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Energy Procedia 137 (2017) 391–400

Energy Procedia

www.elsevier.com/locate/procedia

14th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2017, 18-20 January 2017, Trondheim, Norway

Grid Integration of offshore wind farms using a Hybrid HVDC composed by an MMC with an LCC-based transmission system

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Abstract

This paper presents a hybrid HVDC-transmission system composed by a Full-Bridge Modular Multilevel Converter (FB-MMC) and a Line-commutated Converter (LCC) from the grid integration of offshore wind farms. The operational characteristics of a three-terminal hybrid-HVDC system, e.i. two LCC stations plus one MMC station, are investigated using PSCAD/EMTDC. This paper mainly focuses on the performance of the system under ac faults at the LCC inverter. This condition is critical for the entire system because LCC is prone to commutation failure, which can be translated into dc faults on the hybrid system. Numerical results show that FB-MMC can help to alleviate ac faults conditions in the LCC, and the system is able to restart after clearance of the fault.

Keywords: Line-commutated converters (LCC); Full-bridge modular multi-level converters (FB-MMC); Hybrid HVDC; offshore wind farms.

Nomenclature

i_{DCr}	DC current from LCC rectifier
i_{DCi}	DC current to LCC inverter
i_{DCwf}	DC current from the wind farm
V_{DCwf}	DC voltage LCC inverter
α_1	firing angle of the LCC rectifier
α_2	firing angle of the LCC inverter
γ	extinction angle of the LCC inverter
V_S	AC voltage of the MMC

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10.1016/j.egypro.2017.10.363

1. Introduction

In recent literature, the feasibility of grid integration of offshore wind farms using hybrid HVDC systems composed by voltage source converters (VSC) and line-commutated converters (LCC), have been investigated [1–3]. Such a hybrid HVDC systems are attractive mainly because their low power losses compared to VSC-based HVDC systems. However, hybrid HVDC systems have serious limitations when an ac fault occurs at the LCC inverter [2]. This type of fault can produce a commutation failure which incurred in a short circuit of the dc side. In this case, the dc current of the LCC climbs up quickly while the free-wheeling diodes of the VSC provide a path to feed the current into the fault. Hence, no control action can be performed to alleviate the disturbance. Full-bridge modular multi-level Converters (FB-MMC) have DC fault handling capacity, i.e. when all insulated-gate bipolar transistors (IGBT) in the H-bridge cells are blocked, there is an available path for the fault current through the series connected capacitors of the cells [4].

A few studies have explored the hybrid solution [5–8]. The first attempt to combine both HVDC technologies was made in [5]. A GTO voltage source inverter feeding a line-commutated rectifier was proposed, and its corresponding operational mechanisms were discussed. Moreover, the authors emphasized that the hybrid is only suitable for applications of unidirectional power flow. The same configuration was studied in [6], and simulation studies under normal and abnormal operation were conducted. In [7], the receiving side was an IGBT-based voltage source inverter and the sending side was a conventional LCC, some numerical simulations were shown under different scenarios, but the controller was not explicitly described. In [3] a hybrid HVDC topology for an offshore wind turbine is proposed. [1,9] presented a multi-terminal hybrid HVDC, which shows explicitly their controllers, and the system was studied under normal and fault conditions.

This paper aims to explore the feasibility of using a hybrid HVDC system composed by an FB-MMC and an LCC to integrate offshore wind farms into the main grid. This hybrid is able to clear the ac line temporary fault which produces a commutation failure since FB-MMC have dc fault handling capability. An overall control strategy is presented and numerical simulations verify the behaviour under different operative conditions such as start-up, variations of wind speed and ac faults. The paper is organized as follows: First, the system description and control design of the proposed hybrid HVDC configuration is presented in section 2. In section 3, the most relevant operational characteristic are discussed, i.e. start-up and response to ac faults. In section 4, PSCAD/EMTDC numerical simulations are provided to illustrate the performance of the system under normal operation including changes in wind conditions, and abnormal operation including onshore ac fault. Finally, some concluding remarks are presented in section 5.

2. System description and Control Design

The proposed configuration is shown in Fig. 1 is extended from Cigre HVDC benchmark model. It consists of two ac grids (AC1 and AC2) interconnected by a bipolar HVDC system with 12-pulse line-commutated converters. A large offshore wind farm is connected to the LCC HVDC through an FB-MMC is parallel connected to the middle point of the LCC-based HVDC. This type of configuration not only provides the offshore grid requirements, e.g. high power density and operational flexibility, which are better supplied by a forced-commutated technology, but also exploits the advantages of the LCC in terms of power losses, voltage capability, and low cost.

The parameters of the line-commutated converters are based on the well-known benchmark model proposed by the international council on large electric systems (CIGRE) [10]. The ac supply systems are represented by Thevenin equivalents, i.e voltage sources with the corresponding source impedance. Both AC1 and AC2 are considered weak grids, short circuit ratios of 2.5, in order to evaluate the performance of the proposed control under severe conditions. A detailed model of the system is considered with ac filters, tuned to the characteristic harmonics, and reactive compensation in each LCC.

A large offshore wind farm is connected by the MMC. To reduce the simulation time, an aggregated model using a Norton equivalent is implemented. Variations of the wind speed are directly considered by changes in the current source. The design of the controllers is divided into four sections: the LCC rectifier, the LCC inverter, the MMC, and the offshore wind farm. Below, the control objectives and strategies for each system element are described.

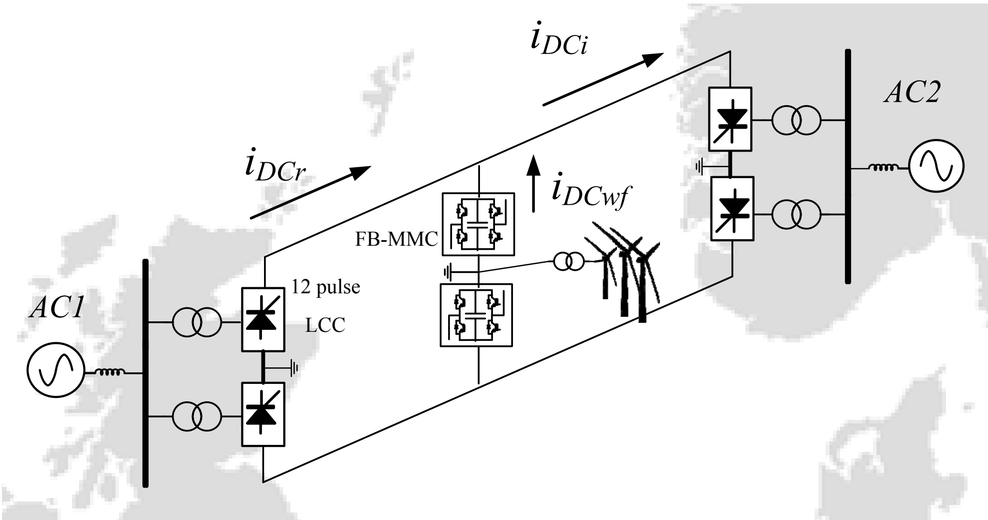

Fig. 1: Proposed Hybrid HVDC for integration of OWF.

2.1. Control of LCC rectifier

The LCC rectifier regulates the power transfer from one grid to another. In normal operation, the LCC rectifier operates in a constant DC current mode. The *control objective* consists of regulating the DC current i_{DCr} toward its reference i^*_{DCr}. Basically, the firing angle α_1 is obtained using a proportional and integral (PI) controller that compares i_{DCr} and i^*_{DCr}. The reference i^*_{DCr} is set using the voltage dependent current order limiter (VDCOL) and the current that comes to the OWF. The controller is depicted in Fig. 2a.

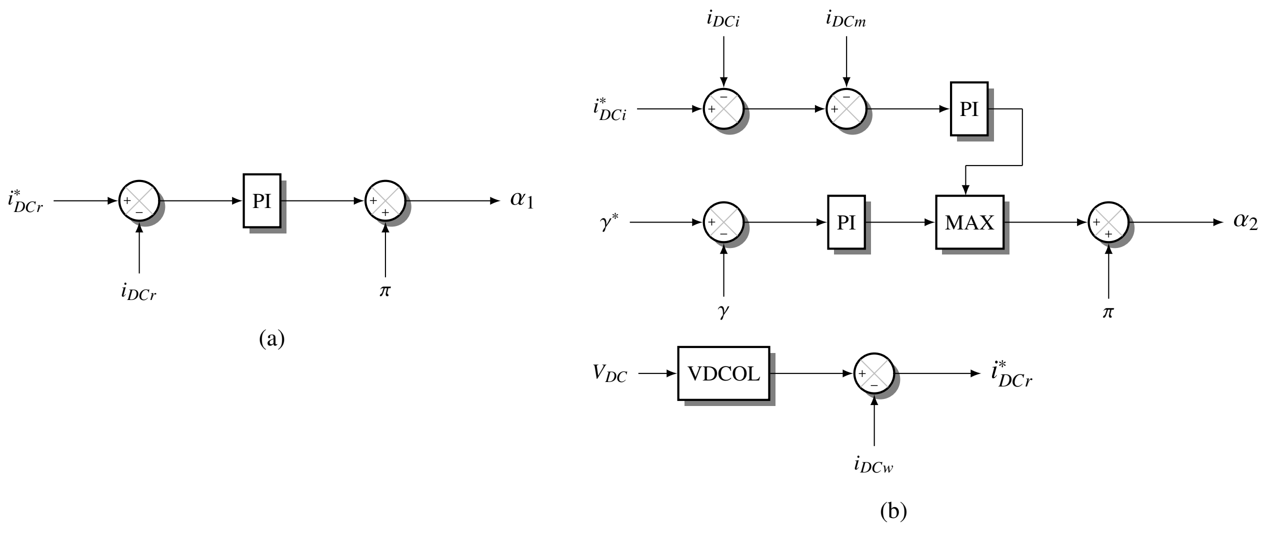

Fig. 2: Block diagram of a) the LCC rectifier controller b) Block diagram of the LCC inverter controller

2.2. Control of LCC inverter

The LCC inverter *control objective* is to regulate the DC link voltage V_{DC}^{*} of the HVDC to its reference V_{DC}^{*}. In normal operation, the firing angle α_2 is produced using a PI whose inputs are the extinction angle γ and its reference γ^{*} as shown in the Fig. 2b. During disturbances, such as ac faults, the controller changes the operation mode to assist the regulation of DC current using a scheme similar to that used for the LCC rectifier but reduced by the margin current i_{DCm} as shown in the Fig. 2b. In this case, the inputs of the PI are the DC current to the inverter i_{DCi} and its corresponding reference i_{DCi}^{*}.

The reference i_{DCr}^{*} is adjusted using both the VDCOL and the measurement of the DC current coming from the offshore wind turbines i_{DCw}. So, this reference is reduced if the DC voltage is lowered or if the production of the wind farm is increased. The entire control is presented in Fig. 2b.

2.3. Control of MMC

Since wind turbines are able to control their power, the main responsibility of the MMC is to establish the offshore grid. The idea behind consist of emulating an infinite bus, so all the power that is generated by the offshore wind farms can be absorbed automatically toward the HVDC. The *control objective* is regulating ac voltage and frequency towards their respective references. A simple controller can be used to accomplish the aforementioned objectives.

Let us consider the classical model for one leg of the MMC

$$\frac{V_{DC}}{2} = R_x i_{up} + L_x \frac{di_{up}}{dt} + v_{up} + R_s I_y + L_s \frac{dI_y}{dt} + V_s$$

$$-\frac{V_{DC}}{2} = -R_x i_{down} - L_x \frac{di_{down}}{dt} - v_{down} + R_s I_y + L_s \frac{dI_y}{dt} + V_s$$

where R_x and L_x represent the arm resistance and inductance respectively. v_{up} and v_{down} are the equivalent arm voltages in the upper and lower arm. i_{up} and i_{down} are the equivalent arm currents in the upper and lower arm. V_S is the ac voltage of the MMC. Each variable can be visualized in Fig 3a. By a simple change of variables, the model can be rewritten as follows:

$$R_x \cdot I_x + L_x \cdot \frac{dI_x}{dt} + V_x = V_{DC} \tag{1}$$

$$R_y \cdot I_y + L_y \cdot \frac{dI_y}{dt} + V_y = -2 \cdot V_s \tag{2}$$

with

$$I_x \triangleq i_{up} + i_{down}; I_y \triangleq i_{up} - i_{down}, V_x \triangleq v_{up} + v_{down}; V_y \triangleq v_{up} - v_{down}, R_y \triangleq R_x + 2 \cdot R_s; L_y = L_x + 2 \cdot L_s$$

Equation (2) shows the voltage in the offshore grid can be independently controlled by imposing a proper frequency and magnitude of V_y. This control is shown in Fig.3b. Notice that the control is developed in the natural reference frame. A PLL is not required due to the fact that frequency is not measured but imposed by the MMC. Current I_x is used for balancing the capacitors in each leg as in the conventional MMC control as voltage V_{DC} is controlled by the LCC in the AC2.

2.4. Control of offshore wind farm

Wind turbines have been simulated as three-phase current sources, delivering current to the measured three-phase voltage at the connection point, in order to speed up simulations. The magnitude of the current is decided by the wind conditions, which is emulated using the wind model provided by PSCAD, and the measured voltage at the interface. Offshore wind farm uses an aggregate model, i.e. the behaviour of a single turbine represents the entire farm.

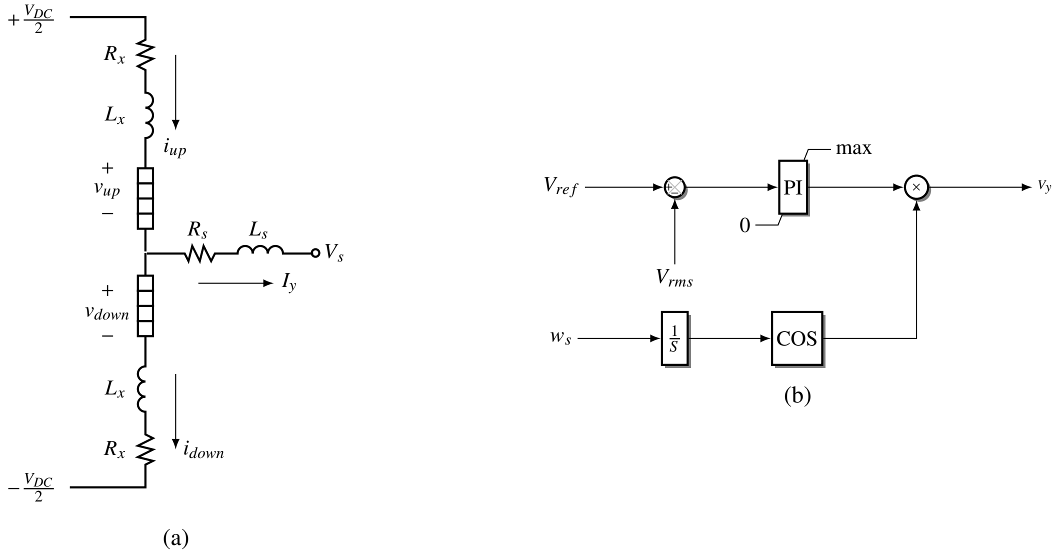

Fig. 3: Diagram of the (a) topology of one leg of the MMC (b) control of the voltage in the offshore grid

When the wind turbines operate below the rated wind speed, the characteristic is based on the steady-state power versus rotor speed characteristic which is shown in Fig. 4 . If the turbine is operating above the rated wind speed, the pitch control system must change the angle, in order to keep the turbine operating at a rated power, and avoid overloading and damaging both the generator and converter [11].

3. Operational characteristics

The proposed hybrid includes an LCC inverter which needs a holding current to perform the start-up procedure. Moreover, LCC inverter is vulnerable to voltage drops. So, all these operational characteristics are discussed as following.

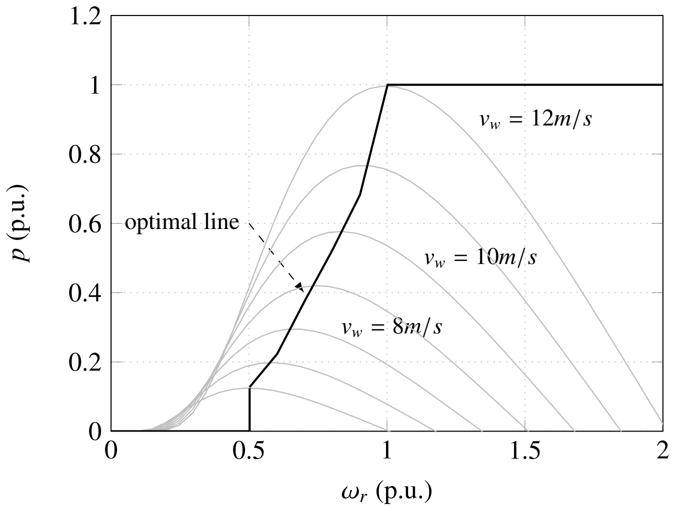

Fig. 4: Power versus rotor speed characteristic.

3.1. Start-up

An LCC inverter needs a holding current to operate. This current usually is low or is a long pulse [12]. When the holding current is established, the inverter LCC is able to ramp up the dc voltage until its reference.So, hybrid HVDC using MMC and LCC needs a special process of start-up. Below the step-by-step procedure is described:

1. All converters are blocked.
2. LCC inverter and LCC rectifier are unblocked.
3. LCC inverter ramps up the DC voltages using the holding current which is provided by the LCC rectifier. DC current reference to LCC rectifier is determined using a voltage dependent current order limiter (VDCOL) function. This is the standard procedure in LCC-based HVDC.
4. Once DC voltage is regulated in the HVDC, offshore MMC is unblocked and operated in island mode, i.e. offshore ac voltage is ramped up to its nominal value.
5. Once offshore ac voltage is regulated by the MMC, wind turbines are unblocked and their power output increases and automatically is transmitted to onshore ac grid. As the power that comes from the wind turbines grows, the power which is sent from the rectifier may decrease. An appropriate communication scheme should be considered.

3.2. AC faults

Generally, a commutation failure (CF) occurs in LCC inverters when there is a significant voltage drop on the ac side. In the hybrid, CF is seen as a short circuit of the dc side. Moreover, dc current of the LCC inverter climbs up very quick due to the CF. In the case of hybrid HVDC consisting of VSC-based technologies, the over-current may flow through the VSC free wheeling diodes of the IGBT devices. Since CF can also be caused by DC over-current, the LCC inverter may have successive commutation failures and therefore leads to unstable operation.

3.3. DC faults

FB-MMC topologies can clear dc fault currents since they are build using full-bridge sub-modules which are able of suppressing the fault current against dc faults. First, FB sub-modules can only be switched in pairs, e.i. S1 and S4, S2 and S3 or all switches off referring to Fig. 5. So, when a DC fault occurs, IGBT are blocked so there is only one available path through the series DC capacitors of each sub-modules as shown in Fig. 5. Moreover, the DC capacitors cannot get discharged completely due to the inherent sub-module configuration. Fig. 5 represent only two phases, however, it is clear that the fault found a path using only an upper leg in one phase and the bottom leg in the second phase. As result of this strategy, the current can be effectively limited using the FB- MMC. In the case of hybrid MMC and LCC, an ac fault will produce a commutation failure in the LCC inverter which is basically a dc fault in the MMC. The over-current which is produced in the process can be effectively minimized using the FB-MMC configuration.

4. Numerical results

The HVDC system, shown in Fig. 1, has been implemented using PSCAD/EMTDC to illustrate its performance of the proposed topology. The system, which is rated at 1000 MW and 500 kV, is composed of two 12-pulse LCCs connected through a long DC cable of 100 km. At the LCC rectifier side, the ac voltage is 345 kV at 50 Hz with a short circuit ratio (SCR) of 2.5. At the LCC inverter side, the ac voltage is 230 kV at 50 Hz with SCR of 2.5. FB-MMC is connected via a 100 km DC cable at the midpoint of the other cable. The simulations were conducted under different conditions to investigate the operating characteristics of the proposed system. These conditions include start-up procedure, ac faults, and dc faults.

4.1. Start-up

Fig. 6[left] presents the start-up process which was explained above. First, all converter are disabled until t = 0.04 s. At t = 0.4 s, the LCC converters are enabled, the voltage at the dc link ramps up since is regulated by the LCC

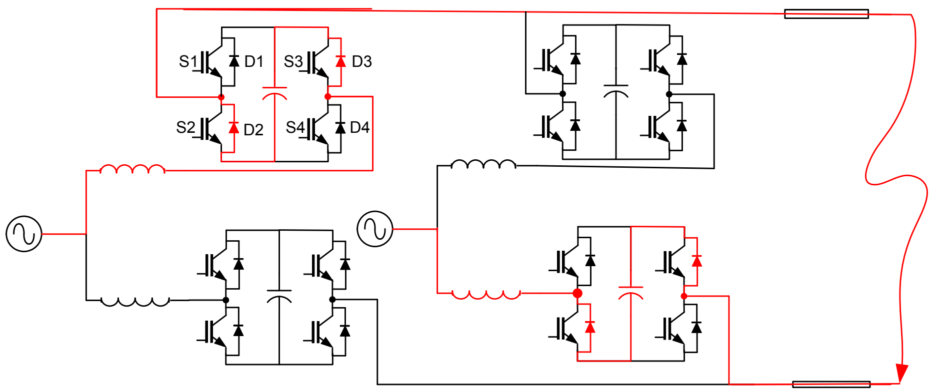

Fig. 5: Full bridge MMC DC fault response

inverter as shown in Fig. 6[left] (d). The holding current is provided by the LCC rectifier as shown in Fig. 6[left] (c). At t = 0.3 s, The FB-MCC is enabled. So, ac voltage ramps up to the nominal value as shown in Fig. 6[left] (a). Once the ac voltage reaches the nominal value is possible to connect the wind turbines. At t = 1.0 s, each turbine is de-blocked allowing the synchronization with the recent imposing ac voltage. The power from wind turbines changes slowly using a ramp function in order to avoid oscillations in the dc voltage as is shown in Fig. 6[left] (b). Fig. 6[left] shows that as the dc current coming from the turbine increases the dc rectifier current decreases.

4.2. Response to Change in the Wind Speed

In order to investigate the response of the hybrid HVDC system to change in the wind speed, the emulated wind farm is tested in various conditions. At the beginning, from t = 0 s to t = 15 s, there is a low wind conditions, i.e. v_w = 10 m/s. After t = 10 s, a ramp begins that increases v_w at a rate of 4 m/s during 30 s. At t = 15 s, a wind speed gust occurs which decreases v_w amplitude 3 m/s with 10 s duration. Finally, the wind speed is set at v_w = 15 m/s which represents a high wind conditions [11]. The nominal wind speed is considered as 12 m/s. During all the simulations the wind is quite noisy. Noise wind data are the following: the number of noise component 250, random seed number 50, the time interval for random generation is 0.35 s, and noise amplitude controlling parameter is 10 rad/s [13].

Fig. 6[right] shows the response to the wind condition described above. Fig. 6(a)[right] presents the rms voltage at the LCC rectifier, the LCC inverter, and the MMC, respectively. All ac voltages are maintained at their nominal values during wind fluctuation as was expected. Fig. 6[right](b) shows the active power at the LCC rectifier, at the LCC inverter and the MMC, respectively. It can be seen the power fluctuation caused by the wind in the active power at MMC. Note also that the power delivered by the LCC rectifier is complementary with the power from MMC in order to deliver the rated power at LCC inverter. Fig. 6[right](d) displays the dc voltages at the terminals of LCC rectifier, LCC inverter, and MMC, respectively. dc voltages are regulated satisfactorily to their references. Fig. 6[right](b) gives the dc currents at the LCC rectifier, the LCC inverter, and the MMC, respectively. It can be seen the complementarity between the dc current in the MMC and the LCC rectifier.

4.3. AC faults

Fig. 7 [left] illustrates the performance of the system during a single-phase-to-ground fault. The fault was applied on the ac side of the LCC inverter at 2.5 s and was cleared after 100 ms. Fig. 7[left](a) shows that the rms voltage at the LCC inverter drops about 0.3 pu during the fault. As a result, a commutation failure occurs that causes an abrupt decrease in the dc voltage as shown in Fig. 7[left](d). This condition causes that the dc currents rise rapidly as shown

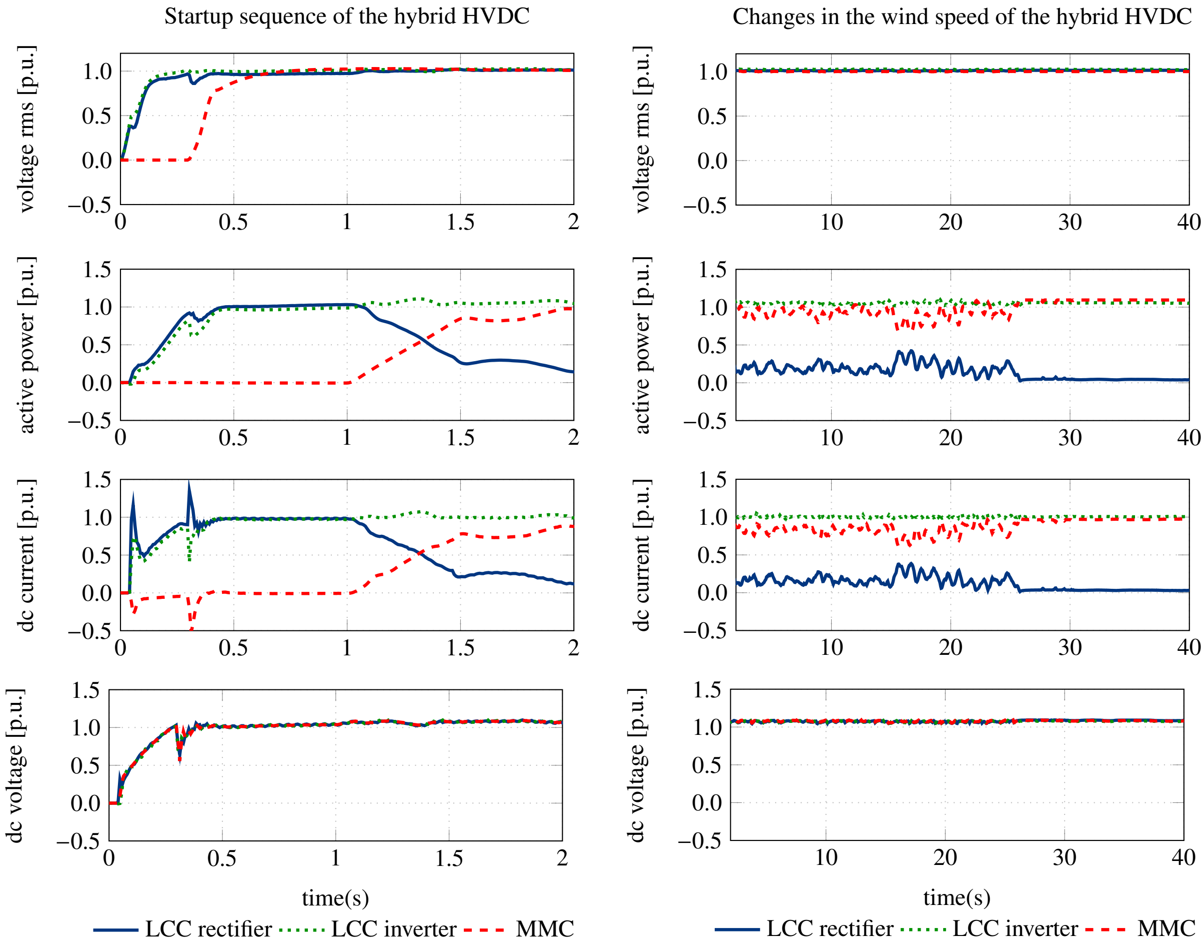

Fig. 6: Start-up of the MMC-LCC hybrid HVDC system [left] and Response to change in the wind speed [right]. [From top to bottom] ac voltages (rms), dc currents, active powers, dc voltages

in Fig. 7[left](c). During the fault, all IGBTs in FB-MMC are blocked, so there is available one current path through the series connected capacitors of the MMC sub-modules. Consequently, the current is limited and the hybrid HVDC is able to recover after the fault is clear as shown in Fig. 7[left].

4.4. DC faults

Fig. 7 [right] illustrates the performance of the system during a pole-to-ground dc fault. The fault was applied at the midpoint between line commuted converter at 2.5 s and was cleared after 100 ms. Fig. 7[right](a) shows that the rms voltage at the MMC drops to zero during the fault. This happens because all-IGBT's of FB-MMC are blocked during a fault. However, the abrupt disturbance in dc current affects the voltage that is regulated by the LCC inverter, which falls to zero at seen in Fig. 7[right](d). However, MMC struggles to keep its DC voltage and this one falls just to 0.5 pu as seen in Fig. 7[right](d). One more time, since the dc current is limited, seen in Fig. 7(c), the hybrid HVDC is able to recover after the fault is clear as shown in Fig. 7[right].

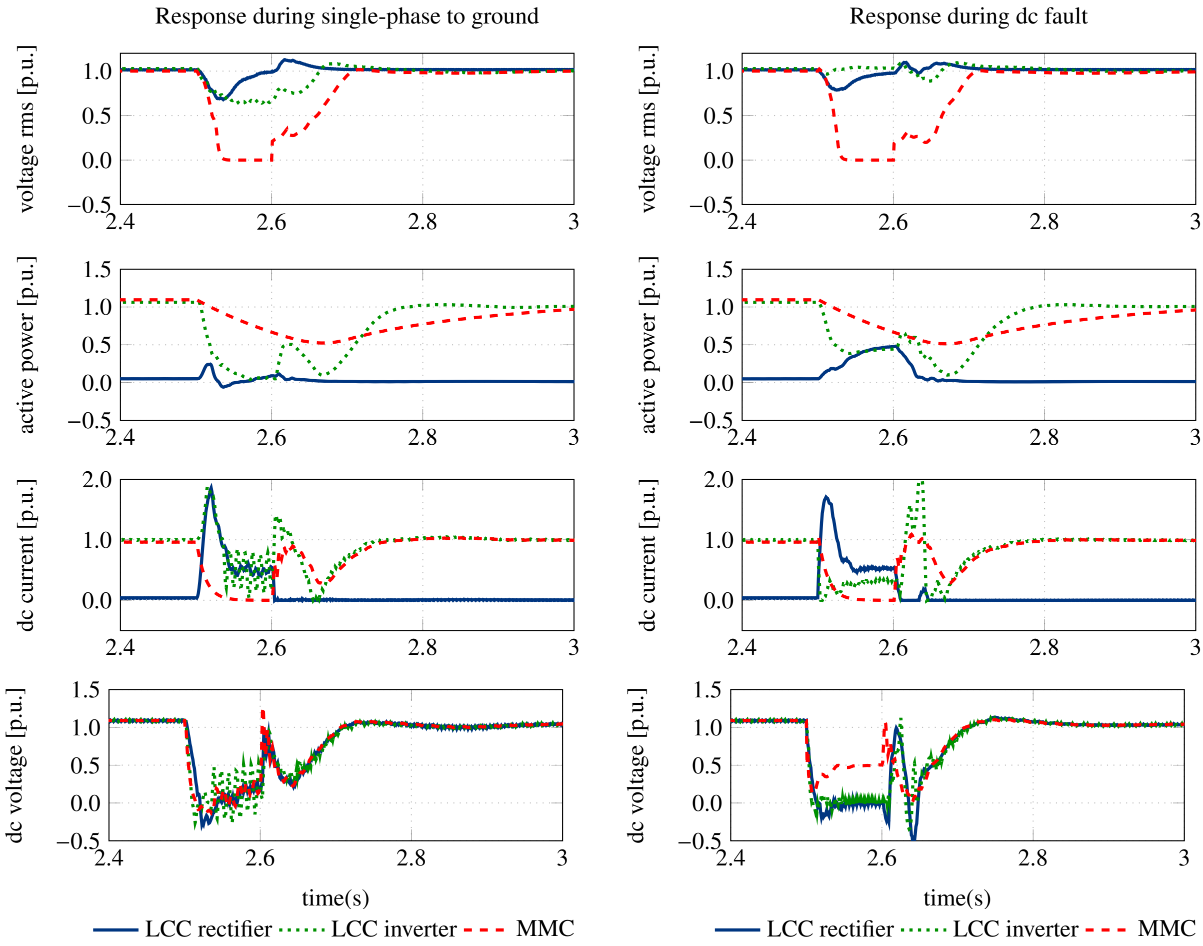

Fig. 7: System response during single-phase to ground fault at LCC inverter [left] and during a dc fault [right]. [From top to bottom] ac voltages (rms), dc currents, active powers, dc voltages

5. Conclusions

This paper studies the feasibility of a hybrid configuration that combines the traditional LCC HVDC with an FB-MMC for the integration of offshore wind farm. The performance of the system using the proposed controller has been tested under various conditions using PSCAD/EMTDC simulations. The cases include the start-up and the response of the system to ac faults at the LCC inverter. AC fault is a very serious condition in a hybrid configuration, because the commutation failure in line-commutated converters is translated into a dc fault in the voltage source converters. This kind of converters is quite vulnerable to dc fault since they need a free-wheeling diode for a proper operation which is a free path to feed the fault when the fault occurs. Full bridge MMC can provide a solution to this problem, since they provide an available current path through the series connected capacitors of each MMC sub-modules. So, an MMC-LCC hybrid is able to clear an ac temporary faults at inverter LCC using the H-bridge cells of the MMC to handle the induced dc fault. Start-up procedure has been discussed in detail and more relevant scenarios such as wind speed variations, and temporary dc fault are also included. The simulation also reveals that hybrid is able to ride through temporary dc faults.

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