes of VSC-HVDC, different AC fault ride through characteristics of onshore converter station, etc.

7) Testing and commissioning. The system commissioning is the final on-site test for VSC-HVDC projects with integration of offshore wind farms, which aims to ensure that the whole system are safely and reliably operated, as well as meet the grid connection requirements. By comparison with the system commissioning of regular VSC-HVDC projects, the system commissioning procedure and method of the VSC-HVDC projects with integration of offshore wind farms are different, due to the special operating condition and the existence of onshore dynamic braking system, the offshore wind farms and converter stations.

8) Black start. For the normal situation, the HVDC converter establishes reference voltage, but in some special situation a number of offshore wind turbines can black start the offshore wind farm island as an alternative. It is necessary to configure the type and capacity of black start power supply according to the actual situation, so as to at least meet the black start of the first or first batch of offshore wind turbines in offshore wind farms.

9) Emerging innovative solution. With the rapid development of DC technology, offshore wind power developer hope to make full use of the advantages of DC technology or from a cost-saving perspective to explore the possibility of applying various DC transmission technologies to offshore wind power integration.

5 Optimal planning

5.1 General

Multiple issues are considered before a wind farm is connected to the grid, including the capacity and commissioning time of the wind farm, the selection of connection point, and the design of the transmission system.

Firstly, the capability of the target power system to accommodate the wind power is evaluated. The power system usually has enough flexibility for load-balance and ramping under any possible scenario, especially when the wind power ramps heavily and reversely to the load. The evaluation is conducted by investigations on the features of the wind resource, and comprehensive simulations on the operation of the wind farm and receiving-end power system.

In terms of transmission, VSC-HVDC technology offers a valuable option for the integration of offshore wind farm. VSC-HVDC technology has higher transmission capability and lower cost for long distance undersea transmission. It also provides dynamic reactive power/voltage support to the AC grid, which helps to reduce voltage fluctuations caused by wind power and improve the system stability under fault conditions. The design of the VSC-HVDC system for a specific wind farm is also optimized for better performance and less investment cost.

Clause 5 mainly focuses on two issues in the planning stage of an offshore wind farm. The first is the transmission planning of the wind farm, and the second is the optimal design of the VSC-HVDC transmission system.

5.2 The core and key issues

5.2.1 Planning process of offshore wind integration via VSC-HVDC

In order to better accommodate intermittent wind power and maximize the cost-benefit ratio of wind farm construction, the following process is usually used in the planning stage of an offshore wind farm:

1) Introduce the basic conditions of the wind farm. Estimate the total capacity of the wind farm based on the area of the site and the wind resource. Collect the wind data of the site and evaluate the power generation profile.
2) Investigate the electricity demand and grid structure of power systems in line with the planned wind farm. Evaluate the appropriate region to consume the wind power and determine the optimal transmission route based on the capacity of the wind farm and the characteristics of the power grid.
3) Optimize the commissioning time and capacity of the offshore wind farm together with the corresponding transmission system to refine the design. In this process, the capability of the power system to accommodate the wind power, especially the load-balancing capability is considered. Time-series simulations of power system operation are conducted with forecasted load and planned generating resources, in order to examine whether the wind power can be accommodated without violating the operating constraints. If not, the following measures are taken: 1) consume the wind power in a larger power system with more flexible resources; 2) modify the size and commissioning time of the wind farm; 3) construct additional flexible generation resources, or allow an acceptable amount of wind power curtailment; 4） provide flexibility on the demand side.
4) Design the transmission system for the wind farm. 1) select the optimal technology for wind power transmission. 2) determine the main technical parameters of the transmission system, e.g. DC voltage and capacity of converter stations. 3) design the structure and topology of the VSC-HVDC system, e.g. point-to-point or multi-terminal, symmetrical monopole or rigid bipole, etc. Finally, determine the connection point(s) of the transmission system to the main grid. Static and dynamic security assessment are conducted to ensure the feasibility and efficiency of the transmission plan. The availability of the transmission line corridors and substation sites is investigated as well.
5) Evaluate the investment cost and environmental impact of the wind farm and the transmission system. Determine the economic feasibility of the plan. Finally, summarize the proposed transmission plan in the conclusion.

The overall process of the transmission planning is illustrated as Figure 2.

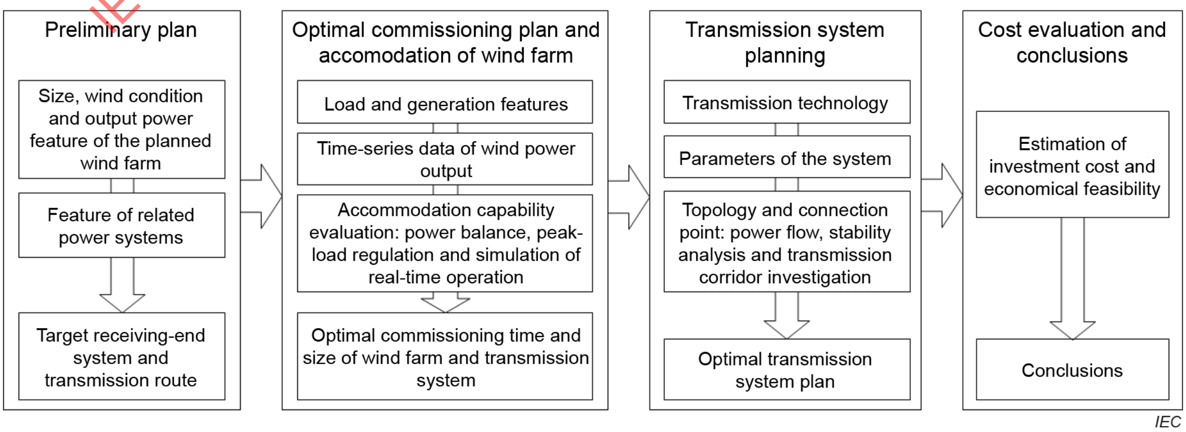


Figure 2 – Overall process of transmission planning of offshore wind farm

5.2.2 Designing of offshore wind integration via VSC-HVDC

5.2.2.1 General

The transmission system design for an offshore wind farm ensures the effective, economic and reliable transmission of wind power to the main power grid. For a VSC-HVDC transmission system, the major issues to be considered include:

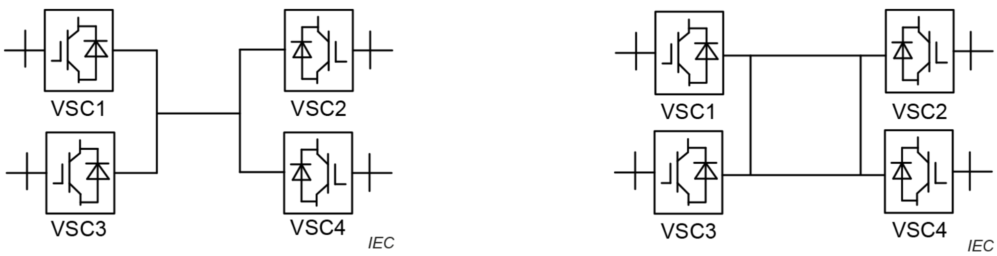
1) The optimal VSC-HVDC system configuration and topology. This includes the number of VSC-HVDC systems, the selection between point-to-point and multi-terminal system, symmetrical monopole or bipolar, and the network topology of the multi-terminal system.
2) The voltage level and rated capacity for each VSC-HVDC system.
3) The connection point of each VSC-HVDC system to the main power grid.

From 5.2.2.2 to 5.2.2.4, the typical topologies of VSC-HVDC systems are introduced first, and then present methodologies on a design of the VSC-HVDC system.

5.2.2.2 Typical topology of VSC-HVDC systems

The VSC-HVDC systems committed or under construction mainly adopt a point-to-point structure, which directly connects the offshore wind farm to the onshore connection point. It requires least number of transmission lines, and is usually the most economic and efficient option. The typical topology of point-to-point VSC-HVDC system connecting offshore wind farms includes symmetrical monopole, and bipole with dedicated metallic return. Symmetrical monopole HVDC with a simple structure has slightly better reliability than the bipole. When counting a pole trip of a bipole as 50 % outage, in addition to pole trips of both poles, there is the chance of a bipole trip. Bipole HVDC has the same operational flexibility as the symmetric monopole. The only difference is that the bipole has remaining transmission capacity in case of a failure of 1 pole. The control and protection system of bipole HVDC is complex and the investment cost is higher.

As scale of offshore wind farms further increases, multi-terminal HVDC (MTDC) systems have attracted more attention. The multi-terminal structure enables the transmission of wind power from multiple wind farms to multiple load centres. The structure of the parallel-type MTDC is shown in Figure 3. The DC sides of converters are connected in parallel, so the DC voltage of each converter is nominally the same. Typically, one selected converter station controls the DC voltage and maintain the power balance of the system, while other converters adopt current/power control. The parallel MTDC can be further divided into radial-type and ring-type. Figure 3 a) is the radial-type. The branches on both sending and receiving ends are concentrated to one point. The reliability is poorer since at least one converter station is cut off when any transmission line is under fault. Figure 3 b) is the ring-type, where all converter stations in the system are connected with a closed loop. A reduction of power transfer is required if any single transmission line is cut out. There is additional investment mainly due to 1 extra pair of DC cables compared to the radial topology. The control of DC power flow is also more complicated.



a) **Radial type** b) **Ring type**

Figure 3 – Topology of parallel MTDC

5.2.2.3 Design for offshore wind integration

The design of the VSC-HVDC transmission system of an offshore wind farm is a complex optimization problem. Detailed considerations are discussed as follows:

1) Voltage level, network structure and topology

   The voltage level, network structure and topology of the VSC-HVDC system are determined based on the size and geographic distribution of the offshore wind farm. If the wind farm has very large size (e.g. more than 2 000 MW) or consists of multiple sections, we consider multiple point-to-point VSC-HVDC systems, or a multi-terminal system if the technology becomes mature. Besides, the topology of the HVDC system (e.g. symmetrical monopole, rigid bipole or bipole with dedicated metallic return) is selected based on the size of the system, reliability requirement, and other technical and economic considerations.

2) Sending-end converter station(s)

   The sending-end converter station(s) are located based on the distribution of the wind turbines, the optimal design of the internal connection network of the wind farm, DC cable corridors, installation constraints, constraints for helicopter approach, marine traffic constraints, and constraints due to ground obstructions or differences in water depth. The capacity of the converter station is optimized based on the probability distribution of total output power of the wind farm thus avoiding wind curtailment and the deterioration of financial efficiency.

3) Connection point(s) to the main grid

   The selection of connection point mainly depends on the conditions of receiving-end grid. The main factors are taken into consideration include the transmission capability of the main power grid, the short-circuit capacity of connection point, the AC voltage stability due to the fluctuation of the wind power, distance and investment cost and so on. The optional connection point(s) ensure efficient accommodation of wind power, as well as reliable operation of the receiving-end grid.

4) DC transmission line and receiving-end converter station

   The transmission capacity of the DC line simply matches the capacity of the converter station for a point-to-point structure. In a multi-terminal system, DC power flow and N-1 faults are examined in order to determine the transmission line capacity. The receiving-end converter station is sized based on the DC power that arrives there from one (point-to-point) or multiple (MTDC) pairs of DC cables.

5.2.2.4 Optimization model for whole system design

Optimization methods for whole system design are being investigated in recent academic work, following the fast development of offshore wind farms around the world. A comprehensive mathematical model for this problem is yet to be developed. The fundamental ideas to construct the optimization model are presented below.

The total cost of the transmission system is commonly adopted as the objective function. The reliability of the system and wind power curtailment are considered either as part of the objective function or in the constraints of the model. In this example, we use the levelized cost of energy ($LCoE$) as the objective function:

$$\min \left(LCoE = \frac{\sum_{t=1}^{n} \frac{Inv_t + C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \right) \tag{5-1}$$

where

Inv_t is the investment cost at year t;

C_t is operational cost at year t;

E_t is the transmitted energy at year t;

r is the discount rate, and n is the lifetime of the system.

The investment cost Inv_t mainly includes the equipment cost Inv_t^e, construction cost Inv_t^c, and cost of land Inv_t^l.

$$Inv_t = Inv_t^e + Inv_t^c + Inv_t^l \quad (5\text{-}2)$$

The operational cost C_t mainly includes the maintenance cost C_t^m, wind curtailment C_t^w and financial cost C_t^f, if applicable.

$$C_t = C_t^m + C_t^w + C_t^f \quad (5\text{-}3)$$

For a practical project, the objective function and constraints are selected based on specific conditions and requirements of the project. In some cases, for some faults, it is used to accept that HVDC link is not delivering power.

5.3 Summary

The core of offshore wind farm planning is to determine the optimal capacity of wind farm and optimal transmission system design to ensure efficient, economic and reliable utilization of wind power. The main factors to be considered in wind farm planning are the features of the wind farm, the structure and operation mode of receiving-end power system, the feature of existing and planned generation resources, and the characteristic of load. A proper receiving-end power system has enough capacity to accommodate the wind power, considering the electricity demand, capability of flexible operation, and capacity of the power grid. VSC-HVDC technology provides an effective option for power transmission from distant offshore wind power sources.

6 Coordinated voltage control

6.1 General

The coordinated voltage control of offshore winds farms connected to the grid by VSC-HVDC presents several different challenges compared to those of onshore wind farms. Due to the complexity of marine meteorological environment, the prediction accuracy of offshore wind power is low, and sometimes it is difficult to meet the needs of engineering application. As a result, for reactive power optimization, the influence of wind power fluctuation on reactive power and voltage variation are considered. Dynamic reactive power compensation equipment could help a lot in suppressing voltage variation rapidly. To save the capacity of dynamic reactive power compensation for emergencies, it is important to make full use of the dynamic reactive power support for wind turbines.

For VSC-HVDC connecting circumstances, large amount of offshore wind plants at the sending side make up an island system to the AC grids with the sending side converter station as the only transmission path. Since there is no synchronous generator in the island system, in order to ensure the stable operation of the system, the converter station at the sending end adopts the control mode of fixed frequency and fixed AC voltage (grid forming mode). Compared with the conventional AC system, the new problems faced by the large-scale cluster of offshore wind farms are as follows:

1) The voltage control of the island system is decoupled from the AC grids, and is not included in the three-level voltage control of the grids.
2) The converter station occupies a dominant position in the voltage control of the island system, so the AC bus of the converter station is the central bus of the system, the corresponding reference value is determined through optimization.
3) The converter station at the sending end has complex operation constraints, and the reactive power capacity is limited, so the voltage control is optimized within the feasible operation range of the converter station. It is usually noted that the introduced technique in this Clause 6 is designed for grid following wind turbines, not quite suitable for grid forming turbines.

6.2 The core and key issues

6.2.1 Coordinated voltage control

The topology diagram of offshore wind farm cluster integrated via VSC-HVDC is shown in Figure 4. Wind farms connect directly to the AC bus of the VSC-HVDC station. Several wind farms can first be aggregated into a collecting station and then connected to the VSC-HVDC station together. Since VSC-HVDC is the only transmission path, those wind farms, collecting stations and sending terminal VSC station form an islanded system. The sending terminal converter provides fixed AC voltage and frequency reference for the island system. It is noted that the power delivery via collecting stations is becoming less common and it is now more usual to bring the wind farm turbine strings directly to the converter platform.

As shown in Figure 4, since the voltage of the AC bus of the VSC station is determined by VSC-HVDC, the voltage regulation of offshore wind farms connected through different transmitting lines cannot interact with each other. But these affect the reactive power margin of sending terminal converter. The use of converter station to control the voltage is the most trouble-free, but if the system wants to maximize the transmission power, it is a better way to consider the cooperation of the wind farm first, control the voltage to a certain extent, and then control voltage in detailed through the converter station.

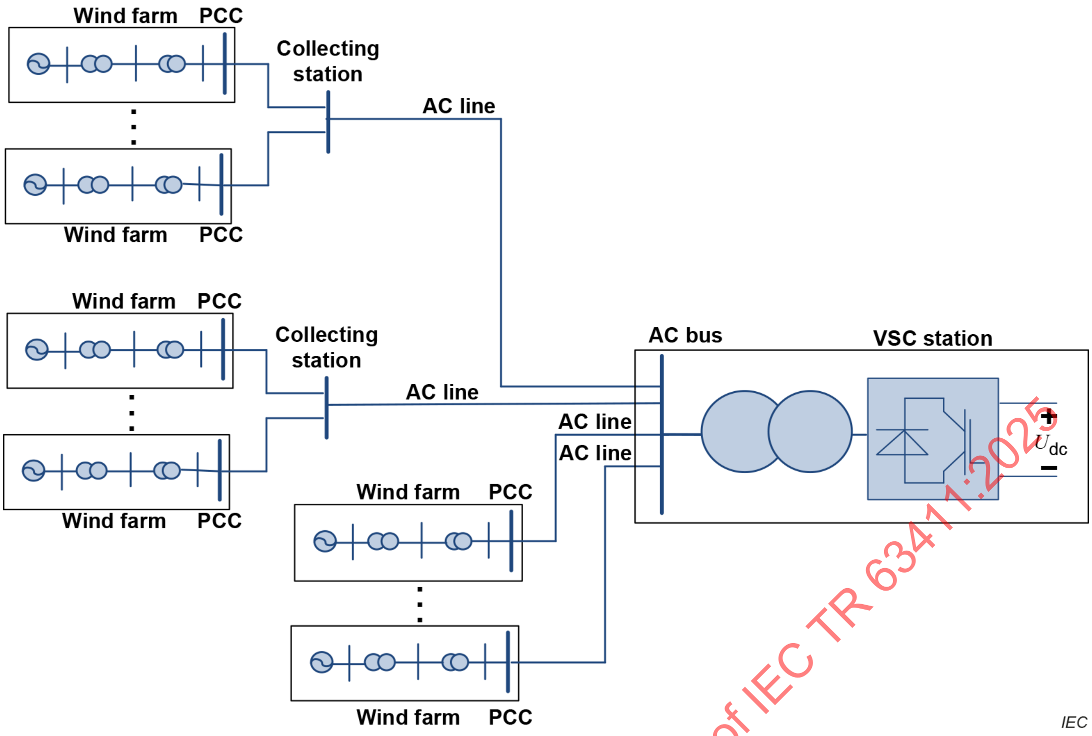


Figure 4 – Topology diagram of offshore wind farm cluster connected via VSC-HVDC

The coordinated voltage control for offshore wind farm and VSC-HVDC includes two modes, as is shown in Figure 5. A two-level voltage coordinated control system is applied to the wind farm cluster, as is shown in Figure 5. The first level is the global voltage control, which is responsible for the coordinated control of all the wind farms and the converter station. The global control is usually located at the dispatching centre and calculate the voltage or reactive power adjusting references in next control step for each AVC (automatic voltage control) substation. The AVC substation is the second level in Figure 5, which is responsible for the local voltage control of a single wind farm. The AVC substation receives control target from the global voltage control system and then calculates control references for each individual reactive power regulation device. When the reactive power margin of the converter station is beyond the threshold value for some reasons, the voltage control mode is changed into emergency voltage mode. The VSC station usually changes its voltage control target according to a predetermined strategy to ensure the safety of VSC station. The emergency voltage control is based on droop control methods.

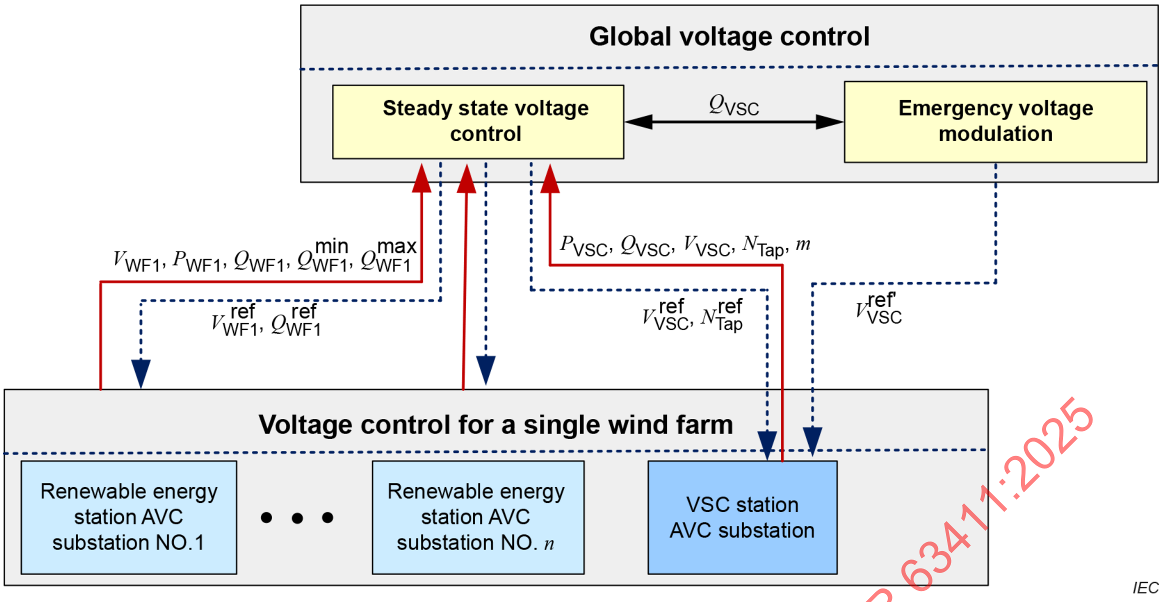


Figure 5 – Two-level voltage coordinated control

6.2.2 Reactive power regulation replacement strategy

On the one hand, the converter station provides voltage support to control the voltage stability of the entire offshore wind power connected to the DC system, and on the other hand, it also needs the coordinated control of the wind farm to achieve internal stability. In addition to making full use of the reactive power of the wind turbine itself, voltage control can also be achieved by configuring a certain reactive power compensation device. The dynamic reactive power compensation equipment has the ability to quickly respond to the voltage fluctuation, and track the rapid change of the voltage by adjusting its reactive power output. The installation of SVGs (static var generators) for offshore wind farms is not quite different from the SVGs for onshore wind farms. When the system voltage fluctuates, the fast-tracking control of voltage is realized through the fast regulation ability of SVG. When the target voltage is met, the regulation of dynamic reactive power compensation is replaced by the reactive power regulation of wind turbines. In this way, the reactive power regulation capability of wind turbines are fully utilized, and the load rate of the dynamic reactive power compensation equipment can be reserved with sufficient dynamic reactive margin for transient system fault. On the premise of keeping the total reactive power output unchanged, the output of multiple reactive power sources is redistributed to maximize the dynamic reactive power reserve of SVG. According to the regulation characteristics of different reactive power sources, the sequence of reactive power replacement is designed as: first replace the SVG operating in constant voltage mode, then replace the SVG operating in constant reactive power mode, and finally use wind turbine to provide reactive power support. The corresponding control modes mainly include two types:

1) Reactive power replacement between SVG in power mode and SVG in voltage mode

   During the replacement, SVG voltage control target remains unchanged, namely, the total reactive power output is unchanged to keep the voltage unchanged.

2) Reactive power replacement between wind turbines and SVG in power mode

   The replacement is achieved by issuing reactive power regulation alternately for SVG and wind turbines. If the reactive power regulation of wind turbines is issued in this cycle, the reactive power regulation of wind turbines in the next cycle is 0, and only the regulation of SVG is issued. During the replacement, the regulation step is limited to prevent the system voltage from large disturbance.

The introduced coordinated voltage control strategy is different from the voltage control method that the HVDC convertor supplies all reactive power compensation. The introduced method optimizes the allocation of required reactive power between the converter station and other reactive power sources, which helps to improve the reactive power margin of the converter station. Such a strategy is particularly suitable for scenarios where multiple offshore wind farms are transmitted through the same converter station.

6.3 Summary

In this Clause 6, a coordinated voltage control strategy for both the VSC-HVDC station and the offshore wind farm is proposed. The strategy considers both the normal and emergency operation conditions. For normal condition, a multi-objective optimization model considering the loss of the island system and the reactive power margin of the VSC station is introduced. Meanwhile, the stress on the converter valves could be less, helping the converter retain higher safety margin. For emergency operation condition, a reactive power and voltage droop modulation function is used to correct voltage reference set value immediately so as to guarantee the safety of VSC converter.

7 Coordinated active power control

7.1 General

As the utilization of renewable energy in the power grid increases, synchronous power generation units are gradually phased out or replaced by wind farms, which leads to the reduction of the inertia and active power reserve capacity of the entire system. The power grid then faces the frequency stability challenges. It is an optimal way for renewable energy system to participate in frequency regulation by the power regulation and frequency controller ancillary system.

Because of the isolation of VSC-HVDC transmissions, the long-distance offshore wind farm can't efficiently detect changes in the power grid frequency. 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 HVDC system such that they can participate in grid frequency regulation in a timely and effective manner can be a challenge.

7.2 The core and key issues

7.2.1 Active power

In most instances, wind farms are required to have different types of active power control, such as absolute power limitation, delta limitation, balance control, ramp limitation and fast down regulation to support system protection. With the increasing penetration level of wind farms in power systems, more and more transmission system operators (TSOs) require wind farms to participate in both over-frequency and under-frequency regulation. It means that wind farms have to reserve the capability to change their power outputs up and down. The reduction of power output can be achieved by the above controls, but to increase power output, new approaches must be introduced.

An ancillary frequency controller designed for offshore wind turbine is shown in Figure 6. It can be divided into two parts: under-frequency controller that is activated if the measured frequency is below 49,8 Hz, and over-frequency controller that is activated if the measured frequency is over 50,2 Hz. In Figure 6, f_{meas} is the measured frequency value of the AC system. The active power reference P_{ω_ref}(pu) is determined by the speed control of the wind turbine, and the reference for speed control is provided by maximum power point tracking (MPPT). The active power reference P_{under}(pu) and P_{over}(%) are generated by the under-and over-frequency controllers respectively. The total active power reference value P_{g}^{*} to the wind turbine generator is then given as

$$P_g^* = P_{\omega\_ref} \times P_{over} + P_{under} \quad (7\text{-}1)$$

The under-frequency controller is applied to emulate the response of the speed governor of a synchronous generator and its output active power reference P_{under} is proportional to the absolute deviation of the system nominal frequency.

The over-frequency controller calculates P_{over} to modify P_{ω_ref} if the measured frequency exceeds 50,2 Hz (e.g. as per the requirements in China).

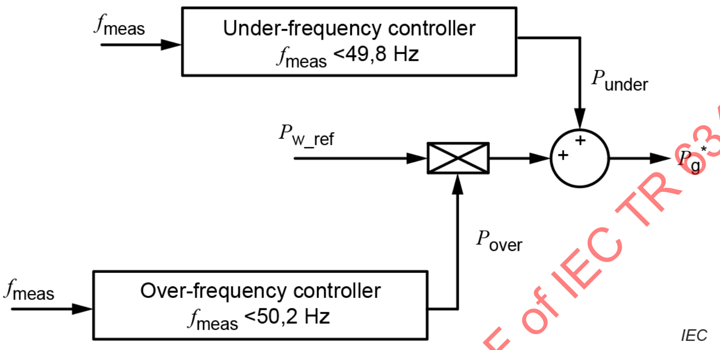


Figure 6 – Illustration of ancillary frequency control for wind turbine

The ancillary frequency control enables wind turbine to response frequency disturbances. Except in cases where wind suddenly changes, wind turbines can provide a certain primary frequency response. To obtain the active power reserve margin, the wind turbine is operated in a reduced power mode instead of in the maximum power extraction mode. That can be fulfilled by increasing the pitch angle of wind turbine, and the increment of the angle determines the amount of the reserve. For the case of over-frequency, the reduction margin of active power depends on the current power reference P_{ω_ref}.

7.2.2 Coordinated active power control

7.2.2.1 General

In contrast to synchronous generators, wind farms are not able to keep the system voltage amplitude and frequency stable independently. The offshore wind farm requires VSC-HVDC to stabilize the system voltage amplitude and frequency. Because of the isolation of VSC-HVDC transmissions, the offshore wind farm can indirectly detect changes in the power grid frequency.

7.2.2.2 Communication-based coordinated active power control

By perceiving the variation of the main grid frequency, the wind farm can provide corresponding frequency support. This can be achieved by transmitting the measured frequency signal through dedicated communication channel from the grid side VSC controller to the wind farm controller as shown in Figure 7.

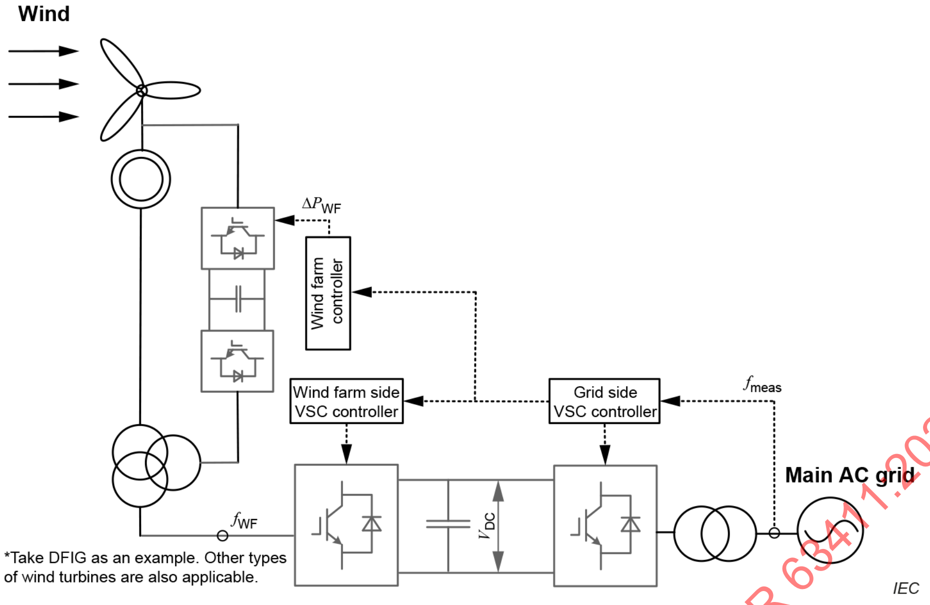


Figure 7 – Frequency control structure with communication

7.2.2.3 Communication-free coordinated active power control

The coupling of the main grid and the isolated wind farm system without remote communication can be established through using HVDC link voltage. Excluding the power loss along HVDC cables, the HVDC voltage at the wind farm side VSC and the grid side VSC are regarded the same.

The Figure 8 shows the communication-free coordinated active power control method for the offshore wind farm. The wind farm frequency is effectively decoupled from the main AC grid frequency by the HVDC. Therefore, there is little change of active power production of wind farm in response to any system frequency variations. And the communication-free coupling scheme between offshore and offshore AC grids for transmitting the main AC grid frequency signal to the offshore wind farm must be properly designed.

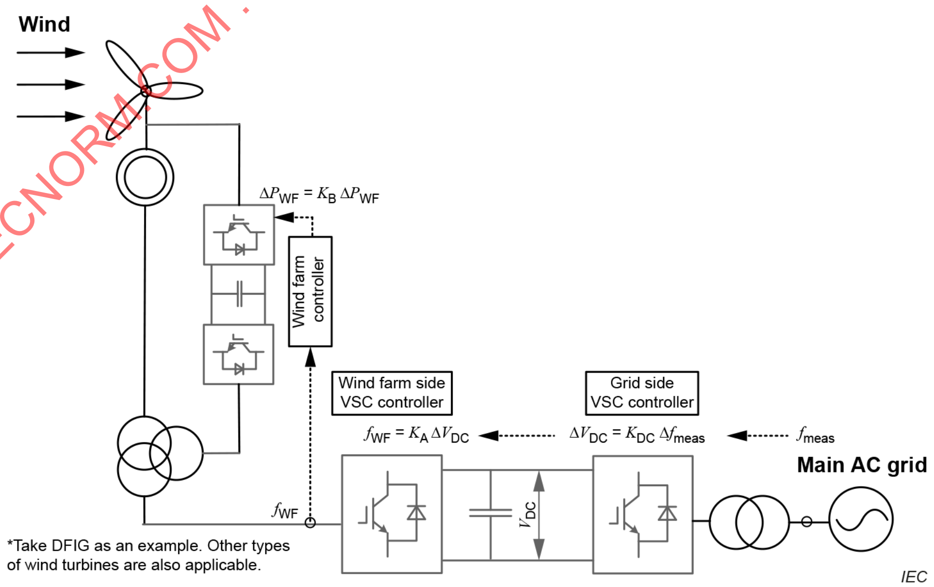


Figure 8 – Frequency control structure without communication

When there is main grid frequency deviation, it can be firstly converted into the variation of the HVDC voltage through HVDC voltage droop control. In the grid side VSC controller:

$$\Delta V_{\mathrm{DC}} = K_{\mathrm{DC}} \cdot \Delta f_{\mathrm{meas}} \qquad (7\text{-}2)$$

where

Δf_{meas} is the deviation of the frequency of the main gird;

K_{DC} is the droop control parameter;

ΔV_{DC} is the DC voltage deviation of the HVDC.

And in offshore wind farm side VSC controller, the isolated wind farm system frequency is as below.

$$\Delta f_{RE} = K_{\mathrm{A}} \cdot \Delta V_{\mathrm{DC}} \qquad (7\text{-}3)$$

where

K_{A} is the control parameter, which stands for the proportion of the isolated wind farm system frequency to the DC voltage deviation at the wind farm side VSC.

Combining Formula (7-2) and Formula (7-3), Δf_{WF} is established as below.

$$\Delta f_{\mathrm{WF}} = K_{\mathrm{A}} \cdot K_{\mathrm{DC}} \cdot \Delta f_{\mathrm{meas}} \qquad (7\text{-}4)$$

A typical and direct way to make wind farm responsive to the offshore AC grid frequency is by adding the power deviation ΔP_{WF} that is proportional to the variation of offshore AC grid frequency Δf_{WF} to the original power reference of the wind farm. K_{B} is the proportional coefficient. Therefore, the wind farm frequency control is actually a droop control, as shown in Figure 9.

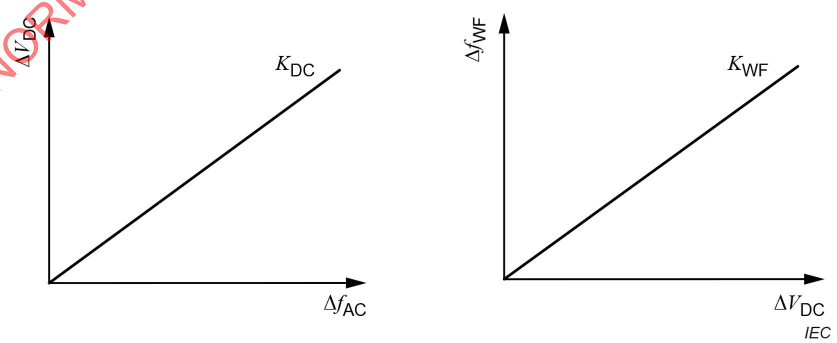


Figure 9 – Frequency droop control schematic diagram

For wind farm power controller, the output power P_{WF} consists of reference power $P_{\mathrm{W\_ref}}$ and deviation power ΔP_{WF}:

$$P_{WF} = P_{w\_ref} + \Delta P_{WF} = P_{w\_ref} + K_B \Delta f_{WF} = P_{WFref} + K_B K_A K_{DC} \Delta f_{meas} \quad (7\text{-}5)$$

In order to achieve this, one possible way is to utilize the reserved energy by increasing the pitch angle of wind turbine to compensate the power gap between output active power of the wind farm and the input wind energy. However, the wind farm deviates from MPPT operating statuses.

7.2.3 Frequency control

7.2.3.1 Key points in frequency control of VSC-HVDC connected offshore wind farms

Based on the frequency control of wind turbine and the coordinated active power control of wind farm and VSC-HVDC, the implementation of these controls in practice was introduced. The technical frame for frequency control of VSC-HVDC connected offshore wind farms are shown in Figure 10.

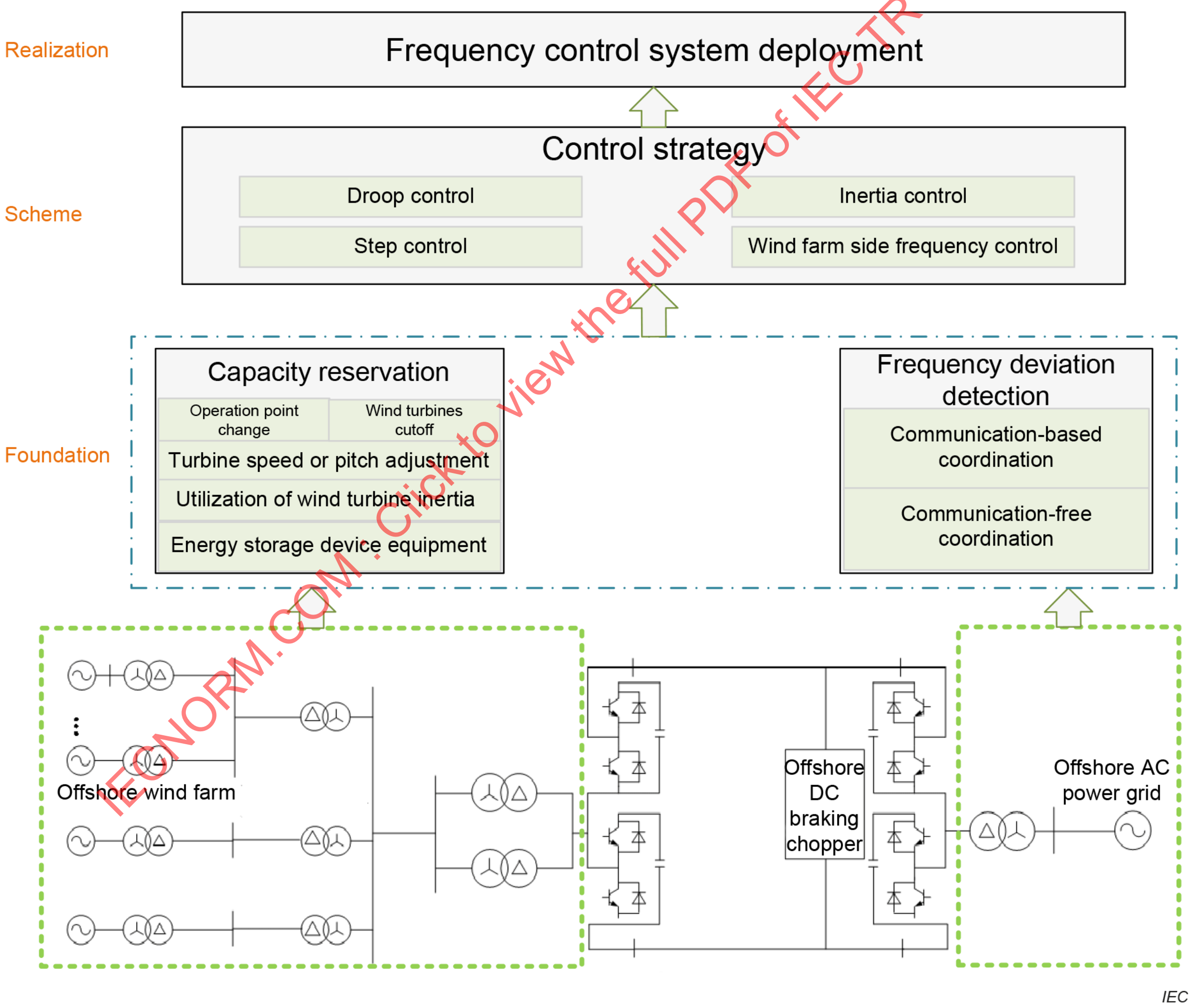


Figure 10 – Technical frame for frequency Control

1) Frequency deviation detection

Isolation of wind farms and main grid with VSC-HVDC converters makes the direct detection of main grid frequency deviation difficult. As the frequency deviation is a fundamental signal in the frequency regulation capability construction, frequency change signal transfer is of great importance. There can be 2 modes of signal transfer which are communication-based and communication-free.

2) Capacity reservation

To provide frequency support in the main grid frequency deviation, wind farms have to be equipped with capacity reservation to increase or decrease output when there is regulation demand from the main grid.

3) Frequency control strategy

On the basis of the main grid frequency deviation detection and capacity reservation, the frequency control strategy properly utilizes the regulation capacity to serve the frequency regulation demand of the main grid.

4) Deployment scheme of frequency control system in wind farms

The implementation of the control strategy also depends on reasonable deployment of the control system, including the information interaction with the existing control system like Automatic Generation Control (AGC) system.

7.2.3.2 Capacity reservation

1) Output increase

In a scenario where the frequency regulation demand from the main grid is to increase the wind farm output, there are three possible solutions to capacity reservation:

a) Operate wind turbines in a de-loading mode by means of converter control and pitch angle control.

b) Energy storage equipment.

c) Utilization of wind turbine inertia: It means to increase the active power of converter. The wind farm side frequency decreases due to no additional control on the output of the wind turbine. Frequency drop is usually within a tolerant range to guarantee the safe operation of wind turbines.

d) Comprehensive solution combining a), b) and c).

2) Output reduction

In a scenario where the frequency regulation demand from the main grid is to decrease the wind farm output, there are three possible solutions to capacity reservation:

a) Turbine speed or pitch adjustment.

b) Wind turbine curtailment.

c) Comprehensive solution combining items 2 a) and 2 b).

7.2.3.3 Frequency control strategy of offshore wind farms interconnected through VSC-HVDC

1) Droop control

Droop control is based on the idea of the traditional synchronous motor governor. The system frequency deviation is used as the feedback signal, and the power or torque additional control signal is generated by proportional amplification. As the additional signal of droop control is the rate of frequency change, it can provide strong support near the lowest frequency point, but the control speed is slower than inertia control.

2) Inertia control

The feedback signal of the controller is the frequency change rate. It is called inertia control because the signal simulates the inertia of the traditional synchronous motor, as shown in Figure 11. The feedback of inertia control is the frequency variation, so it can provide considerable support at the initial time of disturbance and is superior to droop control in speed.

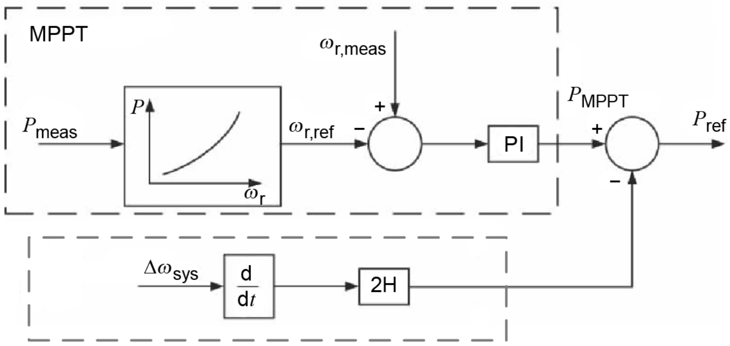


Figure 11 – Schematic diagram for inertia control

3) Step control

Offshore wind turbine adopts power electronic devices, which can increase the output to the maximum allowable output in a short time. Because this type of controller increases the output of wind turbines instantaneously when the system frequency changes, it is also called step control. Compared with droop control and inertia control, step control can increase the output to the upper limit in the shortest time.

It is noted that the step control can make the wind turbines provide considerable active power support in a short time, but at the same time, it causes the speed of the wind turbine to drop rapidly, resulting in rotor stall. And the system could be encountered with a delayed disturbance when wind turbines no longer operate in frequency regulation mode after the grid frequency is restored.

4) Frequency control of wind farm side

The above methods directly control the active power of wind farm to realize frequency regulation. It is also practical to convert the frequency deviation of the main grid into the frequency control request for the wind farm side. Active power output regulation could then be achieved.

7.3 Summary

For coordinated frequency control of offshore wind farm and VSC-HVDC, after the large-scale offshore wind farm is connected to the grid by DC, the effect of VSC-HVDC system frequency regulation or wind farm frequency regulation alone cannot meet the system frequency adjustment and stability limitations, and usually the two are cooperated to adjust the system frequency together. Therefore, it is the general trend to propose the basic principles and control scheme of the two technologies in combination with different application scenarios, propose basic recommendations for coordinated control strategies, and form standards that can be determined to guide the coordinated control of offshore wind farm and VSC-HVDC system.

8 Fault response and coordinated control

8.1 General

The large-scale offshore wind farms are always located in the place that lacks a great deal of voltage support from synchronous generators and synchronous condensers (i.e. synchronous compensators), so VSC-HVDC system is one of the potential technologies to realize the grid-connection of offshore wind farms. Via the rectifier station of VSC-HVDC, offshore wind turbines acquire proper AC voltages for their power output and collection, is firstly collected in its collection system, and then transmitted to receiving-end bulk power system. The fault response, ride-through, control of so many devices is much more intricate. Initially, before the clearance for the fault inside VSC-HVDC system, the DC current increases at a rather fast pace, so it is very critical for DC protections or circuit breakers to avoid converter damages. Subsequently, after the fast clearance for the fault inside VSC-HVDC system, power transmission in VSC-HVDC systems is substantially curtailed and redistributed, and then the problems of power loss due to device overload arise.

There are exist multiple technical options to carry out the fault control for ride-through of offshore wind farm grid-connected with VSC-HVDC, and each of these technical options involves the collaboration among various devices for control and de-loading (such as DC Chopper and AC Chopper). The current technical standards usually lack these collaborations and the experience from operational engineering, and they also lack the technical requirements for duty segregation, cooperation of control strategies, and the high/low voltage withstanding in the coordinated ride-through with the involvement of a series of devices in offshore wind farm grid-connected with VSC-HVDC.

In order to tackle above problems, the fault response of offshore wind farms with the connected VSC-HVDC system is firstly and fully analyzed and understood. The fault response is the voltage, current or active/reactive power reaction, of an offshore wind turbine, offshore wind farm or grid-connected HVDC system during specific faults in the electric power system. On the basis of fault response, the fault ride-through of offshore wind farms with the connected VSC-HVDC system can be appraised with sufficient accuracy.

The fault ride-through is the ability of an offshore wind turbine, offshore wind farm or grid-connected HVDC system to stay connected during specific faults in the electric power system, and the fault control is the act to help these devices to stay connected. The fault response in offshore wind farm and connected HVDC systems is much more complex, and the involved fault ride-through and control requires more coordination among offshore wind farm, connected HVDC, and other devices.

According to the fault location, the relevant technical challenges are indicated as Table 2.

Table 2 – Summary of possible fault response and control

Fault location	Offshore wind farm	Offshore wind power collection system	Connected VSC-HVDC system	Receiving-end bulk power system
offshore wind power collection system	Low voltage ride through before fault clearance; (possible) high voltage ride through after fault clearance	clear the fault as soon as possible	(for rectifier station) low voltage ride through before fault clearance; (possible) over-voltage ride-through after fault clearance	with little involvement
connected VSC-HVDC system	Shut down (for symmetrical monopole topology); Over-voltage ride-through before fault clearance; carry out the (possible) power transfer as soon as possible after fault clearance (for rigid bipole topology with earth return or dedicated metallic return)		Shut down (for symmetrical monopole topology); Clear the fault and carry out the (possible) power transfer as soon as possible (for bipole topology or with earth return or dedicated metallic return)	clear the fault as soon as possible
receiving-end bulk power system	Over-voltage ride-through before fault clearance; (possible) over-voltage ride-through after fault clearance	with little involvement	(for inverter station) under-voltage ride-through before fault clearance; (possible) over-voltage ride-through after fault clearance	clear the fault as soon as possible; (possible) over-voltage ride-through after fault clearance

8.2 The core and key issues

8.2.1 Fault response in different kind of faults

8.2.1.1 Faults in VSC-HVDC system

The possible faults in a VSC-HVDC system can be divided into broken line fault, pole-to-ground fault and pole-to-pole short circuit fault. These faults are very likely to exist in sea water, thus the broken line fault is equivalent to the pole-to-ground fault, and the pole-to-pole short circuit fault is equivalent to the pole-to-ground fault of both poles in a VSC-HVDC system.

The challenge for the protection and clearance of the faults in a VSC-HVDC system is that the rapid increasing short-circuits current can easily devastate IGBTs of VSC. Fault clearing can be done by trip of AC breakers supplying converter (in case of half bridge converters) or by DC voltage reduction and recovery in case full bridge converters are used. “Converter lockdown” is not a used term.

Another method is to use DC breakers for fault clearing. DC breakers are mainly utilized for a VSC-based DC-grid. Owing to their high costs, both the VSC-based DC-grid and the DC breakers are rarely adopted for offshore wind farms via the connected VSC-HVDC systems. So the fault clearance via DC breakers is not discussed in this Clause 8.

If the faults can be cleared within several milliseconds (for example, 6 ms), the voltage swell in offshore wind turbines and their power collection systems are very limited due to the very short length of power transmission hindrance. Hence the next challenge after fault clearance is the maintenance of wind farms power output and VSC-HVDC systems power transmission.

In addition, the main electrical connection scheme and return scheme, play important roles in the remaining power transmission after fault clearance and the shutdown possibility of wind farms and VSC-HVDC systems, and this can be summarized in Table 3.

Table 3 – Summary of power maintenance or shutdown after the clearance of faults in a point-to-point VSC-HVDC system

Main electrical connection scheme	Return scheme	Pole-to-ground fault	Pole-to-pole short circuit fault
Monopole	With earth return or dedicated metallic return	Shutdown	-
Symmetrical monopole	Without return	Shutdown	Shutdown
Bipole	With earth return or dedicated metallic return	Part of offshore wind farms can be maintained via faultless pole of a rigid bipole point-to-point VSC-HVDC system with earth return or dedicated metallic return.	Shutdown
	Without return (e.g. rigid bipole)	Shutdown	Shutdown

In many instances, after the fault clearance in a point-to-point VSC-HVDC system, the offshore wind farms and the VSC-HVDC system are totally shut down. As an example, the Rudong Offshore Wind Power VSC-HVDC project (abbreviated to Rudong VSC-HVDC project) in China, takes symmetrical monopolar main electrical connection scheme, and it has not return circuit. As a result, both poles of Rudong VSC-HVDC project share one converter on rectifier or inverter side. So even after the clearance of pole-to-ground fault, the offshore wind farms and their connected point-to-point VSC-HVDC systems are totally shut down.

If a point-to-point VSC-HVDC system adopts rigid bipole main electrical connection scheme with earth return or dedicated metallic return, part of offshore wind farms can be maintained via faultless pole after the clearance of pole-to-ground fault. In this instance, the cooperation between point-to-point VSC-HVDC system's power shift and offshore wind farms are usually required. However, the return highly increases the cost of a point-to-point VSC-HVDC system.

8.2.1.2 Faults in offshore wind power collection system

Usually, every offshore wind farm has only one rectifier station for its power collection, thus there is no difference for the faults in offshore wind power collection system.

As shown in Figure 12, after the fault in offshore wind power collection system, the activation of AC protection and AC breakers cuts off the faulty line and its connected wind turbine generators. Generally, faults in offshore wind power collection system are very likely to be permanent, so even asymmetrical fault does not require the reclosing process in AC protection.

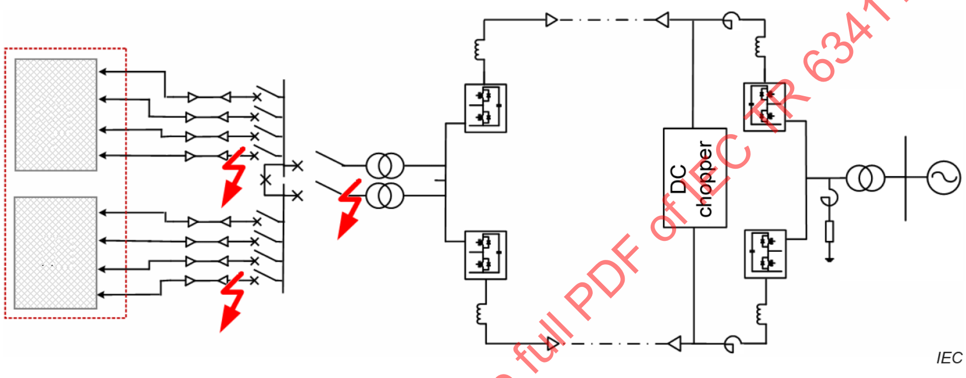


Figure 12 – Faults in offshore wind power collection system

The transient behaviour during faults in the offshore array can differ significantly depending on type of fault (1ph, 2ph, 3ph, with or without contact to ground), earthing impedance and controller functionality. Due to the fact that the activation of AC breaker usually takes place from 60 ms to 100 ms, during the interval from fault to its clearance, the wind turbine generators and rectifier station face severe under-voltage ride-through.

In addition, after the fault clearance, it takes some time to perform the offshore wind and connected VSC-HVDC power recovery. Before the total recovery, the excessive energy and hindered power are accumulated in offshore wind turbines, in offshore wind power collection systems or in grid-connected VSC-HVDC systems, and these systems and devices experience grave voltage swell. Moreover, an overvoltage after fault clearing is not the consequence of stored energy but of the controller behaviour.

8.2.1.3 Faults in main AC system

Generally, the activation of AC protection and AC breakers cut off the faulty line after the fault in receiving-end bulk power system, as shown in Figure 13.

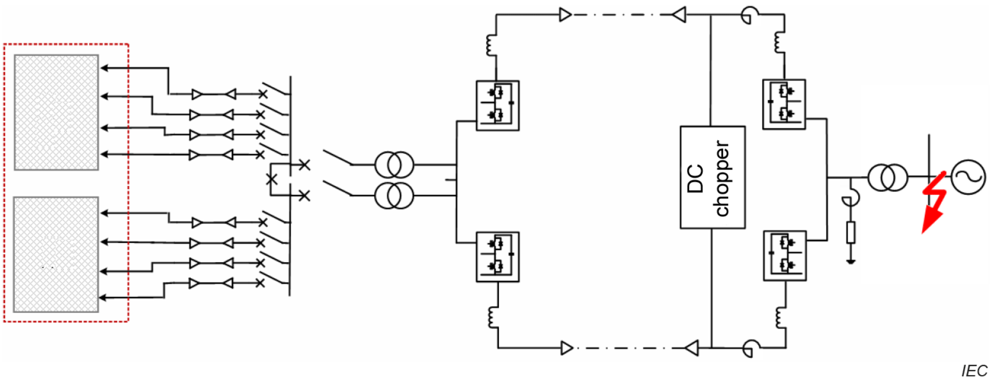


Figure 13 – Faults in receiving-end bulk power system

The asymmetric faults in receiving-end bulk power system cannot reduce all of the power transmission from inverter station, but cause the loop current in converters. Fortunately, the current control for loop current damping and converter transformer's proper connection group are rather effective, in most cases VSC converters are free from risks of loop current.

The nearby three-phase fault is the main problem that hinders power transmission and leads to the undue high voltage. Another is to install a dynamic braking system (such as AC Chopper or DC Chopper) in connected VSC-HVDC systems, so that excessive power can be depleted by the dynamic braking system.

8.2.2 Duty segregation in fault response and coordinated control

1) Short-circuit fault in offshore wind power collection system

   a) Offshore wind power collection system

      In offshore wind power collection systems, the reliable AC protection without reclosing is required for the sake of fault clearance. Before the fault clearance, offshore wind turbines with their power collection systems, and the rectifier station withstands the under-voltage ride-through.

   b) VSC-HVDC system

      The total loss of the offshore array cable system due to one fault is unlikely, in this case it makes more sense to keep the HVDC up and running, to separate the faulty section and restart the healthy part of the offshore AC system. However, if the fault clearance results in the total loss of AC link between offshore wind turbines and rectifier station, the corresponding rectifier station takes the action of immediate lockdown, and then all offshore wind powers with connection to this rectifier are lost.

2) Pole-to-ground fault in point-to-point VSC-HVD

   The fault control concentrates on fast fault clearance. If the point-to-point VSC-HVDC system adopts bipole main connection scheme with earth return or dedicated metallic return, the power transfer from faulty pole to faultless pole is required.

   The fault clearance is realized via faulty pole's lockdown. Usually, the lockdown execution and the successive power transfer are fast enough to avoid the severe excessive power and over-voltage ride-through. The concentration of fault ride-through and control is the speed of successive power transfer after faulty pole's lockdown. If the point-to-point VSC-HVDC system adopts rigid bipole main connection scheme with earth return or dedicated metallic return, the power transfer from faulty pole to faultless pole performs as soon as possible.

   If converter capacity cannot maintain "N-1" principle, i.e., faulty pole's power cannot be fully transferred due to lack of faultless pole's capacity, part of offshore wind power is curtailed. Before the activation of AC breakers for wind turbine generator tripping, offshore wind turbine generators experienced severe DC overvoltage and excessive energy. To tackle this problem, one possible option is to actively lower wind turbines' output via instant communication, and another technical option is to activate DC Chopper inside these wind turbines.

3) Bipolar short-circuit fault in point-to-point VSC-HVDC

   The fault control focuses on the fast fault clearance, but the bipolar lockdown of rectifier station, as the execution of fault clearance, inevitably results in the total loss of offshore wind power. The main challenge is that offshore wind turbine generators often confront severe under-voltage ride-through. This is due to the fact that the rectifier is uncontrollable and can afford no voltage support after its bipolar lockdown.

4) Short-circuit fault in receiving-end bulk power system

   The fault control focuses on the depletion of hindered and excessive energy due to fault in receiving-end bulk power system. It is obvious that the protection in receiving-end bulk power system is obliged for fault clearance, and it is inverter station's duty to dampen its current loop when asymmetric fault occurs.

With regard to the energy depletion, in common practice, both offshore wind turbines and their connected VSC-HVDC system can be equipped with DC Chopper. And these DC Choppers, wherever they are located in, merely be activated according to their own strategy, so the cooperation with each other is required.

8.3 Fault control

8.3.1 Optional fault ride-through technical solutions

There are four optional fault ride-through technical solutions, and the advantages and disadvantages of each solution are as follows:

1) The fault ride-through cannot merely rely on the ability of the devices to withstand under/over-voltage.

   It can be inferred from engineering experience that, the mere reliance on devices' ability to withstand is insufficient. It probably requires excessive margin of this ability for most devices. The future study does not focus on the feasibility of this technical solution.

2) The auxiliary de-loading devices of both offshore wind farms and the connected VSC-HVDC systems cooperatively carry out the energy dissipation to assist the fault ride-through.

   This solution is most technical valuable, but it is the most intricate in practice and the most controversial in duty segregation. It is estimated that a large amount of work was required to clarify the numerous controversial details, such as responsibility in different ownership, control of communication delays, etc.

3) The auxiliary de-loading devices of VSC-HVDC solely carry out the energy dissipation to assist the fault ride-through.

   In most cases of fault ride-through, offshore wind farms don't participate the auxiliary de-loading and theoretically VSC-HVDC does solely carry out the power dissipation due to this solution. And the design of fault ride-through strategy can be largely simplified.

4) The auxiliary de-loading devices of offshore wind solely carry out the energy dissipation to assist the fault ride-through.

   Due to the fact that offshore wind cannot directly recognize the AC fault on inverter side, the involved rectifier station cooperatively reduces its voltage output to indirectly activate islanding offshore wind's under/over-voltage ride-through, which means offshore wind's DC Choppers curtail excessive power and tackle overvoltage. This solution is viable in mechanism, but its engineering feasibility can be validated in future works. Moreover, this solution can be invoked as a back-up protection in the event of a failure of the dynamic braking system of de-loading devices of VSC-HVDC.

8.3.2 Technical requirements in coordinated control

Further study is performed on technical requirements for auxiliary de-loading devices (e.g. DC Chopper), power transfer inside VSC-HVDC, the ability to withstand under/over-voltage ride-through, and the coordination of these three issues during the fault response, ride-through and coordinated control in offshore wind farm grid-connected with VSC-HVDC system.

1) The ability to withstand under/over-voltage ride-through

   This aspect includes the ability to withstand under/over-voltage ride-through, such as the ability to withstand the magnitude and duration of low/high voltage, and involves the devices in the connected VSC-HVDC system, the offshore wind turbines and their power collection system.

2) The activation of auxiliary de-loading device

   This aspect includes the technical specifications for auxiliary de-loading devices (e.g. DC Chopper) in offshore wind turbines and the connected VSC-HVDC system, such as the installation capacity, the maximum energy depletion in once activation, and the rate of depleting excessive energy.

3) The power transfer in VSC-HVDC system

   This aspect includes the ability of power transfer in VSC-HVDC system, such as the capacity, the maximum rate of power ascending for each converter station.

4) The coordination in fault response, ride-through and control

   This aspect includes the time sequence cooperation in strategies of AC/DC protections, converter controllers and auxiliary de-loading devices, in conjunction with the cooperation of active/reactive power output in various converters and wind turbine generators.

8.4 Summary

According to the DC transmission technology and the fault locations, several HVDC topologies and three types of faults are adopted to discuss the fault response and coordinated fault control in an offshore wind farm and HVDC system. The HVDC technologies are point-to-point VSC-HVDC system and VSC-based DC grid, and the fault location includes the offshore wind power collection system, VSC-HVDC systems and the receiving-end bulk power system.

1) In terms of the duty segregation and required performance among the among each device's fault control (e.g. the activation of de-loading devices of offshore wind farm and the connected VSC-HVDC system), the issues are summarized in Table 4.

Table 4 – Summary of duty segregation for VSC-HVDC systems

No.	Fault location	Duty segregation
1	offshore wind power collection system	Offshore wind farm withstands the fault ride-through as longs as V-t characteristic is within required range. Fault in offshore wind power collection system requires being cleared without reclosing. HVDC Rectifier station keeps being operational if possible.
2	connected VSC-HVDC system (unipolar fault)	For point-to-point VSC-HVDC, the fault pole requires lockdown. The power transfer to another pole requires being executed (For a bipolar scheme with dedicated metallic return or earth return). If power transfer function cannot deal with excessive power, the duty segregation among de-loading devices of offshore wind farm and the connected VSC-HVDC system require being clarified. Both offshore wind farm and connected VSC-HVDC system require withstanding the over-voltage ride-through.
3	connected VSC-HVDC system (bipolar short-circuit fault)	For point-to-point VSC-HVDC, it requires to carry out the bipolar block down and AC breaker requires to be activated. Before the activation of AC breaker, wind turbine generators require carrying out its low-voltage strategy. If power transfer function cannot deal with excessive power, the duty segregation among auxiliary de-loading devices of offshore wind farm and the connected VSC-HVDC system requires being clarified.
4	receiving-end bulk power system	VSC-HVDC's controller requires dampening current loop due to asymmetric fault. If power transfer function cannot deal with excessive power, the duty segregation among auxiliary de-loading devices of offshore wind farm and the connected VSC-HVDC system requires being clarified.

2) In terms of the technical requirement among offshore wind farm and the connected VSC-HVDC system, the issues to be contained in further works are summarized in Table 5.

Table 5 – Summary of technical requirement for VSC-HVDC systems

For connected point-to-point VSC-HVDC system	For auxiliary devices (e.g. DC Chopper)
Withstanding to AC temporary high voltage (such as the ability to withstand the magnitude and duration of AC temporary overvoltage); Withstanding to low voltage (such as the ability to withstand the magnitude and duration of low-voltage); Ability of power transfer, such as the transmission capacity and converter's rate of power ascending.	Such as the installation capacity, the maximum energy depletion in once activation, and the rate of depleting excessive energy.
For wind power collection system	**For cooperated fault response and control**
Withstanding to AC temporary overvoltage (such as the ability to withstand the magnitude and duration of AC temporary overvoltage); Withstanding to low-voltage (such as the ability to withstand the magnitude and duration of low-voltage).	One important aspect of this topic is time sequence cooperation in strategies of protections, converter controllers and auxiliary de-loading devices. Another important aspect is the cooperation of active/ reactive power output in various converters and wind turbine generators.

9 Multi-frequency oscillation

9.1 Problem statement

The multi-frequency oscillation phenomenon of the offshore wind farm via VSC-HVDC grid-connected system frequently occurs, which seriously threatens the safe and stable operation of the system and equipment. For example, in 2013, the BorWin1 offshore wind farm in Germany's North Sea has a harmonic oscillation of around 250 Hz, the impedance of the system is small and cannot provide sufficient damping, which causes voltage and current oscillations, resulting in system instability. In 2014, the Nan'ao three-terminal wind farm VSC-HVDC grid-connected system experienced sub-synchronous oscillations in the range of 20-30 Hz. In addition, similar wind oscillations have occurred in other wind farms in the world. The offshore wind farm VSC-HVDC system is a power system with a high proportion of power electronic devices, and the control bandwidth of these power electronic devices reach several kilohertz. Due to the wide control bandwidth and long control delay, the impedances of both RE and VSC-HVDC are negative over a wide frequency range, resulting in the dynamic behaviour characteristics of offshore wind farm VSC-HVDC system being significantly different from traditional power systems dominated by electromagnetic equipment, whose control bandwidths are usually below 100 Hz. In addition, the interaction between offshore wind farm and VSC-HVDC system make the dynamic characteristics of offshore wind farm VSC-HVDC become more complicated.

9.2 The core and key issues

9.2.1 General

The analysis methods for broadband oscillation of power system mainly include impedance-based stability analysis method, impedance scanning analysis method, passivity analysis method, modal analysis method and time-domain stability analysis method.

9.2.2 Impedance-based stability analysis method

9.2.2.1 General

Offshore wind farm VSC-HVDC Integration is a typical power electronic interconnection system. In order to investigate the dynamic characteristics of the system after the interconnection of the power electronic converter, it is necessary to propose a suitable stability analysis method for power electronic interconnection system. The impedance analysis method is a method especially suitable for the study of oscillation or small disturbance stability of complex power electronic interconnection systems. The impedance analysis method decomposes the system into a power subsystem and a load subsystem. The power subsystem is described by an ideal voltage source with output impedance, and the load subsystem is replaced by its input impedance, as shown in Figure 14. If the impedance ratio of the two systems satisfies the Nyquist stability criterion, the system is stable.

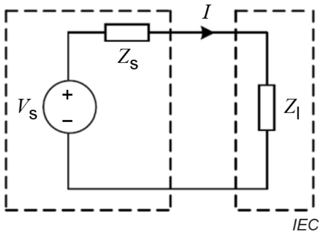


Figure 14 – Mathematical model of impedance method

The method divides the system into a power subsystem and a load subsystem according to the regions of interest, and establishes these two sub-systems respectively. If the source subsystem and load subsystem are stable respectively, the stability of the interconnected system is determined by the ratio of the HVDC impedance to the RE impedance.

The wide-band dynamic model of the system analyzes the interaction process between the two to reveal the broadband oscillation mechanism of the power electronic interconnection system. The impedance analysis method is based on harmonic linearization to model power electronic equipment. It requires less information about the system and is easy to understand and used, suitable for the analysis of resonance characteristics of VSC-HVDC connected offshore wind farms.

9.2.2.2 Typical modelling of VSC-HVDC

In offshore wind farm HVDC connect applications, the onshore side converter of VSC-HVDC adopts grid-following control to maintain DC voltage stability, while the offshore side converter of VSC-HVDC adopts V/f control acting as a voltage source and maintaining the AC voltage and frequency steady. Therefore, no PLL is used in the offshore side converter of VSC-HVDC. The offshore wind farm acts as a current source and transmits power to the HVDC system. A typical control strategy of voltage-controlled VSC-HVDC is as follows. After adopting the circulating current suppression strategy, the effect of circulating current on the impedance of VSC-HVDC is ignorable, so the circulating current suppress control is omitted in Figure 15.

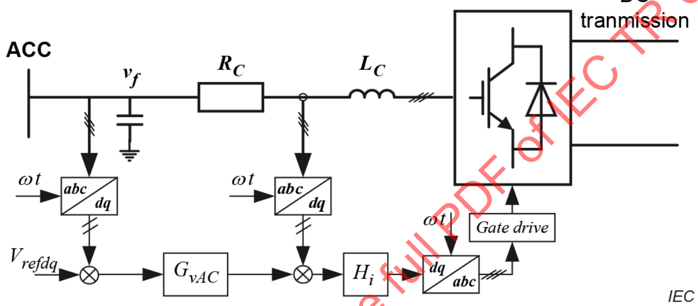


Figure 15 – Typical control strategy of voltage controlled VSC-HVDC

Under the typical control strategy, the positive and negative sequence impedance model of the converter can be established based on harmonic linearization, and the positive impedance of the VSC-HVDC is shown in (9-1). Note that the impedance is highly related to the control strategy, the impedance changes along with the strategy.

$$Z_{\text{vsc}} = \frac{sL + \left(G_{\text{i}} - jK_{\text{d}}\right) G_{\text{si}} G_{\text{d}}}{1 - G_{\text{d}} G_{\text{sv}} + G_{\text{sv}} G_{\text{VAC}} G_{\text{i}}\, G_{\text{d}}} \tag{9-1}$$

where

G_{d}	is the delay;
L	is the equivalent inductance on the AC side of VSC;
G_{i}	is the transfer function of current control loop;
K_{d}	is the decoupling coefficient if current control loop;
G_{si} and G_{sv}	are the transfer function of the current and voltage sampling link, respectively;
G_{VAC}	is the transfer function of voltage control loop.

9.2.2.3 Typical modelling of offshore wind

The typical power circuit and control block diagram of wind power converters are shown in Figure 16. The control system includes phase current control and phase locked loop.

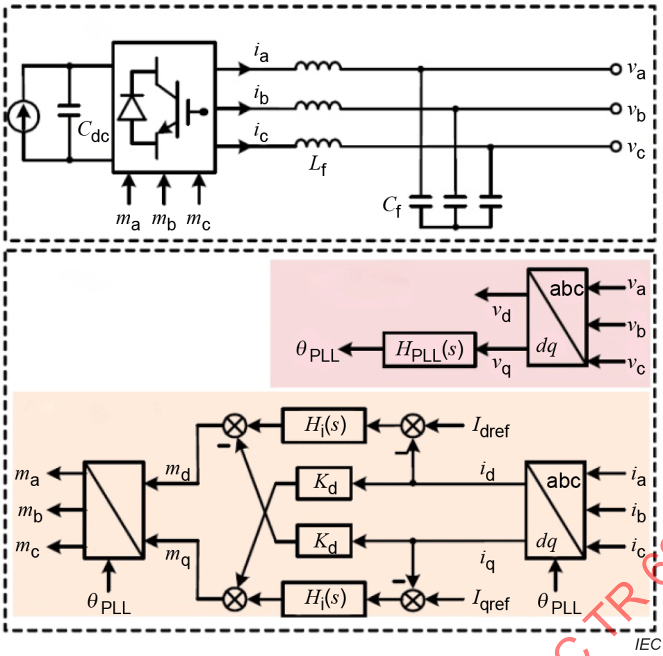


Figure 16 – Block diagram of wind power converter

Based on harmonic linearization, the positive and negative sequence impedance model of the converter can be established, the positive impedance of wind power converter is

$$Z_{PMSG}(s) = \frac{sL_f + K_m V_{dc}\left[H_i(s - j\omega_1) - jK_d\right]}{1 - \frac{1}{2}K_m V_{dc} T_{PLL}(s - j\omega_1)\left[I_1\left(H_i(s - j\omega_1) - jK_d\right) + M_1\right]} // \frac{1}{sC_f} \quad (9\text{-}2)$$

where

L_f and C_f	are filter inductance and filter capacitor at AC side respectively;
I_1	is the peak value of fundamental phase current at AC side;
V_{dc}	is the DC side capacitor voltage;
M_1	is the fundamental peak value of the modulated signal;
K_m	is the modulation ratio;
T_{pll} (s) and H_i (s)	are the transfer functions of PLL and current loop respectively;
K_d	is the decoupling coefficient of current loop;
ω_1	is the fundamental angular frequency.

9.2.2.4 Mechanism analysis method for multi-frequency oscillation

If both curves are plotted in a Bode diagram, each intersection of the curves can be critical. Therefore, the phase margin is calculated at each intersection. If it is low, the system has poor stability margin. At the frequency where the curves of the amplitudes have an intersection, the phase margin is calculated according to

$$\varphi_m = 180^\circ - \Delta\varphi \quad (9\text{-}3)$$

If the phase margin is less than 0, the system is unstable, as shown in the example in Figure 17.

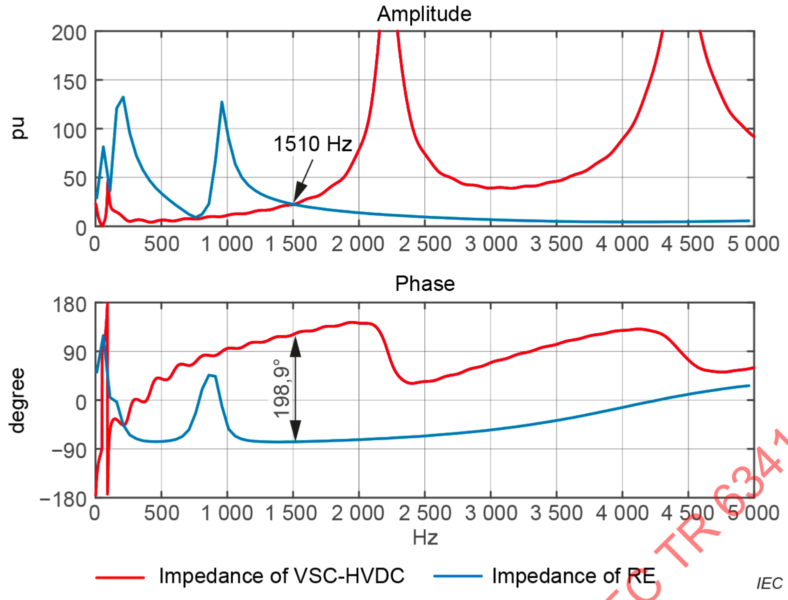


Figure 17 – Comparison of impedance characteristic curve

A big advantage of this method is that the frequency dependent impedance can be calculated with an analytic model, calculated with an EMT-tool or measured at a real generation turbine. Due to commercial and intellectual property reasons, the detailed control strategies and parameters are not available to get the theoretical models. In such cases, the impedance of offshore wind and VSC system can be obtained by testing the control and protection systems, and then the risk of oscillation can be judged using the impedance-based stability criterion. The effectiveness of a solution can be also tested and judged.

It is noted that when the positive and negative sequence impedances of the converter are coupled, the positive and negative sequence impedance matrix is established, thereby improving the accuracy of the resonance characteristic analysis. If Z_{source} and Z_{load} is the impedance matrix, the generalized Nyquist criterion is used to judge the resonance stability of the system.

9.2.3 Impedance scanning analysis method

Network impedance scanning is the most basic form of analysis technique that can be used to predict harmonic problems in power networks. Impedance scanning and subsequent analysis is an important tool in characterizing oscillations, and the way they propagate in the network and amplify or dampen in the process. Resonance analysis is conveniently done using so-called impedance scans, even in complex networks. An impedance scan returns the input impedance seen from a general location and is defined as

$$Z(s)=\frac{\Delta V(s)}{\Delta I(s)} \quad (9\text{-}4)$$

The input impedance $Z(s)$ can be physically interpreted as the ratio between the voltage perturbation $V(s)$ that occurs in a specific location as a result of a broad-spectrum current I(s) injected by an external source at the same or another location in the network. Bode plots of impedance and admittance can be used to easily identify series and parallel resonance through inspection. The high input impedance at a certain frequency indicates that a high voltage occurs at the point of injection if a constant current is injected at that frequency. While, the low input impedance means that even small voltage sources generate a large harmonic current at a particular frequency. These observations can be used as a first stage in harmonic analysis.

The input impedance can also be seen as a transfer function between injected current and voltage. Any impedance characteristic can be approximated by the form

$$Z(s)=K\frac{\prod_{i=1}^{n_b}(s-z_i)}{\prod_{i=1}^{n_a}(s-\lambda_i)} \tag{9-5}$$

where

z_i is the zeroes of the transfer function;

λ_i is the poles of the transfer function.

The zeros and poles of the transfer function are connected to series and parallel resonance phenomena in power systems. Assuming stationary sinusoidal excitation, and assigning s = jω, the poles of the transfer function determine the frequencies where the magnitude of the transfer function steady state gain is very high and its zeroes determine frequencies where the magnitude is very low.

Each pair of complex poles of Formula (9-5) corresponds to a parallel resonance at the natural frequency given by Im(λ_i) and likewise each pair of complex zeroes corresponds to a series resonance at the frequency Im(z_i). The frequency response can be used to determine the phase and steady state gain when harmonics of a certain frequency are injected at a point in the network.

9.2.4 Passivity analysis method

Passivity analysis is based on the calculation or identification of the input admittance/output impedance of converter systems. These can be derived analytically by hand calculation or through measurement and estimation. Specialized tools can also generate models of the form (Formula (9-6)), either through automatic linearization techniques or through curve fitting of calculated impedance responses. Passivity analysis is carried out using scans of the converter system active impedance, as opposed to the passive impedance only.

Modelling the small-signal behaviour of a converter system using its incremental impedance as described by (Formula (9-5)), the following relations hold:

$$U(s)=Z(s)I(s) \tag{9-6}$$

$$I(s)=Y(s)U(s) \tag{9-7}$$

$$Y(s)=Z(s)^{-1} \tag{9-8}$$

Passive systems have the following important properties:

- the inverse of a passive system is passive;
- the parallel interconnection of passive systems is passive;
- the feedback interconnection of passive systems is passive.

The first observation means that if an analysis of the output impedance of a converter results in the identification of passivity in a particular frequency range, the corresponding analysis using the input admittance gives the same results. Nevertheless, it is often useful to consider both since the result of the analysis can be more clearly visualized and interpreted in one or the other.

The second and third observations are useful in the analysis of several grid connected converters – if it can be shown that each of the individual converters as well as the grid connecting them are passive, the interconnected system is also passive. This can serve as a stability guarantee for the interconnected system.

9.2.5 Modal analysis method

The modal analysis method studies the stability of a system by solving the eigenvalues of the coefficient matrix of the system's small signal state equation.

The dynamic characteristics of power system can be expressed by the following equations:

$$\begin{cases} \frac{dx}{dt} = f(x,y) \\ 0 = g(x,y) \end{cases} \tag{9-9}$$

According to Lyapunov's first theorem, after linearizing the system at the equilibrium point, small signal state equation can be obtained

$$\frac{d\Delta x}{dt} = A\Delta x \tag{9-10}$$

where

A is the state matrix of the system.

The stability of the system can be judged by solving the eigenvalues of A.

The modal analysis method can obtain the system's broadband oscillation information and guide the optimal control of the system. Its advantages are high accuracy, and it can obtain quantitative evaluation indicators such as participation factors and sensitivity, which can be used to guide design. However, the modal analysis method relies on the complete information of the system. When the system structure changes slightly, the model is modified greatly, and there is the problem of large amount of computation compared to impedance analysis method, especially for complex power systems.

9.2.6 Electro-magnetic-transient simulation

The analysis and capture of the phenomena can be also performed by means of an electro-magnetic transient simulation (EMT) in the time domain. Using the capability of simulating and solving circuit dynamics, the oscillatory behaviour of the circuit is represented. In order to capture the phenomena, circuit dynamics and converter models are well represented for the frequency range under study. Grid components are modelled by frequency-dependent parameter models. As the damping increases with frequency, it can make the difference between a stable and non-stable system. Additionally, converter models can include all the control loops and represent different dynamics with sufficient level of detail. The use of black-box converter models, without access to the controllers and parameters, can ensure the confidentiality of the vendor’s intellectual property. One disadvantage is that it is almost impossible to identify unstable operating points with an EMT simulation. It is clear at which network configuration and which frequency a problem could occur, otherwise it is hardly possible to find it due to the long computing time in an EMT tool or only possible by coincidence. Furthermore, for EMT models the manufacturer provides a few signals of the control so that it is at least possible for the simulator to find out which converter is currently not running properly in the simulation.

9.3 Multi-frequency oscillation suppression technology

9.3.1 General

If the analysis of the oscillation mechanism shows the converter holds a negative damping ,it is most likely trigger an oscillation. In case the parameter combination results in a zero impedance and harmonics are amplified through AC/DC interaction, then an oscillation is likely to occur. Consequently, corresponding oscillation suppression measures are proposed, including controller parameter optimization design, control structure optimization, auxiliary active damping control loop and additional hardware oscillation suppression equipment, and operational scenarios.

9.3.2 Controller parameter optimization

Controller parameter optimization measures are usually used to suppress mid- and high-frequency resonances. The common suppression methods for mid- and high- frequency resonances include reducing the delay time of control system, reducing the proportional coefficient of current loop PI controller, and optimizing the AC voltage control, etc. The effect of the proportional coefficient of current loop PI controller on MMC’s impedance is shown in Figure 18. The smaller proportional coefficient, the smaller negative damping area of the converter impedance phase, implying that the converter impedance characteristics are improved.

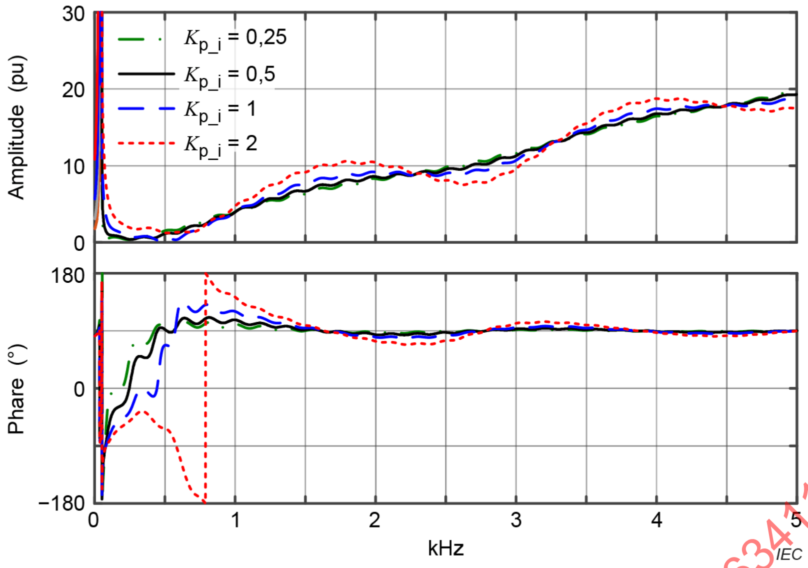


Figure 18 – Effect of control parameters on impedance characteristics

9.3.3 Control structure optimization and active damping control

Control structure optimization and active damping control are essentially to improve the VSC equivalent impedance by changing the control system structure, thereby suppressing the system resonance. In terms of optimizing the control structure or active damping control, the oscillation suppression measures are different for different frequency bands. For mid- and high-frequency resonance, a nonlinear filter or a low-pass filter is usually added to the voltage feed forward of MMC to improve the impedance characteristics. In addition, a suppression method called "virtual arm resistance" to stabilize the sub/super-synchronous oscillations was proposed, whose control diagram is shown in Figure 19. In the diagram, I_{comabc} and I_{comabc}^* are the common-mode currents and their references, R_{v} is the proportional gain that can be regarded as a virtual arm resistance, and the output $V_{\text{diff\_extra}}$ is added to the original modulation voltages. In this way, a virtual resistance is connected in series to each arm of the MMC, and circulating currents is restrained so that the resonance peaks on the impedance curves is suppressed.

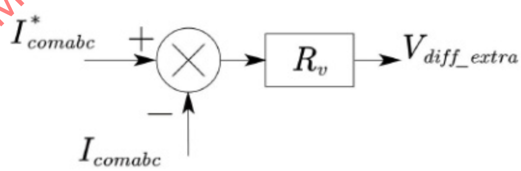


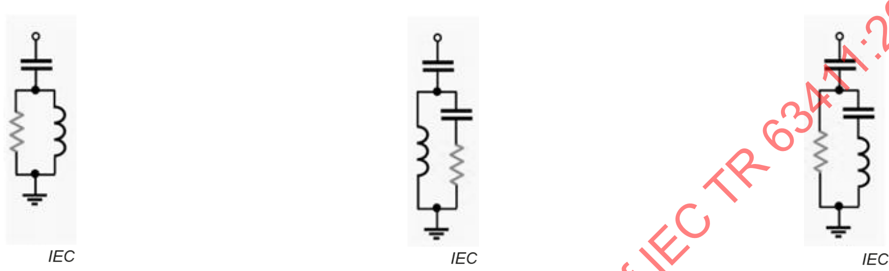
Figure 19 – Control diagram of virtual arm resistance method

9.3.4 Passive filters

From the perspective of system stability, the controller parameter design methods of offshore wind generator and VSC-HVDC is possible. However, experience shows that if there is improvement on one side, this is bought by deterioration on another side. Often, damping is achieved on a certain harmonic range, but other range is deteriorated. Since the fact that the actual system often has a narrow range of adjustable controller parameters and unsatisfactory adjustment effects, parameter optimization is especially difficult when the control delay is long. There is no guarantee that such oscillation can be damped by software optimization.

Consequently, it is possible to consider the use of additional hardware oscillation suppression equipment to improve the damping effect of the offshore wind VSC-HVDC connected system without changing the control parameters and control structure of the original system equipment. This can suppress the oscillation if properly designed at the price of adding extra economic cost land occupation. The passive damping filters can be connected in parallel or in series with the VSC or offshore wind converters.

Figure 20 shows three possible parallel-connected damping filters. These damping filters can greatly reform the impedance characteristic of the converters in mid- and high-frequencies as it is equivalent to a small resistor in these frequencies. Such AC filter has been widely used in LCC-HVDC and has a successful industrial application. As these filters are connected to the high AC voltage, e.g.66 kV, 155 kV, 220 kV or even 380 kV, the land occupation and cost can't be ignored.



a) Second-order high pass filter **b) Third-order high-pass filter** **c) C-type filter**

Figure 20 – Potential parallel-connected damping harmonic filters for VSC

Figure 21 shows a typical serial-connected second-order damping filters circuits based on single-tuned filters. The single-tuned filter is formed by L_r and C_r, and is a series resonant circuit connected in parallel with the damping resistor. The L_r and C_r is designed to resonate at the fundamental frequency, the series resonant circuit bypasses the fundamental current. For mid- and high-frequencies, the additional damping R_d is inserted.

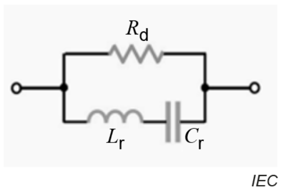


Figure 21 – A typical serial-connected damping filters

There are many different options to achieve similar damping effects, and they can differ significantly from each other in terms of size and power loss. Therefore, design for a specific application includes a trade study to compare different options and their performances. The added single-tuned or broadband filter inductor and capacitor also form new resonance with other components in the system, which is carefully evaluated.

9.3.5 Operational scenarios

In the project operation stage, the above suppression measures all have certain limitations. Changing operational scenarios can be very effective solution in the operational phase of a project. Oscillation is caused by the interaction of VSC-HVDC and AC system. By changing operating scenarios, the AC system impedance can be adjusted to suppress oscillations.

9.4 Summary

As explained in 9.2, there are multiple methods to analyze and estimate the potential oscillatory behaviour. The common methods include impedance-based stability analysis method, impedance scanning analysis method, modal analysis method and time-domain stability analysis method.

The advantages and disadvantages of each method are shown in the Table 6.

Table 6 – Comparison of different analysis methods

	Methods	Advantages	Disadvantages
1	Impedance-based stability analysis	(1) It can accurately reveal the resonance mechanism (2) It requires less information about the system and is easy to understand and used. (3) The frequency dependent impedance can be calculated with an analytic model, an EMT-tool or measured at a real generation unit.	Accurate frequency dependent impedance of subsystem is used.
2	Impedance scanning analysis	(1) It has a wide range of applications and can analyze the impedance characteristics and stability of various complex power electronic converter systems in a wide frequency band. (2) It can be used as an auxiliary means to verify the correctness of the theoretical derivation of the impedance model.	(1) It is difficult to analyze the mechanism of oscillation and the nonlinear characteristics of the system. (2) The accuracy of the frequency scanning results is easily affected by the simulation step size.
3	Passivity analysis method	(1) It is an intuitive and relatively simple method that is easy to understand and apply. (2) It can be applied to various types of linear and nonlinear systems. (3) It provides a detailed description and analysis of the passive properties of a system.	(1) It has limitations and constraints when applied to nonlinear systems. (2) It relies on accurate physical models of the system. (3) It is highly sensitive to changes in system structure and parameters.
4	Modal analysis	(1) It can accurately judge the stability of the system and determine the dominant factors of oscillation. (2) This method is rigorous, accurate and can provide rich information.	(1) For high-order systems, modelling is difficult and computationally expensive. (2) It is only suitable for studying the stability near the equilibrium point of the system, and cannot characterize the nonlinear characteristics of the oscillation.
5	Time-domain stability analysis	(1) It is accurate, intuitive, can and provides abundant waveform information. (2) It can describe the dynamic characteristics of the system at different time scales, and comprehensively reflect the influence of the nonlinear characteristics of the system on the oscillation.	It is difficult to analyze the occurrence mechanism, influencing factors and suppression measures of oscillation

Accurate modelling of RE VSC-HVDC integration is the key to analyze the multi-frequency oscillations of this interconnected system. The system stability can be analyzed by applying the Nyquist Stability Criterion to the ratio of HVDC impedance and offshore wind turbine impedance. The negative damping of the VSC-HVDC and/or offshore wind turbine is the essential reason for multi-frequency oscillations. From system perspective, the oscillation can be damped by optimizing the control strategy or parameters or adding extra passive damping.

10 Control and protection function verification

10.1 Problem statement

The control and protection (C&P) system is the vital equipment for the safety operation of VSC-HVDC connection of offshore wind farm. Compared with the conventional VSC-HVDC project or wind power projects connected to the grid via AC transmission mode, the C&P system of wind power projects connected to the grid via VSC-HVDC has different functions and dynamic performance requirements, such as different charging modes of offshore converter station (DC charging mode from onshore converter station, or AC charging mode from offshore diesel generator), different control modes of VSC-HVDC converter (AC voltage and frequency control), different AC fault ride through characteristics of onshore converter station, different reactive power control and coordinate active power control, open line test mode, etc. In order to verify the C&P system functions and dynamic performance and meet VSC-HVDC connected offshore wind farms project design requirements, it is the mainstream practice to build the Hardware-in-the-Loop system with simulator and the C&P cubicles before on-site commissioning. As Figure 22 shows, the off-site C&P system verification is the link between the design and manufacture of C&P system and the on-site testing. It is useful to illustrate the simulation of the C&P system of VSC-HVDC connected offshore wind farms project.

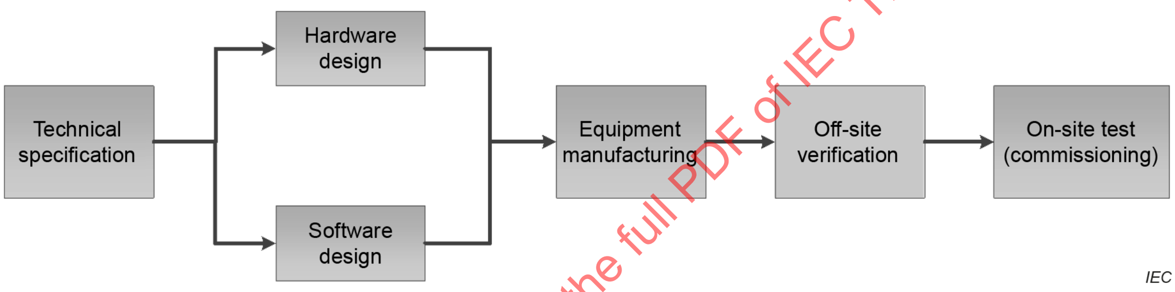


Figure 22 – Control and protection system life cycle diagram

10.2 The key issues

10.2.1 The C&P verification system

The C&P verification system includes C&P system and simulation models. The simulation model simulates the main circuit of offshore wind farm system, AC system of receiving end and VSC-HVDC transmission system. As shown in Figure 23, the C&P Hardware-in-the-Loop verification system mainly includes three parts.

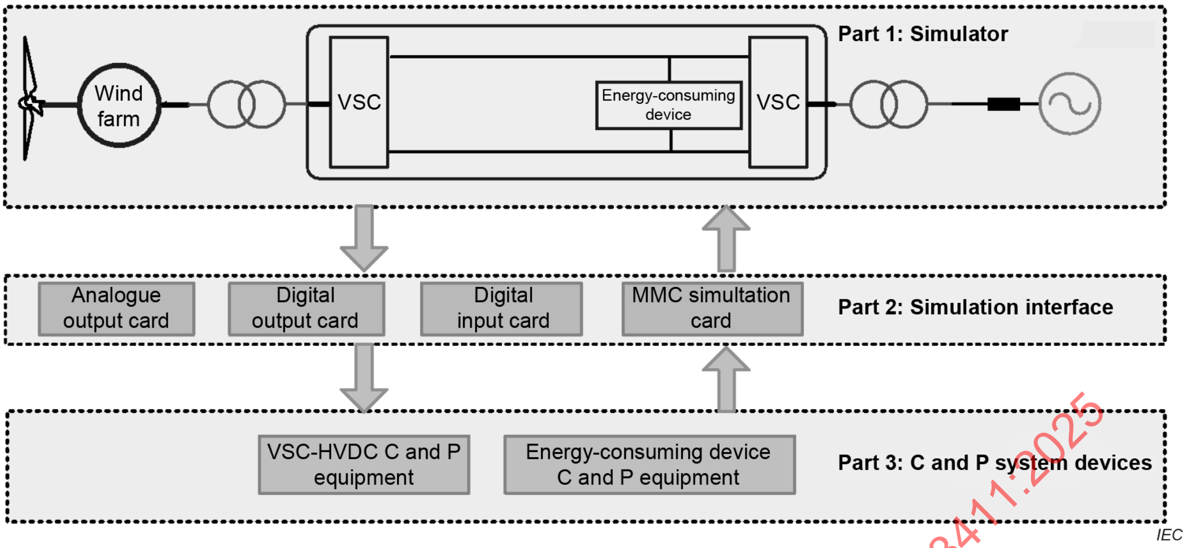


Figure 23 – The schematic diagram of simulation system

The first part is the simulator which is used to simulate the primary main circuits. The second part is the simulation interface devices. The third part is the control and protection system for the VSC-HVDC connection of offshore wind farm project. The verification system includes the C&P real-time simulator, simulation interface devices and the C&P devices of VSC-HVDC, offshore wind power and onshore braking chopper. The simulator is used to simulate main circuit components of VSC-HVDC, wind power and onshore braking chopper, adjacent AC system, and/or adjacent HVDC transmissions. Simulation interface devices are used for the connection and communication between simulator and C&P devices.

10.2.2 Functions of C&P verification system

In order to ensure the safe and stable operation of the VSC-HVDC system connection of offshore wind farm, it is of great significance to test the control and protection system. In general, the control and protection functions of the VSC-HVDC system connection of offshore wind farm mainly include the following categories as shown in Table 7, which can be tested in C&P verification system.

Table 7 – C&P system Functions

Function	Sub-function	Content
Control functions and dynamic performance	Sequences control [a]	-
	Converter transformer energizing	Transformer with Saturation characteristic
	Black start control [a]	Transformer with Saturation characteristic; Valve control equipment and its simulation interface devices are equipped.
	Open line test [a]	-
	Deblock-block	-
	Control mode transfer	-
	Steady state performance	-
	Coordinated active power control [a]	The offshore wind power farm model as detailed as possible
	Reactive power control [a]	Adjacent AC system(s), and/or adjacent HVDC (if any)
	Step response	-
	Abnormal measuring performance [a]	Measurement system loop as consistent as possible with the field
	Multi-frequency oscillation control [a]	The offshore wind power farm model with precise impedance characteristics; adjacent AC system(s), and/or adjacent HVDC (if any) on onshore converter station
	AC fault ride through control [a]	Energy-consuming device models based on FPGA hardware Energy-consuming device control and protection system and its simulation interface devices are equipped; adjacent AC system(s), and/or adjacent HVDC (if any) on onshore converter station
	Energy-consuming device control [a]	
	Valve control [a]	MMC models based on FPGA hardware; Valve control equipment and its simulation interface devices are equipped.
	Accessory control function (if any)	-
	Coordinated control for VSC-HVDC and offshore wind farm (if any) [a]	-
	Other control functions (if any)	-
Protection function	Trip circuit and action	-
	Converter/pole protection selectivity	-
	DC line area protection [a]	The common way is to use the distributed parameter frequency-dependent model for cables and transmission line.
	Valve protection	
	Energy-consuming device protection [a]	Energy-consuming device models based on FPGA hardware Energy-consuming device control and protection system and its simulation interface devices are equipped
	Other protection (if any)	Control system, protection system, measurement system, monitoring system, and fault recording system are equipped.
	Redundant control system	Redundant control and protection devices are equipped.
	Redundant protection system	
	Evaluation of C&P system delay [a]	Valve control equipment, energy-consuming device control and simulation interface devices, submodule control board are equipped.

[a] means the special characteristics for VSC-HVDC system connection of offshore wind farm.

10.3 The key verification and evaluation items

10.3.1 General

The C&P system functions are verified in the simulation system, to verify whether these functions meet the requirements of the design specifications or not. The control function and protection areas depend on projects. If the following function and protection area(s) don't exist for a specified project, the related verification is unnecessary. The test methods of several functions closely related to the VSC-HVDC system connection of offshore wind farm are presented below.

10.3.2 Verification for multi-frequency oscillation control

1) Function: the multi-frequency oscillation control function mainly includes the multi-frequency oscillation suppression function on the AC side and VSC-HVDC side.
2) Test items design: the common way is to consider different AC grid connection modes and active wind turbines capacity and power.
3) Special requirement for verification system: The offshore wind power farm model with precise impedance characteristics. Adjacent AC system, and/or adjacent HVDC (if any) on onshore converter station are suggested to be included in the simulation model. The feeder lines from wind turbines and offshore station are suggested to be modelled as detailed as possible. The Wind turbine converter controller devices or detail digital controller model are suggested to be equipped.
4) Evaluation method: the multi-frequency oscillation suppression function can work effectively in different operation modes.

10.3.3 Verification for AC fault ride through control

1) Function: AC fault ride through coordination function with energy consuming device for onshore station AC side fault, AC fault ride through coordination function with wind farm for offshore station AC side fault.
2) Test items design: the common way is to consider different AC fault modes, fault duration and active wind turbines capacity and transmission power.
3) Special requirement for verification system: Energy-consuming device models based on FPGA hardware, and energy-consuming device control and protection system and its simulation interface devices are equipped. The adjacent AC system, and/or adjacent HVDC (if any) on onshore converter station.
4) Evaluation method: the HVDC system and wind farm can recover smoothly when the fault disappears, and the power recovery time meets the design requirements.

10.3.4 Verification for energy-consuming control and protection device

1) Function: energy-consuming device includes power electronic switch and energy-consuming resistor with different topologies. The main verification of energy-consuming devices involves the following functions: switching strategy control, over voltage suppression effect, power electronic switch control and essential protection functions of power electronic switch, the protection and supervision for energy-consuming device in different work states. The work states mainly include: startup, charge, block and deblock control functions.
2) Test items design: the common way is to consider different fault types, locations and work stage for energy-consuming device. And consider the test for supervision, overvoltage protection for the energy consumption, and overload protection of the dynamic braking resistor device, etc.
3) Special performance for verification system: Energy-consuming device models based on FPGA hardware, and energy-consuming device control and protection system and its simulation interface devices are equipped.
4) Evaluation method: the control and protection function can work normally in different work stages. The energy-consuming device control acts properly in coordination with the rest of the HVDC system control when AC fault occurs in the onshore grid.

10.3.5 Verification for black start control

1) Function: the offshore wind farm with VSC-HVDC system black start control is one of key functions. The following function performances require special attention and test: AC side charging strategy for onshore converter station, DC side charging strategy for offshore converter station, DC voltage control strategy for onshore station, VF control strategy for offshore station, protection and protective monitoring function in case of fault in black start process, and the energization control of the offshore wind farm.
2) Test items design: It is useful to consider the charging progress from offshore station to feeder and wind farm transform step by step after the black start of the offshore station; and consider not only the normal black start process, but also the ground fault in the black start test.
3) Special performance for verification system: transformer with saturation characteristic model is included; MMC valve control equipment and its simulation interface devices are equipped.
4) Evaluation method: onshore/offshore stations and wind farm can deblock and block smoothly without trip in black start progress. If any fault occurs in black start progress, protection can act to protect equipment.

10.4 Summary

Hardware-in-the-loop simulation verification is an effective method and mainstream practice for C&P system before on-site testing. It is able to verify whether the requirements of function and design specifications of control and protection systems can be achieved to provide practical guidance for the functional performance verification for the offshore wind power integration via VSC-HVDC projects, and to minimize the possibility of control and protection systems defects on-site and the risk of failure, to improve and ensure the high reliability and availability for the projects.

11 Testing and commissioning

11.1 General

Commissioning happens during the last stages of connecting offshore wind farms using VSC-HVDC transmission. It assesses the functionality of all system elements and subsystems, including DC control and protection, converter valves and valve controls, transformers, water cooling systems, AC and DC field equipment, etc. The entire system is tested and certain performance parameters are measured. The purpose of commissioning is to verify whether the various subsystems are coordinated and whether they meet the requirements of relevant design specifications and the performance indicators guaranteed by the equipment technical specifications. In the commissioning process, the performance of the entire system and coordination among different subsystems are verified in order to investigate and solve the problems of the overall system in the grid-connection scheme of offshore wind farms using VSC-HVDC transmission. In addition, some necessary data and parameters are collected to ensure the economic and stable operation of the system in the future. After commissioning and trial operation, the grid-connection scheme of offshore wind farms using VSC-HVDC transmission is capable of being put into operation.

11.2 Special scheme of testing and commissioning

11.2.1 Process of testing and commissioning

For the grid-connection scheme of offshore wind farms using VSC-HVDC transmission, the factory tests, pre-commissioning, and subsystem tests of VSC-HVDC and wind farms are implemented independently. Eventually, the commissioning of the two systems is conducted together as the last step of the test process.

Testing and commissioning of the grid-connection scheme of offshore wind farms using VSC-HVDC transmission have to go through a long process, including a factory test stage and a site test stage. The former examines the separate primary and secondary devices in their factories, consisting of type test, routine test, and delivery test. The latter verifies the devices themselves and the systems formed by them in the field, consisting of pre-commissioning, subsystem test and commissioning.

1) Type test – the equipment test that verifies whether the equipment meets the relevant industrial standards and meets the requirements of the operation environment. The test cycle is carried out in accordance with the relevant national standards. Type tests are performed once for each type of equipment. Type tests can be omitted if corresponding type tests had been performed before for the same type of equipment.
2) Routine test – test required for each device leaving the factory. The test mainly verifies whether the electrical performance of the equipment meets the relevant industrial standards and the operation environment. All types of equipment used in the project are tested.
3) Delivery test – equipment test that is conducted in detail before leaving the factory to verify the function, performance, and correctness of parameters. Before the equipment is delivered to the field, the function and performance of any single device are verified.
4) Pre-commissioning – the equipment commissioning and tests which are the electrical and mechanical commissioning and simple functional tests performed on all installed items of equipment or plant.
5) Subsystem commissioning – the proving of interconnection and functioning of all individual items of equipment within a functional group (or subsystem) and that these items operate and interact correctly. Generally, subsystem commissioning relies on the local power source.
6) Joint commissioning – the start-up and testing begin with the initial energization of the equipment, while ending with the total system in operation and at full power transfer. Once islanded offshore wind farm operation is not available, the energization of the complete HV system happens step-wise from the onshore side using some AC power from the onshore grid.

Also as elaborated in Figure 24, the test of an offshore wind farm includes factory test and site test. The site tests are implemented in the sea where lack of necessary power source. A vessel with electricity generators can be utilized to supply power. Test of every wind turbine is conducted in this stage, after which the commissioning is carried out for the whole wind farm with VSC-HVDC.

Clause 11 focuses on the commissioning part, which is marked in bold in Figure 24.

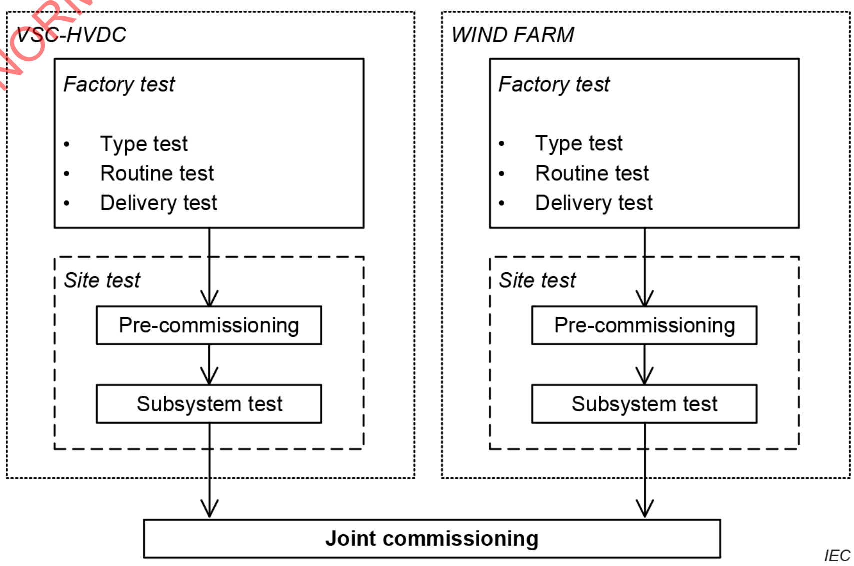


Figure 24 – Test process for the grid-connection scheme

11.2.2 Joint commissioning

Compared with the commissioning of conventional VSC-HVDC projects, the commissioning procedure, method and requirement of the VSC-HVDC project with integration of offshore wind farm are different, because of the special operating condition and the existence of onshore DC braking chopper, the offshore wind farm and converter station, as well as special transmission test items.

1) The system characteristics are different between the VSC-HVDC project with integration of offshore wind farms and conventional VSC-HVDC. In order to realize fault ride-through, a DC braking chopper is applied to the VSC-HVDC project with integration of offshore wind farms, which leads to the addition of commissioning steps related to the DC braking chopper. In addition, the energization path is disparate. Converters of the VSC-HVDC project with integration of offshore wind farms are energized one by one from onshore to offshore. The energizations of the onshore and offshore station are carried out from the AC side and DC side, respectively.
2) The onshore grid is prepared to provide active and reactive power for energization and to absorb the active power from the offshore wind farm during transmission tests. While converters of conventional VSC-HVDC can be energized at the same time since they both are connected to the AC power grid. In addition, the control modes are different. For the VSC-HVDC project with integration of offshore wind farms, no converter actually works to control the active power itself. It can transfer all the power generated from the wind farm. In contrast, at least one converter works to control the power in conventional VSC-HVDC.
3) The offshore converter station is usually built on land and then transported to the final place in the sea far away from the mainland. In order to reduce costly and inconvenient offshore work, pre-commissioning and tests are done on land before transportation. These items include auxiliary system tests as well as transformer and converter energization. However, the power transmission test is only done with the offshore station in place, while the wind farm can provide corresponding power.
4) The grid connection requirements are different between the VSC-HVDC project with integration of offshore wind farm and conventional VSC-HVDC. Close coordination tests among offshore wind farms, onshore grid, and HVDC transmission system are commonly used during the joint commission. The items include, but are not limited to coordination test between VSC-HVDC and onshore braking chopper, coordination test between VSC-HVDC and offshore wind farm, coordination test between VSC-HVDC and automatic generation control (AGC). In addition, in order to examine the fault ride-through performance of the whole system, an artificial short-circuit test is usually done.

In sum, commissioning is a significant step for the VSC-HVDC project with integration of offshore wind farm before it is put into operation. Since there are some differences between the VSC-HVDC project with integration of offshore wind farm and conventional VSC-HVDC, special items and methods are considered during the commissioning for grid-connection of offshore wind farms using VSC-HVDC transmission.

11.3 The core and key issues

11.3.1 The process and sequence of commissioning

The commissioning process and sequence of grid-connection of offshore wind farms using VSC-HVDC transmission has a number of differences from that of conventional VSC-HVDC, which is shown in Figure 25 (some special items are marked in bold) and discussed in detail.

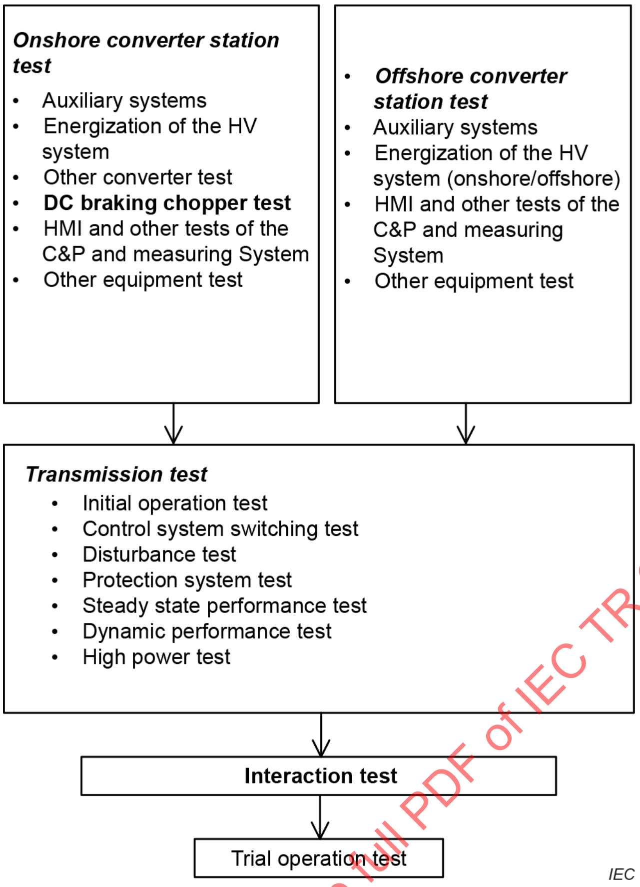


Figure 25 – Commissioning process of the VSC-HVDC project

Commissioning for grid-connection of offshore wind farms using VSC-HVDC transmission mainly comprises converter station test, transmission test, interaction test and trial operation test.

1) The converter station test aims to get ready for the following interconnection of different stations by examining the station separately. In this step, all the primary equipment inside the station is energized and some related functions are tested. The onshore converter station test includes transformer test, converter test, DC braking chopper test, energization test of submarine cable and other equipment tests. The purpose of these tests is to examine all the primary equipment inside the onshore converter station and be ready to provide a power supply for the offshore converter station. The DC braking chopper test is a special item in this test stage. The offshore converter station test includes transformer test, converter test and other equipment test. For the reason that the transformer and converter are vital equipment in the station, they can be examined in advance on land once they are installed. After the station is transported into the sea, the primary equipment can be tested again in the real situation during the transmission test period.

2) In the transmission test period, different converter stations are connected and examined under the condition that power flows in the system. The transmission test is conducted after the converter station tests are completed, including the initial operation test, control system switching test, disturbance test, auxiliary system test, human-machine interface (HMI) test, protection system test, steady state performance test, dynamic performance test, high power test and coordination function test. The special power flow mode and converter control strategy result in the differences in the test process between offshore wind farm VSC-HVDC and conventional VSC-HVDC.

3) The interaction tests can verify the correct functionality and/or response of the VSC-HVDC system due to AC network and/or remote generation interactions. Each HVDC system has its own unique characteristics associated with the AC network to which it is being connected and the location of the connection on that AC network. These unique characteristics, as well as regulations and contractual requirements, drive the commissioning requirements and acceptance criteria of the AC network and remote generation interaction commissioning tests and these are developed uniquely for each HVDC system. The interaction test of the VSC-HVDC project with integration of offshore wind farms mainly includes the AGC function test and artificial short-circuit fault test.

4) The final step of the commissioning is the trial operation test. In this part, the VSC-HVDC runs in actual conditions for a certain time period. After this step, the system is capable of being put into commercial operation. Compared to conventional HVDC, the trial operation of the grid-connection scheme of offshore wind farms using VSC-HVDC transmission cannot be planned for the reason that the available wind power varies randomly. The purpose and process of the trial operation test of the VSC-HVDC project with integration of offshore wind farm are nearly the same as that of conventional VSC-HVDC.

11.3.2 Offshore converter station test

The offshore converter station is built on land and then transported into the sea. Therefore, its test can be divided into two test stages. One is the onshore test stage, and the other is the offshore test stage.

The dockyard test can include the tests on the correct installation and basic functionalities of switchgear, auxiliary, and C&P systems. An energization of the high-voltage system as part of the dockyard tests is not used. If it is used, then the following is considered.

During the onshore test stage, there is no original high-voltage power supply that is necessary for the energization of the primary equipment. Thus, an additional power source is the key point in this stage. Figure 26 illustrates a possible test method. The temporary testing power source is a medium voltage source with a small capacity, which is easier to obtain compared with a high voltage source with a large capacity. A regulating transformer is utilized to connect the source and the original transformer in the station. It can increase the output voltage slowly from zero in order to avoid a current surge on the temporary source. According to the testing equipment, the energization test of transformers and converters can be performed, ensuring that the equipment and installation problems can be identified in time.

In the offshore test stage, the offshore converter station is installed in the sea, and is connected to the onshore converter station via submarine cable. Hence the onshore converter station works as a power source to energize the offshore converter station. It is the regular operating mode of the VSC-HVDC project with integration of offshore wind farm. The complete converter station test can be conducted such as equipment energization, converter deblocking, and AC breaker switching.

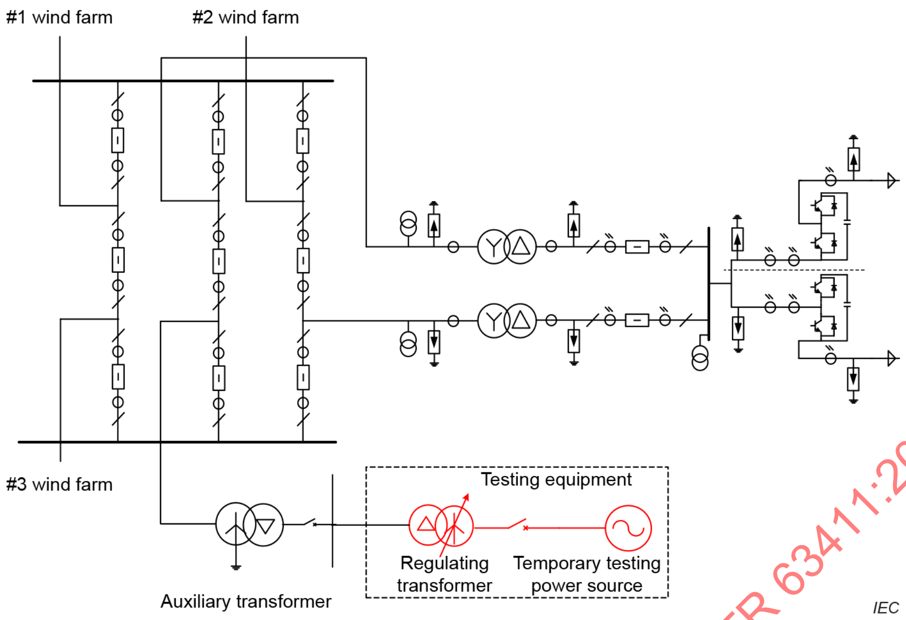


Figure 26 – Offshore converter station test on land

11.3.3 Dynamic braking system test

The wind farm and its grid-connected system have a certain fault ride-through capability. When different types of faults occur in the connected AC grid, the wind farm ensures that it does not separate from the grid within the pre-defined time and voltage fluctuation range, and continues to operate after the fault is cleared. For offshore wind farm grid-connected with VSC-HVDC, when the voltage of the connected AC system drops due to faults and other reasons, the output power of the entire DC system decreases instantaneously, while the power generated by the wind farm remains unchanged for a short period of time. This power surplus causes the DC voltage to rise, which triggers the operation of protection system and the blocking of the converter. Then the wind farm separated from the grid. In order to avoid this situation, a dynamic braking system is usually equipped on either DC side or AC side to consume surplus power and keep the stability of the DC voltage. Since a dynamic braking system on DC side is the most commonly used, the following text of this 11.3.3 focuses on this one named of DC braking chopper.

The working principle of the DC braking chopper can be explained according to Figure 27. A number of DC braking chopper structures have been presented, which can be equivalent to the series connection of a control switch K and an energy consuming resistor R, as shown in the dashed box in Figure 27. Note that Figure 27 only illustrates the working principle and it cannot represent the specific system structure. For example, a distributed resistor system is also utilized. The switch K is composed of a large number of power electronic modules, which withstand the high DC voltage and control the on-off of the branch. The resistor R can be configured as a centralized large resistor, which is independently connected in series in the branch. It can also be configured as a large number of distributed small resistors which are scattered in each power electronic module.

The DC braking chopper is configured with VSC converters, which is connected between the positive and negative DC pole-bus corresponding to the monopolar project, and is connected between the DC pole-bus and the neutral bus corresponding to the bipolar project. When the DC transmission system is operating normally, the switch K is open and no current flows through the energy consuming resistor. Therefore, no energy is consumed. When the AC system fault causes the DC voltage to fluctuate in a wide range, the energy consumed on the resistor R is dynamically adjusted to maintain the stability of the DC voltage by controlling the closing and opening of the switch K.

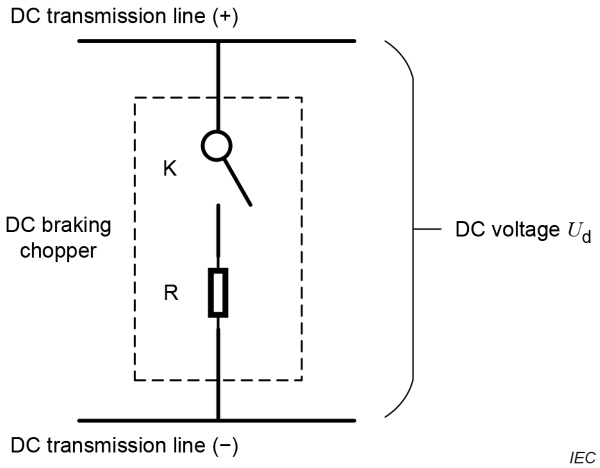


Figure 27 – Schematic diagram of DC braking chopper

The DC braking chopper test can be performed during the onshore converter station test period, including energization test, switching test, trip test, and so on. The purpose of these tests is to examine the equipment voltage withstanding ability and whether the chopper can work as the predetermined strategies. A high DC voltage source is necessary for the test. It can be gained from either a temporary power source or the converter in the real operation situation.

11.3.4 Transmission commissioning

As the discussion above, the transmission test consists of various test items. This 11.3.4 discusses some of the special aspects.

Firstly, the startup path and procedure for offshore wind farm VSC-HVDC is different from that of conventional VSC-HVDC. Since there is no stable AC source in the offshore converter station, the converter cannot be energized from the AC side. Therefore, in the startup process, the converter in the onshore station operates at first and provides power source for the offshore converter station, and then the converter in the offshore station starts up to generate a stable voltage in the AC side. Next the AC source produced by the offshore converter energizes the wind farms, which generate electricity afterwards. At last, the power flows from the wind farm to the AC grids through VSC-HVDC.

Secondly, the switch test of offshore converter station power supply is rather particular. For conventional VSC-HVDC station, there are both internal and external power supplies for load inside the converter station. When one of them fails to operate properly, the other takes the replacement. In contrast, it is difficult to have an external power supply for the offshore converter station since it is far away from land. Independent electric generators are used as a backup. Therefore, the switch test of the internal power supply and the electric generators are carried out when the offshore converter station is in the position at sea.

Thirdly, two or more transformers are applied in parallel in the offshore converter station to ensure the redundancy and safety. In the startup process, one transformer boots at first and the others are charged afterwards. Thus, the energization tests of spare converter transformers are considered to examine whether the exact energization infects other equipment or the voltage of offshore converter station.

Fourthly, active power step test of offshore wind farm VSC-HVDC is different. For conventional VSC-HVDC, the reference value of active power can be changed directly in the control system to examine the dynamic performance of the system. While for offshore wind farm VSC-HVDC, the active power is determined by the wind farms that cannot be directly controlled by VSC-HVDC. Therefore, the test method varies. For example, the cut-off of a wind farm can produce the step change of active power.

Last but not least, high power transmission test is a little different for the same reason that the active power cannot be artificially controlled. Since the wind speed varies randomly, the power generated by the wind farm changes a lot. It usually takes a long time until the wind speed is suitable and the power reaches rated value, when the high power transmission test can be implemented.

11.3.5 Interaction commissioning

The interaction test aims to examine the coordination performance of the VSC-HVDC project with integration of offshore wind farm and the power grids, including AGC function commissioning, artificial short-circuit fault test, offshore wind farm performance test, etc.

1) AGC function commissioning

   The AGC provides power command values for the offshore wind farms, of which the orders come from power grid control centre. In the AGC function commissioning, the signal transmitting among different systems are demonstrated. Furthermore, it is confirmed that the power generated from the wind farms follows the AGC orders.

2) Artificial short-circuit fault test

   The artificial short-circuit fault test is optional which depends on the determination of the owner, commissioning supplier and the power grid dispatching department. It can be performed at disparate location, such as the onshore AC system and the offshore AC system. The test can verify the fault response performance of all the primary equipment and the fault ride-through of the whole system.

3) Offshore wind farm test

   1) Offshore-onshore joint test

      For offshore-onshore joint test, the following contents are included:

      i) The adjustment of the fibre channel protection of the cable is completed, the fibre channel loss is measured, and the fibre channel protection function is verified;

      ii) The test of five-prevention blocking between two submarine cables is completed;

      iii) According to the four-remote signal list of dispatch, the joint test from the offshore booster station to the onshore centralized control centre is completed, including the test of the protection system, automation system, remote control system, communication system, and other systems;

      iv) According to the four-remote signal of dispatch, the joint test from the offshore booster station and onshore centralized control centre to the power grid dispatching centre at all levels and the monitoring centre of the power generation group are completed;

      v) The test of the remote terminal unit (RTU) system, dispatching data network, and secondary security equipment of the system is completed;

      vi) The test of the dispatching communication system of the whole plant (including system communication and communication between the system and dispatching at all levels) is completed.

2) Startup test of the offshore booster station

The steps for startup test of offshore booster station are as follows:

i) Supply power to the offshore booster station;

ii) Check the charging status of the new equipment, the impact on the transformer, and the charging status of the line, all of which are normal;

iii) Check whether the voltage value, phase sequence and phase meter indication of the busbar at all levels are correct;

iv) Check whether the test data of the primary equipment is qualified;

v) Check whether the control, protection, and signal of the electrical equipment are correct and whether the automatic or interlocking circuit is normal;

vi) Carry out the load test of the booster station, and check the protection and measurement circuit;

vii) Measure the phase of the current loop and the unbalanced voltage of the differential protection when the booster station is with different loads;

viii) Complete the whole set of test records and test reports for startup test.

3) Grid-connection test of wind turbine

The steps for grid-connection test of wind turbine are as follows:

i) Check the equipment, engine room, and tower of the wind turbine;

ii) Check the wiring of the control system and fibre of the wind turbine;

iii) After the incoming line switch of the box transformer is closed and energized, power on the wind turbine according to its specifications;

iv) Within the allowable working wind speed, complete the test work in the static state, including test of communication, safety chain, pitch, yaw, hydraulic, gearbox, converter, and other parts;

v) Unlock the impeller and start the idling test;

vi) After the idling test is completed, the wind turbine enters the grid-connected test stage. Send the inverter operation command, and check whether the wind turbine can be connected to the grid by itself for power generation.

11.4 Summary

Clause 11 discusses the complete process of testing and commissioning, focusing on the special aspects of commissioning due to system characteristics, special location of the offshore converter station, and grid connection requirements. There are some differences between offshore wind farm VSC-HVDC and conventional VSC-HVDC, such as offshore converter station test, DC braking chopper test, transmission commissioning and interaction test.

12 Black start

12.1 General

With the increasing penetration of intermittent renewable energy, the operating environment of the power system becomes more complex with more uncertainties. In recent years, blackouts and power disruptions have become more frequent, and the risk of large-scale blackouts still exists. If the normal and stable operation of the power grid can be restored quickly in a short time, the load loss and economic loss can be minimized, which brings significant social benefits. The overall aim of post-black-out restoration, namely power system restoration, is to restore electric sources in the grid safely and quickly after a total or partial shutdown of the power grid and minimize the impact of the blackout. The restoration process of the power system can be divided into three stages: black start, power network reconfiguration, and load restoration. The black start electric source achieves self-start and supplies power plants to form subsystems. The main network frame of the system is gradually restored through important substations and transmission lines in the region. Finally, the local load is connected to restore the normal electric supply to the grid. The power system restoration process is long and complex. It takes about 8-10 hours to complete the above three stages. As the primary operation to quickly restore electric supply to the grid after a black-out, black start plays an important role in the whole power system restoration process. The so-called black start refers to the fact that after the whole system is shut down due to a fault, the system is in a completely "black" state. Then the generator set with self-start capability in the system is started to drive the generator set without self-starting capability, gradually expanding the restoration range of the system, and finally realizing the restoration of the whole system. The restoration operation in the black start stage mainly includes the startup of the black start electric source, the charging of transmission lines, the energizing of large power plants, the reconnection of the started power generation units to the grid, and a certain amount of load connection to ensure the stability of the system. The whole process lasts about 30 min to approximately 60 min. The goal of black start is to realize the safe start of the shutdown units in the shortest time and provide power support for the subsequent restoration of the system.

In 1987, the System Operation Committee of IEEE Power and Energy Society established a special working group on power system restoration, which defined the basic principles of starting objects and restoration steps of power system black start and laid a foundation for the research of black start technology. The North American Reliability Council (NERC) has also developed standards for black start, which are mainly contained in the 2006-03 project, including: (1) EOP-005-2: System Restoration from Black Start Resources-Operations. (2) EOP-006-2: System Restoration from black start resource-coordination. The traditional black start scheme is an emergency plan for restoring a large power grid, where thermal power units or hydropower units are usually used as black start units. The black start scheme mainly includes the initial restoration strategy of black start, the optimization of the grid restoration path, the evaluation of the black start scheme, the division of the black start subsystem, etc. Many principles involved in the black start are the theoretical basis for making the black start scheme. Normally, the black start of a system is realized by partition. Each subsystem has black start capability under the black start partition, which contains at least one black start electric source, a generation unit to be energized, and a feasible restoration path. The partition subsystem has better frequency and voltage control capability, where the power matching between generator and load is ensured within the prescribed frequency limit and each subsystem can maintain voltage control in a suitable range, etc. In addition, there are some other principles involved in the black start process, such as the selection principle of the started unit, the planning principle of the black start path, the load recovery principle during the black start process, etc. With the continuous development of offshore wind power resources, offshore wind power development gradually enters deep and distant sea areas. Using VSC-HVDC technology to realize the transmission of large-scale offshore wind power has become one of the main development trends. As one of the main local power sources, large-scale offshore wind farms also used to meet the designed capacity of the power grid for the black start power supply.