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Multi Terminal VSC-HVDC Based Offshore Wind-Farms Integration System

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Abstract : **This paper presents a new centralized supervisory control strategy for controlling the power sharing and voltage regulation of MT VSC-HVDC integrating offshore wind farms. The main purpose of the proposed strategy is selecting the optimal parameters of the HVDC system VSCs local controller. These optimal parameters are selected in order to achieve optimal system transient response and desired steady state operation. In this work, an adaptive droop-based power-sharing control strategy is proposed. The primary objective is to control the sharing of the active power transmitted by a MT VSC-HVDC network among a number of onshore AC grids or offshore loads based on the desired percentage shares.**

Index Terms **– Multi-Terminal VSC-HVDC Transmission system, offshore wind power, voltage control and wind power generation**

I. INTRODUCTION

Wind power generation is expected to increase worldwide. The European Wind Energy Association (EWEA) anticipates that installed wind farms (WFs) will generate approximately 180 GW annually by 2020 and 300 GW by 2030 [3], with a considerable contribution from offshore wind farms. The rise in offshore wind generation is attributable to a number of factors, such as the limited number of suitable onshore sites, as well as the associated visual and noise pollution that gives rise to public opposition to future onshore installations. Offshore sites can also harness wind speeds of up to 20 percent higher velocities, with resulting energy yields up to 70 percent greater than on land [4], [1]. Due to increases in the size of offshore WFs and their distance, as shown in Figure 1. [1], their integration with onshore AC grids using AC transmission, is limited by the reactive power demand of both submarine cables, and wind-turbine induction generators [5]. High-voltage direct current (HVDC) transmission systems, Figure 1. especially the ones equipped with voltage- source converters (VSCs), are considered a promising solution in the field of offshore bulk power transmission because of their considerable advantages: ability to connect asynchronous AC grids that have different frequencies, higher flexibility and controllability, limited short-circuit fault currents, smaller filters, and black-start capabilities [6], [7]. In addition, the use of multi-terminal (MT) HVDC networks, rather than point-to-point HVDC links, increases system reliability, power-trading capability, and the ability of smooth wind power fluctuations [8], [9].

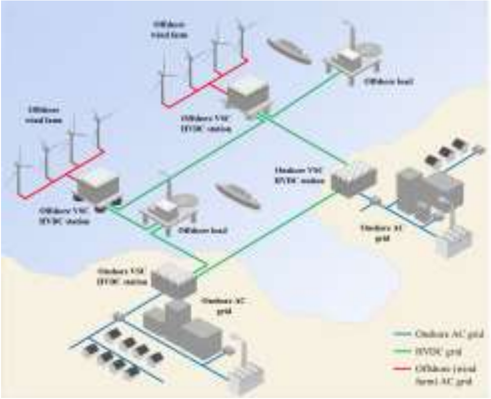


Figure 1. Typical multi-terminal VSC-HVDC based offshore wind farms integration system

II. RESEARCH MOTIVATION

The integration of remotely located power generation plants, such as offshore wind farms, into the AC grid faces a number of challenges. For example, there are problems that may appear when disconnecting these power generation plants after fault. Moreover, there is a need for transferring huge amounts of power and the need for more reactive power support for induction based generation [10]. These challenges stimulate more interest in MT HVDC transmission systems which benefit from the technological advances of power electronics and VSC technologies. Point-to-point and multi-terminal HVDC transmission, based on LCC converter technology, research has been conducted in the past. However, recently, VSC based HVDC system has become a new topic of research, especially multi-terminal VSC-HVDC systems. The MT VSC-HVDC technology needs to mature before being used in practical and commercial applications. Despite encouraging works in the literature on operation, control and protection of VSC-based MT HVDC, there still remain several gaps in this system which need further investigation and understanding such as : 1. On large scale MT HVDC system, an accurate power sharing control and voltage regulation based on predefined desired shares using DC voltage droop control is needed. In addition, the droop gains effects on the DC voltage dynamics need to be studied, thus, a methodology of selecting the droop gains considering the DC grid voltage dynamics is required. 2. Due to the nonlinearity of the MT VSC-HVDC systems, Local VSCs controller parameters need to be tuned to mitigate the change in the operating conditions to maximize the system bandwidth and minimize the damping. The overall HVDC network dynamics and the interaction between the different components of the system should be considered in the tuning algorithm. 3. While sufficient work has been done in the area of temporary outage, caused by an AC fault in the onshore grid, fault ride through in offshore wind farm integration systems based on point-to-point HVDC transmission, few of them deal with MT VSC-HVDC networks. The permanent or long-time onshore converter outage case scenarios in MT HVDC system were not studied. Hence, a new communication-free DC voltage control strategy is needed to relieve the effects of permanent onshore VSC outages in offshore MT HVDC systems by regulating the DC voltage of the HVDC network with improved system power and voltage dynamics.

III.RESEARCH OBJECTIVES

The proposed work focuses on the integration of offshore wind farms and loads to different onshore AC grids using offshore MT VSC - HVDC transmission systems. In such systems, the generated power, from the offshore wind farms or the surplus active power of onshore AC grids, need to be transmitted and shared among different onshore AC grids based on a certain desired share. The desired shares are predefined in order to fulfill various objectives such as increasing the penetration of renewable energy sources, supporting the grid frequency and grid energy adequacy, and loss minimization. Regardless of the system configuration and topology, power sharing control should be performed without violating the system limits (e.g. voltage operating region, line current capacity and VSC power rating etc.). Furthermore, improved dynamic performance and system stability are needed. Importantly, the system is a nonlinear system, where the dynamic performance and stability margin change depending on the change in the system operating conditions. In case of an occurrence of a permanent outage in one of the inversion mode grid side converters, which produces power imbalance and voltage instability in the HVDC grid, the system must continue to operate in order to deliver power to the non-faulted terminals. The effects of that outage should be cleared in order to achieve a proper stable operation in the remaining system. To fulfill these requirement, The research objectives of this work are: 1. Achieving Accurate power sharing based on pre-defined desired sharing schemes while consider the DC voltage transient and steady state dynamics. 2. Improving the system stability and dynamic performances by increasing the system bandwidth at acceptable damping. 3. Mitigating the effects of the onshore converter outage occurrence especially the permanent outage and recover the system to the pre outage state.

IV. LITERATURE REVIEW

The exploitation of multi-terminal (MT) HVDC (High Voltage Direct Current) grids for offshore wind farm integration into continental bulk AC system raises several technical issues, in particular the verification of the compliance of MTDC grids and offshore wind farms to the performance requirements (in terms of frequency, voltage support and fault ride through) which are being established by the grid codes, and the availability of general and customizable models to simulate their response. Lot of research is going on in the subject to overcome the challenges. A brief review of the research till date is presented. The goal of this work is to provide a set of “open” general models, able to fulfil the grid code requirements. After a preliminary static security assessment study on the integrated AC/DC system, some simulations are performed to check the fulfilment of grid code requirements in case of typical contingencies. The goal of the work is two-fold: 1. To provide a set of open control models, with special focus on an innovative controller which assures the fulfilment of grid code requirements. 2. To provide a set of open control models, with special focus on an innovative controller which assures the fulfilment of grid code requirements. Achieving these objectives can be useful for both new vendors accessing to the HVDC equipment market. The present paper presents a subset of the results obtained from the dynamic simulations and security studies on an integrated AC/DC system where a grid code compliant model of a MTDC grid for offshore wind power integration has been connected to on shore AC grid. A multi-terminal VSC-HVDC transmission system is the interconnection of more than two VSC stations via DC cables in different topologies, e.g., radial, ring and meshed. It is the evolution of traditional two terminals (point-to-point) HVDC transmission systems. The MT HVDC system provides the ability to connect multiple AC grids, remote power plant and remote loads together. This transmission system is considered a promising technology for the integration of massive generation from renewable sources into the power system. Furthermore, it can be used to trade the electric power safely across national borders.

V. MULTI-TERMINAL HVDC SYSTEM COMPONENTS

5.1 VDC VSC Converter Stations

The converter stations are used to connect the HVDC transmission network with other grids, e.g., AC grids, DC grids, remote power plants. There are two types of HVDC converter station based on the type of connected grid: AC-DC converter to interface with AC grids and bidirectional DC-DC converter to interface with other DC grids with different voltage level and configuration. The commonly used converter station in MT HVDC networks is based on AC-DC VSC. The VSCs work in two modes of operation: rectification mode (AC to DC conversion) when the power flows from the AC side to the DC side, and inversion mode (DC to AC conversion) as the power flows from the DC to the AC side. The main components of the VSC station are the converter, the phase reactor, the AC filter and the DC capacitor as shown in Figure 2. On the AC side of the converter, the converter is connected to the AC grid through a three-phase reactor, shunt low-pass filter and transformer. On the other hand, the DC network is connected to the converter through DC smoothing capacitors and high frequency filters.

5.1.1 AC-DC converters

As a result of the development of the fully controlled semiconductor technologies, the VSC has been promoted to reach important voltage levels. The VSC consists of IGBTs and diodes. The IGBTs are fully controlled devices that conduct the current in one direction. Therefore, a diode is connected in anti-parallel to enable current conduction in the opposite direction. The VSCs operate at a switching frequency of more than 1 kHz to eliminate low order harmonics. Thereby, a filter is required only for high order harmonics that is significantly smaller in size than the LCC smoothing filter.

5.1.2 Phase Reactor and the low-pass filter

The phase reactor is part of low pass filter; it has high inductance with low resistance. The reactor is one of the main components that affects the active and reactive power control. The shunt low-pass filter prevents the output high frequency harmonics of the converter from entering the AC grid.

5.1.3 DC capacitors

The DC capacitor is used to smooth the DC voltage at the terminals of the converter by keeping it within a small range via charging and discharging. It is used also as an energy storage unit. It has a dominant effect on the voltage and power dynamics in the DC network.

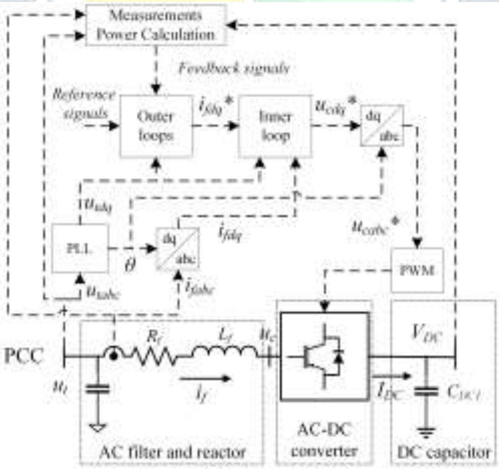


Figure 2. HVDC components and control structure

5.2 HVDC transmission line

The multi-terminal HVDC transmission lines has two configurations: unipolar (2 terminals) or bipolar (3 terminals). There are many topologies such as radial, ring, or meshed topologies as shown in Figure 3. The selection of the topology depends on a number of factors. One of these factors is the economic consideration that depends on cable length and ratings, geographic nature of the cable path, the number and the ratings of protection devices, etc. In addition to the economics, the technical aspects such as the system reliability, flexibility and efficiency need to be taken into account [3],[4]. The radial topology has the lowest cost and transient short circuit fault current, but it also has lower reliability and efficiency in comparison to the other topologies. On the other hand, the meshed topology is more reliable and has lower transmission loss; however, it is more expensive.

VI.MULTI-TERMINAL VSC-HVDC CONTROL STRUCTURE

In the MT-HVDC system, the system converters control their local variables through their local controllers based on desired set-points and control parameters. These set-points and control parameters are calculated and then sent by a central controller to the system converters for achieving global objectives of the overall systems. Thereby, the MT HVDC transmission network control system has a two-levels hierarchal structure. The two levels of the control systems are the primary and the secondary control levels, as shown in Figure 3.

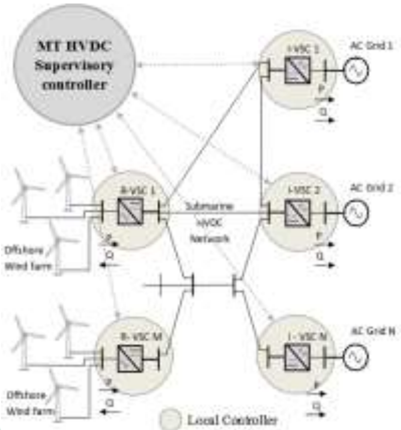


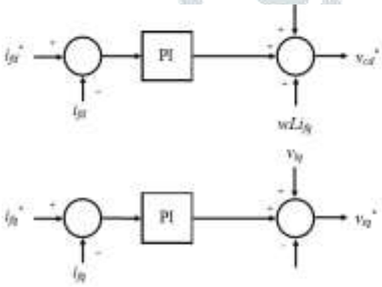
Figure 3. VSC-HVDC control structure

6.1 Primary Control Level

The primary control level is the local controller of the VSC stations, the purpose of this controller is controlling the local variables of the VSC, such as the AC filter reactor current, terminals AC voltage, terminal DC voltage, active and reactive power. Decoupled dq – current control technique is the commonly used technique in VSC controllers. This technique provides the possibility to control the two components of the AC current, i.e., the direct (real) and quadratic (imaginary) components, independently. The local controller consists of a number of cascaded control loops. The main control loop is the inner current loop, which controls the AC reactor current. the reference current values are calculated by the outer loops, which define the VSC mode of operation.

6.1.1 Inner control loops

The inner loop is based on a PI controller that is responsible for controlling the decoupled current components of the filter reactor, ifd and ifq. these two current components are controlled by generating the reference voltages u*cd and u*cq, in dq frame, of the converter. The reference current signals i*fd and i*fq are generated from the outer loop which will be explained later. A feed forward signal for the PCC voltage is used to fully decouple the VSC's inner control loop dynamics from those of the load. Figure 4. illustrate the implementation of inner current control loop.



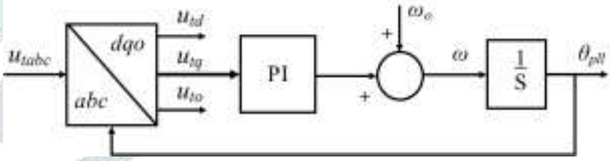


Figure 5. Inner decoupled-current control loops

Figure 4. Inner decoupled-current control loops

6.1.2 Phase locked loops

The phase locked loop (PLL) is used to synchronize the VSC to the AC grid by making sure that the d-axis is always aligned with the terminal voltage phase a. This process is performed by controlling the VSC frequency and the transformation angle $\theta_p ll$, which is used in the transformation from abc to dqo frames and vice versa, to make the q component of the terminal voltage always zero. In addition, the PLL is used to measure the connected AC grid frequency. The implementation of the PLL that is used in this work is shown in Figure 5.

6.2 Outer Control loops

The outer loop is the part in the VSC local controller that defines the mode of operation of the converter. It produces the reference decoupled currents i*fd and i*fq for the inner loop, so that it is possible to control two different variables independently. As shown in Figure 6. in grid-imposed frequency VSCs, the active power or the DC voltage are controlled by controlling the d-axis current component. On the other hand, the reactive power or the AC voltage at the point of common coupling (PCC) are controlled by controlling the q-axis current component. For the grid-imposed frequency, there are four possible modes, P-Q, P-Vac, Vdc-Q and Vdc-Vac. While, in the frequency controlled VSC, as in the WF VSC, the outer loops are responsible for controlling the dq components of the voltage at the PCC, Figure 7. shows the outer control loop of the WF VSC.

Figure 6. Outer control loops of the grid connected VSC (a) DC voltage controller, (b) Active power controller, (c) AC voltage controller, (d) reactive power controller

Figure 7. Outer control loop of the WF VSC

6.3 Droop control in DC grids

In AC systems, the synchronous generators control their output active power by means of power frequency droop characteristics. By increasing the system demand, the system frequency decreases, which in turn makes the output active power of the synchronous generator increase, and vice versa. On the other hand, reactive power voltage droop controls the system voltage by delivering reactive power to the system. In the DC grid, the DC voltage level and the Active power at any bus are correlated, while, the DC voltage and the active power are directly controlled by controlling the d-axis AC current component, it is not possible to directly control both of them simultaneously. Therefore, as in AC grid, the frequency and the active power can be controlled by means of droop control concept. In the DC grid, the DC voltage and the active power can be controlled simultaneously by means of V-I or V-P droop control, see Figure 8. In this work, DC voltage current droop is used.

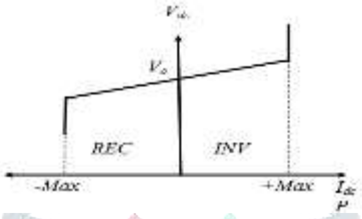


Figure 8. Droop characteristics in DC grids

6.4 The secondary (supervisory) control level

The supervisory control level of a MT HVDC transmission system is responsible for calculating the control parameters and set-points of the system VSCs' local controller to achieve certain transient and steady state operation objectives. The supervisory control levels can be based on centralized controller that receives the measurement data from the local controllers, then calculates the required control parameters and set-points and then sends them back to the local controllers. Otherwise, distributed control concept can be used on the supervisory level to increase the system reliability, in which the system VSCs share some common data, i.e., measurements and set-points, and locally calculate their local control parameters and set-points. In this work, the main objective of the supervisory controller is to calculates and tune the optimal control parameters for power sharing control and the DC voltage regulation process and enhancing the transient responses of the local controllers.

VII. CONCLUSION

The main objective of this paper is proposing an operation and control strategies for a MT VSC-HVDC based offshore wind farms integration system by developing a centralize (supervisory) controller for both the steady-state operation and the transient dynamics performance perspectives.

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