Effects of HVDC Connection for Offshore Wind Turbines on AC Grid Protection

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***Abstract*—When a transmission line close to points of common coupling (PCCs) encounters a short circuit (SC), the resulting PCC voltage dip triggers fast reactive power control of the corresponding grid side voltage source converter (GSVSC) to boost the PCC voltage. The control action can cause the fault distance to be overestimated by its backup relay located on the adjacent line. It is possible for a Zone 2 fault to be viewed as a Zone 3 event, resulting in mis-coordination between protective relays. Numerical simulations demonstrate the effect of HVDC offshore wind network on distance protection of an ac grid. On the other hand, HVDC reactive power adjustment can increase the stability margin of onshore ac grids, as shown by contingency simulations. With the addition of HVDC-connected offshore wind turbines, the voltage source converter based HVDC (VSC-HVDC) control can function as an element of the overall power system defense plan to prevent system instability, reducing or avoiding the implementation of the last resort remedial option – load shedding.**

***Index Terms*—VSC-HVDC, offshore wind farms, distance relays, defense plan, decoupling control of VSC, system stability.**

I. Introduction

DURING the last decade, the penetration of renewable energy, including offshore wind turbines, has increased dramatically in order to achieve an overall reduction of green house gas emissions. A report from European Wind Energy Association (EWEA) has shown that the installation capacity of EU offshore wind units will be increased to 150 GW by 2030 as additional generation resources to meet 14% of the EU electricity demand [1]. The rapid growth of offshore wind power and its inherent characteristics (e.g. large scale and long distance) make the integration of offshore wind power to onshore ac grids a great challenge. With the innovation of transmission technologies, the VSC-HVDC technology has shown its advantages to overcome limitations of the conventional ac transmission technology for offshore wind power integration. The typical advantages of the VSC-HVDC technology include fast and independent control of active and reactive power, feasibility of multi-terminal dc grids, and black start capability [2]-[3]. In a HVDC offshore wind network, the function of the HVDC connection is to collect offshore wind power and deliver it to onshore ac grids. Generally, the wind farm side VSC (WFVSC) adjusts the magnitude and frequency of the wind farm terminal voltage to enable the collection of all offshore wind power. The GSVSC is used to control the dc link voltage. A constant dc voltage can automatically balance the sending end and receiving end active power of the HVDC. In addition, the GSVSC also allows reactive power support for onshore ac grids to maintain the PCC voltage at a pre-determined level.

When the PCC experiences a voltage dip during a nearby SC fault, the transmission capability of the HVDC is reduced. Since the offshore wind power received by the WFVSC cannot be decreased instantaneously, the resulting power imbalance in the dc link causes dc capacitors to be charged, leading to a dramatic increase of the dc voltage [4]. It has been shown that the installation of dc choppers can effectively dissipate unbalanced power and protect dc transmission devices.

In addition, the HVDC control can significantly affect the fault performance of onshore ac grids. Due to the constant ac voltage control mode, the GSVSC reactive power control is activated to boost the PCC voltage during the SC fault. This tends to impact bus voltages and line currents close to the PCC. Generally, the capacity of VSC stations is expected to be large for bulk offshore wind power transmission. The resulting effect of reactive power on the performance of ac protection schemes can be significant. Distance protection is a good example. The basic principle of distance protection is based on the apparent impedance measurement that determines the approximate distance between the relay location and fault point during a SC fault [5].

Most reactive power compensation devices are based on the full-controlled power electronic switch technology, such as static var compensators (SVCs) and static synchronous compensators (STATCOMs). The technology allows devices to fast regulate reactive power exchange with ac grids. It has been discussed in existing studies that fast reactive power adjustment can affect the performance of distance relays on ac grids. The study in [6] evaluates the performance of distance relays on the transmission lines equipped with SVC and STATCOM shunts, respectively. In addition, the work of [7] focuses on reactive power adjustment of unified power flow controllers (UPFCs) and analyzes its impact on distance relays located on the UPFC terminal buses. Compared with these

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flexible alternating current transmission (FACTS) controllers, VSC stations provide a much higher capability of reactive power adjustment. The resulting effect on the operation of distance relays needs to be addressed.

With the addition of HVDC-connected offshore wind turbines, more control options from the HVDC are provided to enhance the stability of onshore ac grids, such as multi-HVDC active power regulation and reactive power support. They can be applied to damp system oscillations and increase the stability margin. In severe situations, the available HVDC control may prevent system instability and reduce or avoid load shedding. In contrast with conventional ac grids, a higher level of control capability can be provided by the ac grid with HVDC-connected offshore wind turbines for the design of system protection schemes that is intended to reduce the impact of severe contingencies.

The organization of this paper is as follows. Section II outlines an 'H' shaped HVDC offshore wind network. Section III analyzes the effect of HVDC control on distance relays of the ac grid. Numerical simulations with the IEEE 39-Bus system are performed to demonstrate the possible mis-coordinated operation of distance relays with the proposed HVDC offshore wind network. Based on contingency analysis, Section V highlights the potential opportunities brought by HVDC-connected offshore wind turbines for the design of system protection schemes.

II. System Configuration

A. HVDC Offshore Wind Network

Fig. 1 illustrates the configuration of a HVDC offshore wind network. Two offshore wind farms based on doubly fed induction generators (DFIGs) are connected to an onshore ac grid through an 'H' shaped HVDC connection. Two WFVSCs are controlled to collect the generation of offshore wind farms and convert it to dc power. Two GSVSCs are used to deliver the received dc power to the onshore ac grid. Due to the large scale of offshore wind farms, the HVDC connection for wind power transmission is expected to be connected to the transmission levels of onshore ac grids.

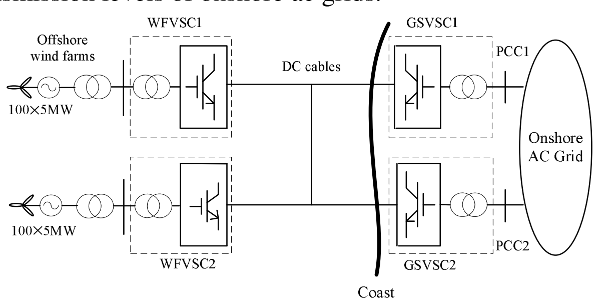

Fig. 1 'H' shaped HVDC Offshore wind network

B. VSC-HVDC control

In the multi-HVDC network, both WFVSCs apply the constant ac voltage and frequency control mode that enables the collection of all offshore wind power. The simplified control configuration of WFVSCs is shown in Fig. 2. Offshore wind farms are modeled as voltage sources with a closed-loop controlled magnitude (v_{wf}), constant frequency (f) and phase angle (θ). M is the modulation index of PWM control of WFVSCs. The subscript "*_ref*" is used to indicate the reference value.

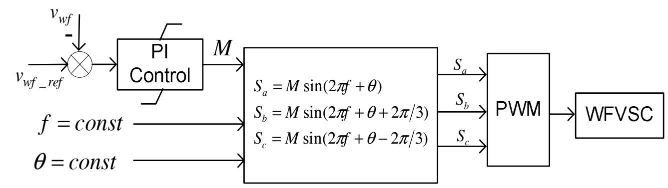

Fig. 2 Simplified control configuration of WFVSCs

Fig. 3 shows the GSVSC control configuration. The dc grid voltage is adjusted by the power-voltage droop that determines the power flow distribution of the dc grid. It can be represented as

$$v_{dc\_ref} = v_{dc} + k(P - P_{ref}) \tag{1}$$

where v_{dc} is the dc side voltage of a GSVSC, P is the active power transmitted by the GSVSC, and the symbol k is the slope of the power-voltage droop characteristic curve.

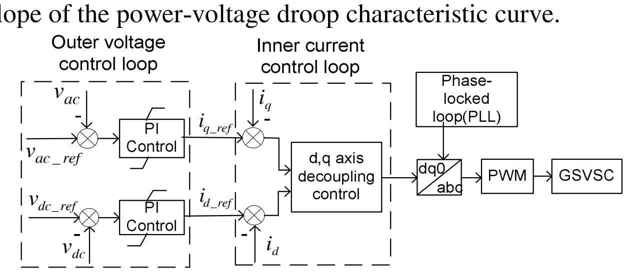

Fig. 3 Simplified control configuration of GSVSCs

Applying d,q-axis decoupling control, GSVSCs can independently regulate their reactive power output to maintain the corresponding PCC voltage (v_{ac}) at an expected level. As shown in Fig. 3, the error between the reference and measured PCC voltage is used to control the q-axis component of the GSVSC ac side current that determines the GSVSC reactive power output. When a PCC experiences a voltage dip during a disturbance, say, SC, the corresponding GSVSC control is activated to provide reactive power to boost the PCC voltage. With the high frequency switching technology, the time constant of the VSC control can be in the order of tens of milliseconds, much faster than that of excitation systems of conventional synchronous generators.

III. Distance Protection of AC Grid

A. Distance Protection of AC Grid

The distance relay is a widely adopted protective device that is designed to provide the primary and backup protection of transmission lines. Zone 1, as the primary protection, is required to protect 80%-90% of the line length without an intentional time delay. Zone 2 functions as a backup protection and its protection range reaches 40%-50% of the shortest line emanating from the remote bus. A time delay (typically 15-30 cycles) is applied to coordinate with Zone 1 relays [8]. In some of ac grids, Zone 3 is utilized to offer a remote backup protection that is required to exceed adjacent lines with the typical time delay of 1 s [5]. The operation of