Modular Multi-level Converter Based HVDC Systems Integrating Offshore Wind Farm

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Abstract: This last decade, VSC-HVDC based on Modular Multilevel Converter (MMC) has earned a considerable attention, leading to intensive technical and operational enhancements which made the MMC an attractive solution to achieve efficient renewable energy harvesting mainly for Offshore Wind Farms (OWF). The present paper discusses the state of art of modulation strategies, and mathematical modeling techniques that are best suited to simulate large HVDC systems including the OWF which rise the challenge for computing capacity. Moreover, a test system is proposed to demonstrate the performance of the chosen techniques under convenient scenarios. Overall, this work will provide a complementary guide and a shortcut to pertinent literature touching this research field.

Keywords—MMC, HVDC, VSC, wind farm, control.

I. INTRODUCTION

The last few decades, renewable energies earned a valuable attention, owing to exceptional climate awareness and decreasing cost of technologies, so they had been improved extensively during this period, which increases their penetration that gives birth to new challenges in power system operation induced by the intermittent nature of renewable power generation mainly from wind and solar photovoltaics. Moreover, wind power plants record the fastest growth compared to other renewable energies, especially offshore farms, because they have better wind velocity profile leading to a higher energy yield. On the other hand, onshore wind farms suffer from construction restrictions which limit their deployment. By the way, modern OWFs use variable speed wind turbines most commonly through Doubly Fed Induction Generator (DFIG) that offers dynamic reactive power control. Coupled to Voltage Source Converters (VSCs), this system will allow independent control of active and reactive power and it will rely on fast-switching transistors (e.g. IGBTs) that are not expected to cause harmonic currents that may significantly distort the voltage waveform [1].

As the availability of shallow water sites declines, the forthcoming offshore wind farms (OWFs) will become larger and more distant from the onshore grid which motivate novel and creative offshore foundations that allow accessing deeper water and unlock the full potential of the offshore wind market. A great demonstration of what future OWFs tend to be, is the DolWin2 project which is connected through a 45 km long DC sea cable system and a further 90 km long land cable to an HVDC onshore station. Moreover, the 320-kV converter station is housed on an offshore platform, with power transmission capacity of 916 MW. For more details, see [2], [3] and [4]. However, the above discussed constraints will make the HVAC transmission systems inefficient and troublesome, mainly due to frequency and voltage instability and large charging currents of submarine cables [5] which will foster one attractive alternative that comes to get over these issues which is the use of a point to point (P2P) VSC-HVDC system [6] which have the ability to supply weak grids or passive networks. In addition to the fast control of both active and reactive power flow in either direction, a VSC-HVDC system also provides black start capability and a compact substation structure, which is an advantage for offshore applications [7].

The Modular Multilevel Converter (MMC) [8] brings the VSC-HVDC transmission system to a higher level through its various features including modularity which easily enable scalability to higher voltages [9], low switching losses, low transient peak voltages [10] and lower harmonics content (high-quality AC voltage), which reduces greatly the filtering requirements. As this topology benefits from the redundant combination of module connections for each required AC level, balancing capability is better than the one of conventional VSCs [11] which result in better performance during unbalanced operations and symmetrical/asymmetrical AC faults, reducing the risks of device failure and system collapse [12].

This paper presents a test system subjected to various analyses in different operational and control aspects (under balanced/unbalanced conditions) of a potential OWF connected to the onshore grid through a VSC-HVDC link based on 401 level MMC converters. However, this manuscript can be divided into three complementary sections. The first one will describe the DFIG and MMC systems briefly. The second part should give an overview of the modular multi-level converter. Finally, the simulated system and simulation results are presented in the last part.

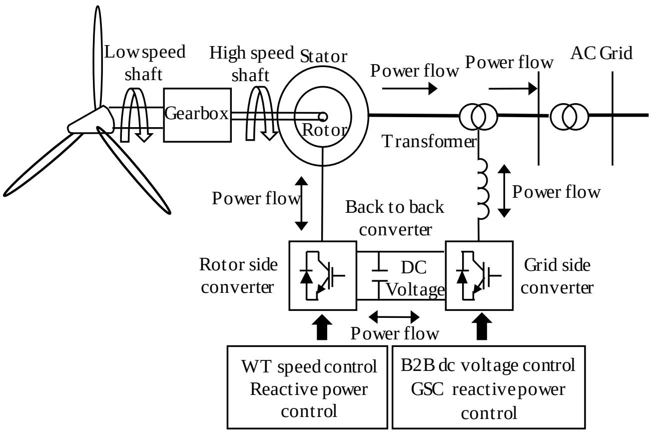

Fig. 1. Schematic diagram of a DFIG wind turbine

II. DFIG Based Wind Turbines

A. DFIG description and composition

According to [13], the DFIG wind turbine has been the dominant variable speed technology in the market for models above 1.5 MW. The stator windings are connected directly to the AC grid through the turbine transformer, whilst the rotor windings are connected to the AC grid via slip-rings and a Back to Back (B2B) power electronic converter (see Fig. 1).

The combination of the B2B converter with the rotor blades pitch control enables variable speed operation which leads to higher efficiency and high energy yields compared to fixed speed wind turbines. The B2B converter partially decouples the network electrical frequency from the rotor mechanical frequency, enabling variable-speed operation of the wind turbine. The main components of a DFIG wind turbine are described in [14] and [15].

The B2B converter consists of two (VSCs), one is the Rotor-Side Converter (RSC) and the other is the Grid-Side Converter (GSC) that are linked via a common DC bus. The RSC controls the wind turbine speed and reactive power consumption by modifying the rotor currents, while the GSC mainly keeps a steady DC voltage level on the B2B DC bus and provides, to some extent, reactive power support to the AC grid. The architecture of both converters allows bidirectional power flow making the B2B converter a rotor slip-power recovery device. [25-29].

B. DFIG Control System

The key variables to control in a DFIG are the rotor speed, the reactive power of the DFIG, the DC voltage of the B2B converter and the reactive power of the GSC. **Erreur ! Source du renvoi introuvable.** Figure 2. shows a block diagram of the control loops for a DFIG wind turbine.

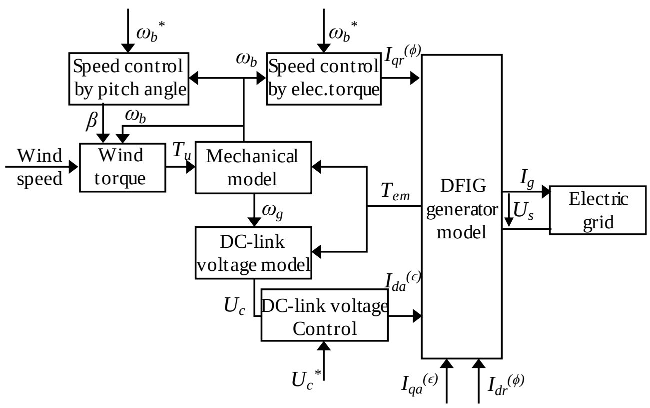

Fig. 2. DFIG Models and control loop interaction

A feed-forward decoupled current control is used for both of the converters controls [16] which is as the one used for the Receiving End Converter (REC) of the VSC-HVDC. When the wind speed exceeds its nominal value, the pitch control pitches the rotor blades to reduce the mechanical torque and thereby recover the generator rated speed. A complete description of the DFIG control system can be found in [17], [18], [19] and [20]. MMC modeling and control

The Fig. 3 shows three phases of a modular (n+1) level converter, consisting of n cells in each arm. This converter relies on the cell capacitors to create a multilevel voltage waveform at the converter terminal. Typically, hundreds of cells are required to build a single valve for DC transmission requirements. As the number of level increases, the quality of AC voltage waveform becomes better and the harmonic content is lower.

The use of a large number of SMs with small voltage steps results in low dv/dt at each switching and reduced voltage stress on the insulation of the interfacing transformers. This allows the use of standard transformers without the need to withstand the DC link voltage or harmonic currents. Furthermore, the effective switching frequency per device is low, resulting in lower switching losses and lower harmonics. [29-33]

C. MMC converter

Since the MMC topology is of VSC type, it uses an upper-level control similar to the previous generation. Furthermore, the MMC requires additional controllers in order to stabilize internal variables (Lower Level Control): The DC capacitors are now included in each SM and the series reactors, used to control the power flow and circulating currents, are embedded in the converter's phase arms. A Balancing Control Algorithm (BCA) is required to control these variables and inject the modulation [21]. A top-level view of the control structure is presented in [22] see figure 4.

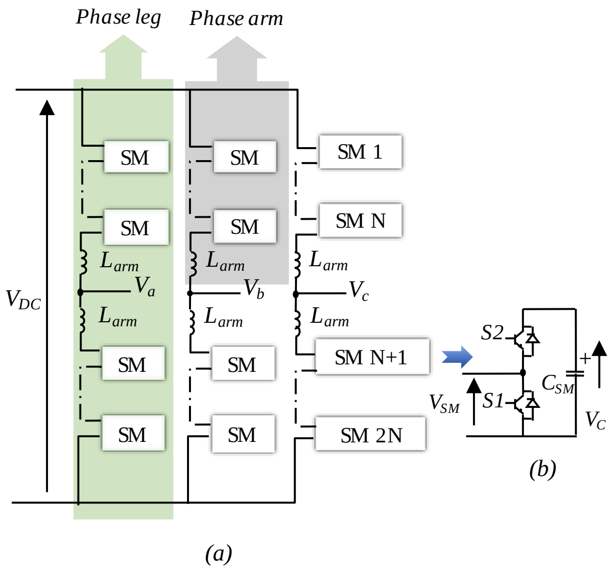

Fig. 3. (a) MMC Converter topology, (b) Sub module configuration

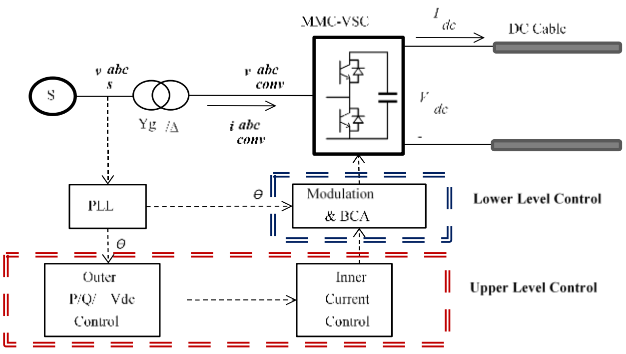

Fig. 4. Control hierarchy for the MMC station

For the Upper Level Control block, the power angle and vector current controls are widely used. Power-angle control (or V/F control) is used when the VSC converter is connected to an AC system with passive load or for wind-turbine applications [22]. It uses the phase angle shift between the VSC and the AC system to control the active power, while the reactive power is controlled by varying the VSC voltage magnitude [23]. Vector current control is a current control based technology. Thus, it can naturally limit the current flowing into the converter during disturbances. The basic principle of vector-current control is to regulate the instantaneous active and reactive powers independently through a fast inner current control loop, see figure 4. Due to its successful application in HVDC transmission system, vector-current control has become the dominant control method for grid connected VSCs in almost all applications [23][35-39].

III. SYSTEM DESCRIPTION

The simplified single-line diagram of an offshore system is shown in Fig. 5. The MMC-HVDC system is used to integrate up to 1000 MW of offshore wind generation through a single core 100 km submarine cable modeled with a frequency dependent (wideband) model under ±320 kV voltage. The onshore MMC is connected to a 400 kV, 50 Hz AC grid represented with Thevenin equivalent.

The HVDC system of Figure 5, based on switching function model and the NLC strategy (nearest level control),

Fig. 4. VSC HVDC link connecting OWF to the transmission System under fault

is simulated in the EMTP-rv environment. The simulated test cases evaluate dynamic performance of the overall system of Figure 5, including power and control subsystems, under various conditions.

IV. MODEL PERFORMANCE ANALYSIS

Several simulations were conducted to investigate the operation of the above MMC converter based **wind power evacuation**system. The dynamic performance of the transmission system is verified by simulating the:

A. Normal operation of the HVDC Connection of Offshore Wind Farms to the Transmission System.

B. Dynamic responses to step change applied to the reactive power regulator and DC voltage regulator at MMC 2.

A. Case A

Figure **6** present the active powers generated by wind farms (666 × 1.5 MW) and exported from MMC1 (offshore station) to MMC2 (onshore station), respectively. The power reference at MMC1 is set to -1 p.u during the 3s simulation interval. The MMC2 operates in the constant active power and constant reactive power mode، and the DC voltage is set to 640 kV (±320KV), the MMC 2 operate at unity power factor. The MMC 1 operate in VAC/F control and constant AC voltage mode, the active power setting is 1000 MW in MMC1 (rectifier) and - 1000 MW in MMC 2 (inverter). The reactive power in MMC 2 is kept at 0 MVAr. The offshore converter is initially set to absorb 150 MVAr while operating at maximum active **power. Figure** 4.12 shows that the MMC-HVDC link is capable of responding to the power demands **of the wind** farm and that the converter is able to meet the required reactive power demands set out on the grid code (leading and lagging power factor of 0.95). **Figure** 6 shows the capacitor voltages of the phase-a sub-modules of MMC 1 and MMC 2, **respectively, which are kept balanced at their nominal values, only the average capacitor voltage of each arm is** plotted for the sake of clarity**.The phase voltages at the PCC for the onshore network)VAC1a(and the offshore network)VAC1**a) are shown to be almost sinusoidal and as such have a small harmonic content. The DC voltages are smooth and stable.

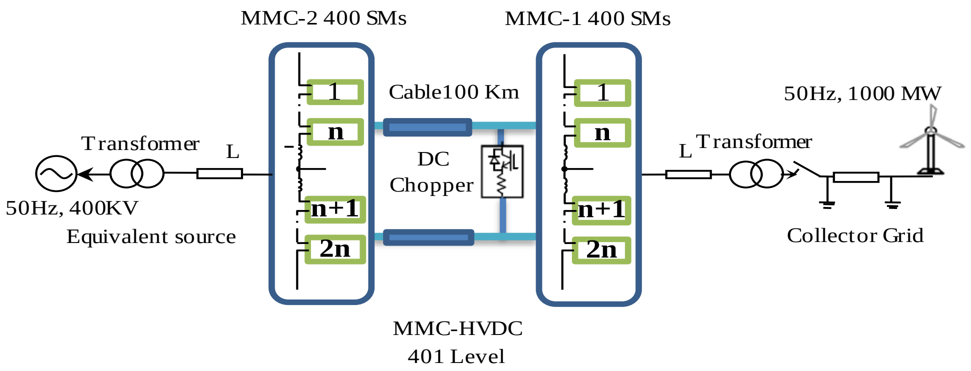

Fig. 5. MMC-HVDC 401 level HVDC Connection of Offshore Wind Farms to the Transmission System

B. *Case B*

In order to test the dynamic responses of MMC converters regulators, two test cases have been studied. At t = 2 s, the reactive power order was increased from 0 p.u to 0.1 p.u of MMC station 2 (onshore station). We can see that it has a good tracking accuracy. It is achieved in 80 ms, without any effect on real power as shown in Figure 7, confirming the decoupling of real and reactive power control loops. ‹**Obviously** the reactive power flow can be independently controlled at each AC network‹ and the reactive power and the active power control is independent. **Figure** 8 shows the response of onshore MMC to a sudden change in dc voltage order from 1 p.u to 0.9 p.u at t= 2 s. It is achieved in 50 ms‹ without any effect on reactive power. This step change cause transient on the active power.

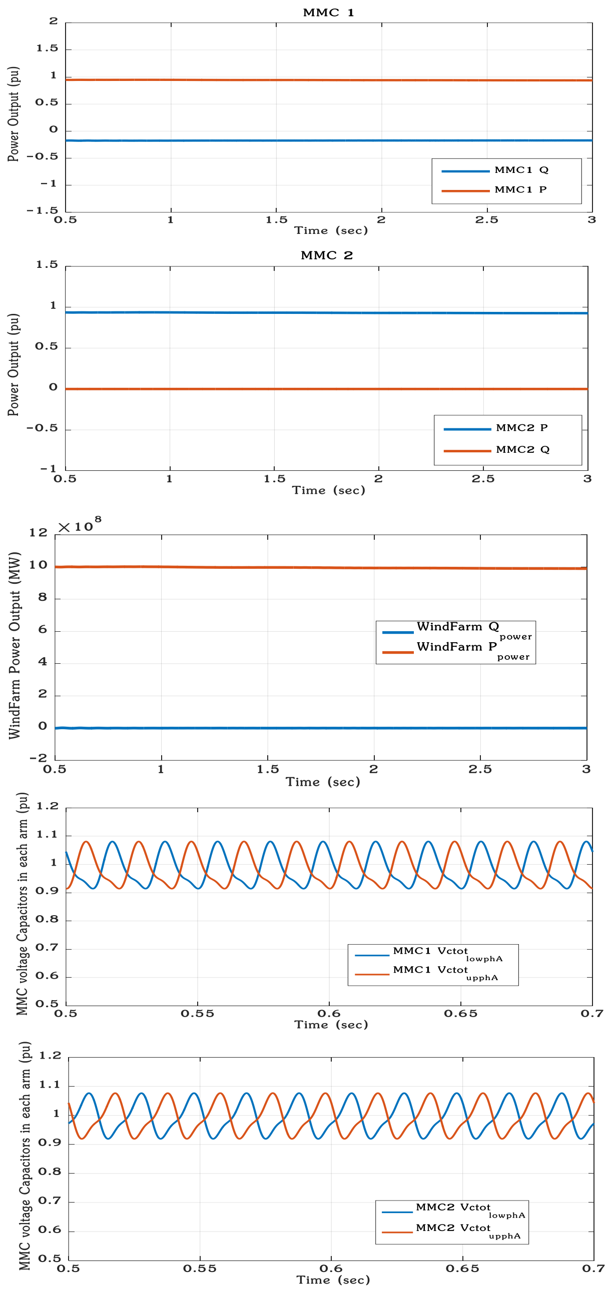

Fig. 6. HVDC Connection of Offshore Wind Farms to the Transmission System in normal operation

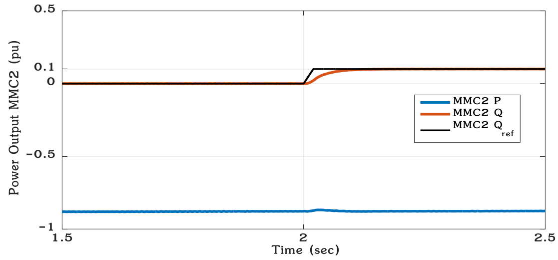

Fig. 7. HVDC system responses for reactive power step changeesat MMC2

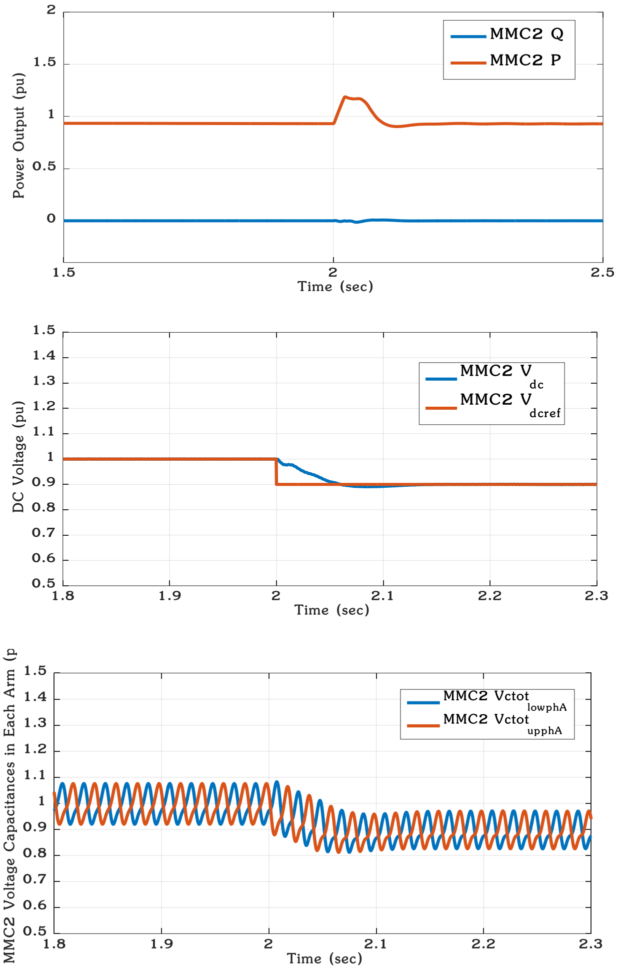

Fig. 8. HVDC system responses for dc voltage step changes at MMC2.

V. CONCLUSION

This paper has assessed the steady-state and dynamic performance of the MMC-HVDC link models through conducting a range of typical studies. The simulation results are shown to be in agreement with the control theory outlined above. The models developed in this thesis were used to investigate the links' ability to respond to reactive power demands. The results show that the models were able to meet the reactive power requirements.

This paper also investigates the mathematical models for the modular multi-level converter based HVDC system with the controller's design of the power flow controllers and dc bus voltage regulators, under balanced grid conditions. The studies are conducted in time domain using the EMTP-rv simulation environment. The study results demonstrate that the modular multilevel converter, based on appropriately designed controllers, provides the desired dynamic response, under balanced grid conditions, for HVDC system applications. The studies also show that the balancing capacity algorithm BCA strategy can effectively provide voltage balancing for the MMC capacitors under steady state and dynamic operational conditions. Furthermore, the inherent scalability of the MMC renders it as a promising configuration, compared with the multi-level and multi-module VSC configurations, for HVDC system applications.

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