Protection Coordination between HVDC Off-Shore Wind System and AC Grid

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SUMMARY

As part of the European renewable energy project launched about a year ago – "TWENTIES," Work Package 5 (WP5) is focused on optimal operation of AC/DC interconnected power systems, local protection and control of High Voltage Direct Current (HVDC), and operation under normal and emergency conditions. This paper reports the preliminary results obtained by University College Dublin (UCD) on local protection requirements and control of HVDC offshore wind networks, in the framework of WP5.

An off-shore wind farm integrated to an ac grid through Voltage Source Converter (VSC) based HVDC transmission technology is studied in this paper. In this study, the wind farm side VSC (WFVSC) uses an ac voltage control mode, which enables the collection of energy from off-shore wind farms to be transferred to the dc link. To maintain the balance between the input and output of HVDC link, the dc voltage needs to be controlled at a constant. This task is assigned to the grid side VSC (GSVSC). Also, GSVSC can provide reactive power support for the ac grid to maintain the voltage of the point of common coupling (PCC) at an expected level.

When the HVDC off-shore wind system suffers an ac grid fault close to the PCC, say, a short circuit, the PCC voltage severely declines. The reduced voltage will decrease the GSVSC power transmission capability. Since the wind farm generation is not reduced instantaneously, the unbalanced power in HVDC link has to be stored in dc capacitors. This in turn can lead to a serious dc overvoltage, which may cause tripping of dc devices by its overvoltage protection. In a point-to-point HVDC system, this will interrupt the transmission of off-shore wind power, resulting in a deficit in generation. It is likely to bring voltage and frequency problems in the integrated ac grid.

The studied system has been developed in DIgSILENT, and simulation results of ac grid faults are presented in this paper, including ac three-phase and single-phase short circuit faults. During an ac grid fault, the ac grid experiences abnormal operation conditions, i.e., high ac fault currents and low ac fault voltages, which might lead to a faulted performance in the dc side due to the interaction among voltages, currents and power on the ac and dc sides. As the main protection, the ac grid protection is required to accurately detect and locate the ac grid fault according to these abnormal features, and rapidly isolate it. To avoid an undesirable operation of the dc side protection, the dc side protection needs to be coordinated with the ac grid protection.

KEYWORDS

Coordinated protection, off-shore wind farms, high voltage direct current transmission (HVDC), voltage source converter (VSC), ac fault ride through.

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I. Introduction

During the last decade, the installed capability of wind power dramatically increases at the average annual growth rate of 29% [1]. This significant increase reduces fossil energy production and the associated carbon emissions. In the utilization of wind power, off-shore wind is beginning to play a significant role due to the better wind condition and saving in on-shore land. Some EU countries, such as Denmark, UK and Ireland, are making a great effort in developing the off-shore technology. The European Wind Energy Association (EWEA) has a goal to increase off-shore wind power to 40-50GW by 2020 from 2 GW by 2009 in EU [1]. To meet this target, off-shore wind power capacity in EU would reach an average growth in annual installation of 28% [2].

High voltage alternating current (HVAC) technology has been used to transmit off-shore wind farms to on-shore power grid. Due to the high capacitance of shielded power cables, the length of ac cables is limited by the charging current of the cable [3]. Since off-shore wind farms are usually large-scale and far from shore, the HVAC technology may not be suitable for the off-shore wind power transmission. Some research has shown that the HVDC technology is better suited [3]. Advantages of HVDC technology include fully controlled power and fewer cables required [2, 3]. Based on the power electronic switch technology, HVDCs are classified into line commutated converters (LCCs) and VSCs. VSCs consist of full-controlled electronic switches, i.e., insulated-gate bipolar transistors (IGBTs), which make it possible to independently adjust the active and reactive power. In addition, the VSC based HVDC has no minimum short circuit levels and it is feasible to extend it to a multi-terminal HVDC (MTDC) and develop the black start capability [4, 5]. Compared with LCC based HVDC, VSC based HVDC is considered more suitable for transmission of off-shore wind power to the on-shore grid.

The capacity of the planned or on-going off-shore wind farms is usually large. Some of them will reach the level of several GWs [6]. Although MTDC technology has been proposed for the future off-shore wind power transmission, the number of GSVSCs MTDC systems in the existing studies is limited to one or two [7, 8]. This causes heavy loading of the ac local transmission grid near PCCs, when bulk off-shore wind power is injected into the ac grid. If one of transmission lines is de-energised due to a fault, it may in turn lead to overloading of other lines. This is likely to result in cascading events in the integrated ac grid. In addition, the local grid will face other challenges, such as upgrading of the local grid infrastructure, voltage and frequency stability problems, and new requirements of protection systems. The security of the integrated ac grid needs to be identified.

The task of ac protection is to accurately detect and rapidly clear the ac grid fault. When a HVDC off-shore wind network suffers an ac grid fault near the PCC, the ac grid protection is required to clear it as soon as possible. Before the fault is cleared, however, the PCC voltage declines, which will lead to the decrease of the power transmission capability of the GSVSC. Since the output from wind farms cannot be reduced instantaneously, the unbalanced power between WFVSCs and GSVSCs causes charging of the dc capacitors, resulting in a dc overvoltage. If the dc overvoltage endangers the safety of HVDC devices, the dc side protection system is required to respond rapidly to protect costly devices. If the overvoltage is not severe, the dc side protection is required to be coordinated with the ac grid protection and avoid undesirable operations [9].

Currently, the dc protection research mainly focuses on the impact of dc faults and the relevant protection solutions [10-13]. Based on protection devices, DC protection devices are classified into ac devices, i.e., ac circuit breakers (AC-CBs), and dc devices, i.e., dc circuit breakers (DC-CBs). The AC-CB is less costly and its technology is fully mature compared with the DC-CB [14]. With the development of MTDC network, AC-CBs are no more sufficient to eliminate dc faults in a selective way [15]. Some dc side protection devices, such as DC-CBs (including semi-conductor-CBs), have been discussed. Reference [10] describes a relay coordination method, which is based on overcurrent and dc voltage drop characteristics. A protection scheme of MTDC based on IGBT circuit breakers is proposed in [16]. It also introduces the corresponding fault detection and location method. The work of [13] involves an overcurrent protection scheme that utilizes VSCs as fast-acting current-limiting circuit breakers. These dc protection schemes do not consider the influence of ac grid faults, and the coordination between the dc and ac protection systems. This paper reports preliminary results on the impact analysis of an ac grid fault on HVDC system and discusses the concept of coordinated protection between HVDC off-shore wind network and the ac grid. The control of HVDC off-shore wind system and the relevant simulation results are also reported.

II. Test System

An off-shore wind farm based on induction generators (IGs) is connected to an ac grid through a point-to-point two terminals bipolar HVDC link, as shown in Fig. 1. Shunt capacitors are connected at the generator outlet to provide the reactive power support. Two dc cables are used to connect the WFVSC and GSVSC. WFVSC is used to collect power from off-shore wind farms to be transferred to the dc side. GSVSC converts dc power received into ac and sends it to the ac grid. Also, GSVSC can provide reactive support for the ac grid. The ac grid is a small portion of a North American transmission grid. The load model in the test system consists of 50% static and 50% dynamic load.

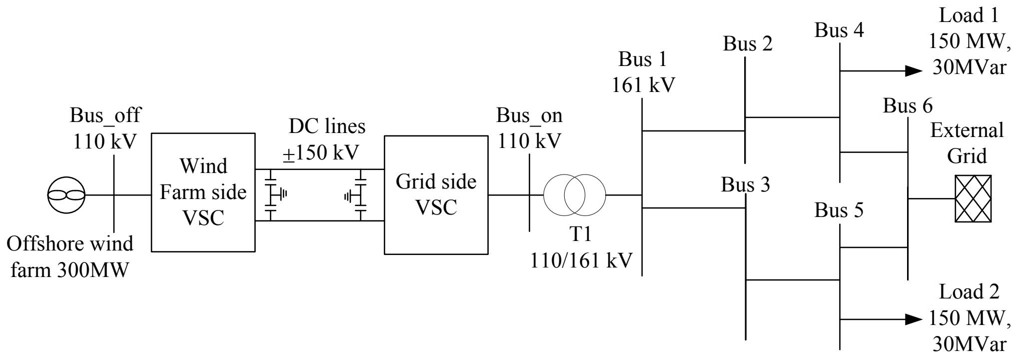


Fig. 1 Configuration of HVDC offshore wind network

III. System Control

As previously mentioned, the VSC-HVDC link is used to transmit off-shore wind power to the ac grid. So far, VSCs for HVDC are mostly based on two or three-level technology with the pulse width modulation (PWM) technology. To improve the dynamic performance and reduce the impact of harmonics, new VSCs technologies, such as modular multilevel converters (MMCs), have been developed. Independent adjustment of the active and reactive power in HVDC is achieved by current control technologies that are classified into indirect and direct current controls. Indirect control is based on the phase and amplitude control and direct control is based on synchronous rotating frame current control [17]. As the direct current control uses current feedback, system dynamics usually have a better performance than the indirect scheme [17].

A. WFVSC controller

The VSC control strategy used to connect off-shore wind farms has been well documented in the literature [18, 19]. The main tasks of WFVSC are to collect power from off-shore wind farms to be transferred to the dc side. To collect all power from wind farms, WFVSC uses an ac voltage control mode. As VSC has one more degree of freedom than the traditional LCC, frequency control of off-shore wind farms is also used in VSC. The slip of IGs connected wind turbines depends on the frequency of the ac system of wind farms. To simplify the control, the wind farm side frequency is usually controlled at a constant. The simplified control configuration of WFVSC is shown in Fig. 2. The wind farm is controlled as a voltage source with a closed-loop controlled magnitude (V_{WF}), a constant frequency (f) and phase angle (θ). M is the modulation index of PWM control of the WFVSC. This is an indirect current control, which does not include a current feedback control loop. When WFVSC suffers an overcurrent, the ac current limitation can only be indirectly achieved by setting the WFVSC ac voltage or blocking the semiconductor switches of converters.

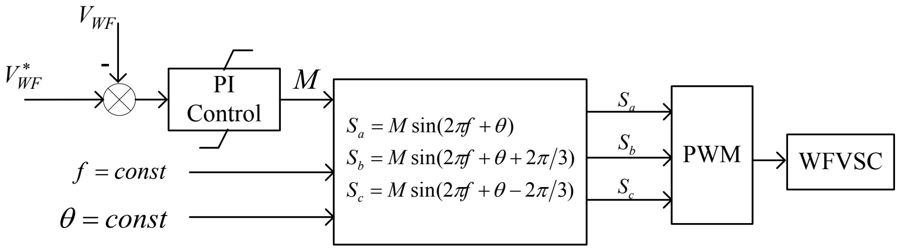


Fig. 2 Simplified control configuration of WFVSC

B. GSVSC controller

In HVDC link, a constant dc voltage can automatically balance the sending and receiving active power. It does not need extra communication between the rectifier and inverter VSCs [18]. GSVSC is usually assigned to control the dc voltage (V_{dc}), which is to ensure that energy collected by the WFVSC is transmitted to the ac grid. Also, GSVSC can provide reactive power support for the ac grid to maintain the ac voltage (V_{ac}) at an expected level. The control configuration is shown in Fig. 3. GSVSC uses a current feedforward decoupling control in the synchronous d-q reference frame. The inner current control equations are given as follows:

$$v_d = -(K_{ip} + \frac{K_{iI}}{s})(i_q^* - i_q) + \omega L i_q + v_{sd} \quad (1)$$

$$v_q = -(K_{ip} + \frac{K_{iI}}{s})(i_d^* - i_d) - \omega L i_d + v_{sq} \quad (2)$$

where K_{ip} and K_{iI} are the proportional and integral gains of the current controller. The superscript $*$ refers to reference values. The symbols, v_d and v_q, are d, q axis components of the VSC ac side voltage, respectively. The currents i_d and i_q are d, q axis components of the ac side current, respectively. The voltages v_{sd} and v_{sq} are d, q axis components of the GSVSC outlet voltage, respectively. The angular speed ω corresponds to the synchronous d-q frame and inductance L is for the commutated reactance.

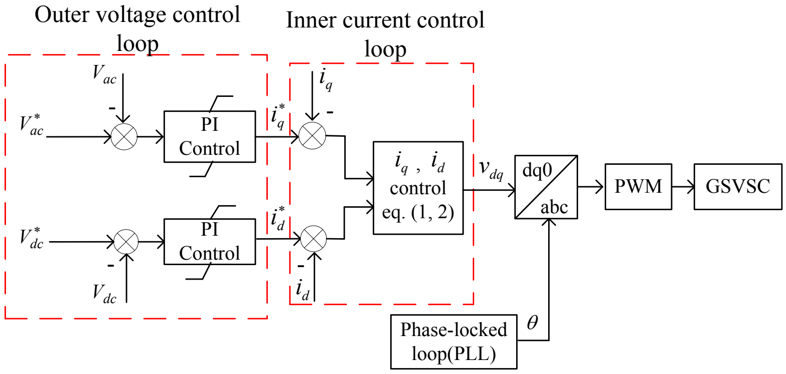


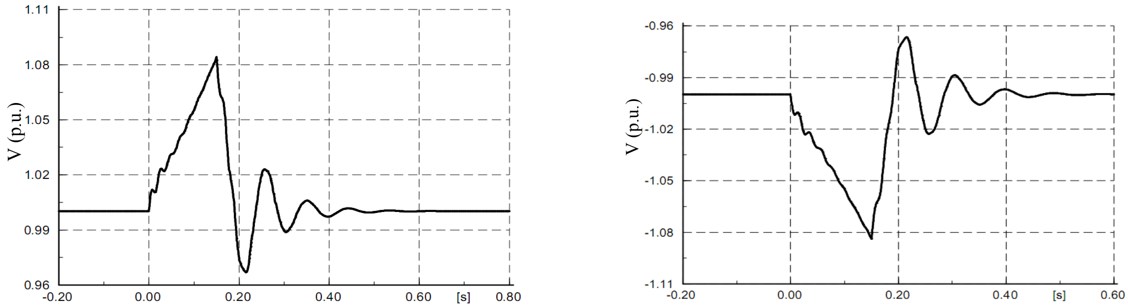
Fig. 3 Simplified control configuration of GSVSC

IV. AC grid faults study case

As shown in Section II section, the test system is a 300 MW wind farm based on IGs connected to an ac system through a bipolar VSC-HVDC link, as shown in Fig. 1. The test system is developed in DIgSILENT, a commercially available software tool. The HVDC topology consists of two 300 MW/300kV VSCs, 100 km dc cables and 100 μF dc capacitors. The test system of ac grid is a portion of a North American transmission system, which operates at the voltage level of 161 kV.

A. Three-phase ac short circuit

At 0 second, a three-phase short circuit fault is initiated at line 1-3. After 0.15s, the fault is cleared. During the fault, the dc positive and negative voltages curves are shown in Fig. 4. When the line 1-3 suffers the three-phase short circuit, the PCC voltage is reduced to almost zero. DC positive and negative voltages are increased rapidly to 1.08 p.u. After the fault is cleared, the HVDC control system activates and dc voltages are recovered to a normal condition.

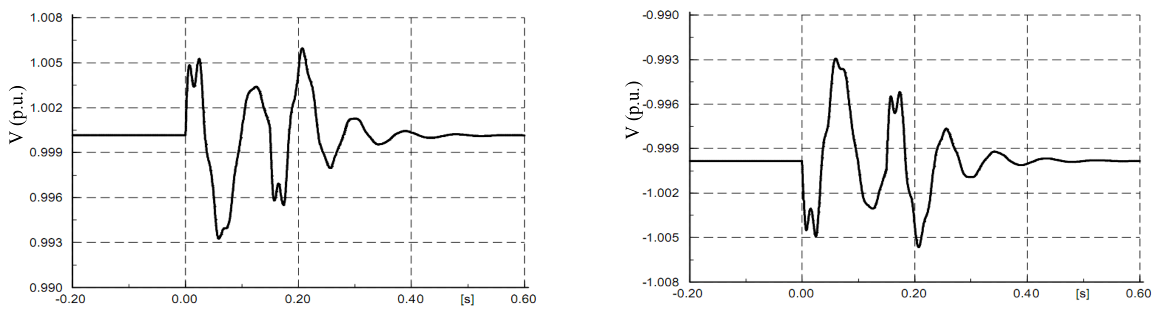


(a) Positive-pole voltage (b) Negative-pole voltage

Fig. 4 Three-phase ac short circuit simulation results

B. Single-phase ac short circuit

A single-phase short circuit fault is initiated on line 1-3 at 0 second. After 0.15 seconds, the fault is cleared. As the single-phase short circuit does not cause the PCC voltage to severely decline, most of the GSVSC transmission capability is maintained. The small-scale unbalanced power does not lead to a serious overvoltage. However, since the ac grid is in an unbalanced condition during the fault, this in turn results in second order harmonics in the dc side due to the PWM control, which can be seen from Fig. 5.



(a) Positive-pole voltage (b) Negative-pole voltage

Fig. 5 Single-phase ac short circuit simulation results

V. Protection coordination

To effectively protect every device in the power grid under different fault conditions, the protection zones of different devices must overlap. Operation of the protective devices must be fast, reliable and selective. A fast speed of response and high reliability are vital in order to limit the damage that can be caused by a fault. In addition, protection must be selective so that only the faulted element is isolated. Reliability is achieved by using high-quality equipment and redundant protection schemes for each element called the main protection and back-up protection. To meet the requirement of the protection, all protections in the HVDC network must be coordinated, which can be accomplished by coordination between ac protection and dc protection, and coordination between operation times and thresholds of all protective devices.

The ac grid fault simulation results are presented in Section IV. When the HVDC off-shore wind system experiences a three-phase short circuit close to the PCC, the dc side encounters a severe overvoltage. This might damage the insulation of dc devices and reduce the reliability of costly HVDC system. To avoid these unnecessary damages, the dc overvoltage protection is required to rapidly activate if the dc voltage exceeds the threshold of the overvoltage protection. The ability of the devices to withstand overvoltage depends on the insulation capability of devices. The threshold of dc overvoltage protection needs to be coordinated with the insulation parameters of switches and cables. If the ac grid fault location is not close to PCC, the PCC voltage reduction will be modest. The small-scale unbalanced power between the receiving VSC and sending VSC does not cause severe overvoltage to activate the dc overvoltage protection. However, this minor overvoltage condition may be confused with other overvoltage cased by abnormal conditions on the dc side, such as an overload. To selectively and reliably protect HVDC system, the dc protection system is required to accurately distinguish ac grid faults from dc faults.

When an ac grid encounters an ac grid fault, say, a short circuit, the ac grid will experience abnormal operation conditions, e.g., low voltages and high currents. According to these ac grid fault characteristics, the ac protection is designed to detect the location of ac grid faults and isolate ac grid faults. As the main protection, the ac protection is required to clear ac grid faults within a specified duration. In the unusual case when ac protection fails to clear ac grid faults, the dc side needs to be equipped with a backup protective function to protect HVDC networks from ac grid faults. Due to the harmonic characteristics of the dc side under unbalanced faults, the dc side may adopt 100Hz protection as the backup protection of ac grid faults. The 100Hz protection on the dc side is a protection scheme against ac faults, which is used to judge an ac grid fault through detection of second order harmonics on the dc side. To meet the selectivity and sensitivity of the protection, the operation time of the backup protection for ac grid faults needs to be coordinated with the maximal clearing time of the ac grid fault. Namely, the operation time of the backup protection should be reasonably longer than the maximal clearing time of the ac grid fault. The ac transmission system uses the 3-zone distance protection. In the ac grid, if the protection of Zone 1 fails to operate during an ac grid fault, the dc side voltage can sharply increase before the operation of Zone 2. If the incremental voltage poses a threat to the system device insulation, the dc side overvoltage will immediately activate to isolate devices experiencing overvoltage, such as converters and dc cables, from the interconnected system. The loss of dc cables might cause other healthy dc line(s) to become overloaded. In order to relieve the overload, wind turbines may have to be tripped.

The incremental dc voltage might cause the off-shore wind farm bus voltage to increase during ac grid faults, which is a risk to activate the overvoltage protection of wind turbine generator. Due to the high capacity of off-shore wind farms, tripping of the wind turbines might cause voltage and/or frequency problems, reducing the stability of the ac bulk grid. Furthermore, if both the ac grid protection devices in Zone 1 and Zone 2 fail to clear the grid fault, the overvoltage on the wind farm side can be severe. Therefore, it is necessary to identify ac grid faults which might, for given conditions, trip wind turbines so that the system operator can be informed of such serious events during system operation and be prepared to take proper actions.

VI. Conclusion

An off-shore IGs based wind farm connected to an ac grid through a VSC based HVDC link is studied in this project. The corresponding operation principles and control strategy of VSC stations have been described. Simulation results of ac grid faults close to PCCs in the studied system have been presented, including three-phase and single-phase short-circuit faults. The performance of the system under balanced and unbalanced grid faults has been analysed. Requirements of the dc protection under ac grid faults and protection coordination between HVDC off-shore wind network and ac grid have been discussed. As the ac and dc systems are connected via VSC station, the voltages, currents and power of two sides interact. When the ac grid experiences a fault, the dc side will also be in abnormal operation conditions, e.g., high dc voltage and harmonics. To reliably and selectively protect HVDC off-shore wind network, the dc side protection needs to be coordinated with the ac grid protection. Some preliminary conclusions about protection coordination have been presented. The detailed coordinated protection design will be studied in the future.

Acknowledgement

This research is sponsored by European Commission project “Twenties,” Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions. The authors gratefully acknowledge the helpful discussions and suggestions from the Work Package 5 team, especially Anne-Marie Denis, Olivier Despouys, and Diego Cirio.

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