PMSG Based Offshore Wind Farm Grid Integration by VSC-HVDC with LCC-HVDC Transmission and improvement in Dynamic Stability using STATCOM

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Abstract: For the transmission of large amount of power over long distances, LCC-HVDC is the most widely used technology around the world. However, VSC-HVDC is appreciated for the integration of renewable energy sources, e.g., offshore wind farms. This paper deals with the feasibility of using a conventional LCC-HVDC in combination with a VSC through a dc cable to integrate offshore wind farms. The integrated model is a hybrid HVDC. The operational features of a model of three-terminal hybrid HVDC, two LCC stations and one VSC station, is investigated using MATLAB/Simulink. The simulations include an aggregate model to emulate the wind farm. The corresponding control strategies are proposed for each terminal and verified under various conditions including wind speed variations and ac faults. This paper also investigates the use STATCOM along with wind farms for the purpose of stabilizing the grid voltage after grid-side disturbances such as a three phase short circuit fault, temporary trip of a wind turbine and sudden load changes.

Keywords: HVDC transmission, Hybrid HVDC, line-commutated converter (LCC), offshore wind farm (OWF), voltage source converter (VSC), PMSG, Dynamic stability, FACTS Controllers (STATCOM).

I. INTRODUCTION

In the recent years ever increasing energy demand and challenges like pollution, consumption of conventional energy sources, global climate changes, global warming and because of carbon emission etc. have made renewable energy sources to penetrate into the grid. This had an important impact over the entire world. Offshore wind energy has been recognized as one of the most appreciable renewable energy resources available. It is estimated that in Europe the installed power capacity of offshore wind power is about 3.8 GW by the end of 2011. There are offshore projects under construction of about 6 GW and there are 18 GW of fully consented projects [1]. However, the main challenge of HVDC is the transmission of large amount of energy over long distances [2]. HVDC appears to be the best option for the integration of offshore wind farms (OWF) because of the following advantages:

1. Dc transmission is not affected by the cable charging currents, i.e., there is no critical distance;
2. Cable power losses are lower compared with an equivalent ac cable;
3. There is large power transmission capacity up to 1.6 GW; and 4) full power flow control [3].

The two HVDC technologies available in the market are LCC-HVDC and VSC-HVDC. LCC uses thyristors, which are line commutating devices, and VSC uses insulate-gate bipolar gate transistors (IGBT), which are self commutating devices [3]. Nowadays, the VSC has attracted more attention due its the beneficial features such as 1) independent active and reactive power control; 2) the VSC can feed island and passive networks; 3) the VSC is about 60% of the size of a LCC station; and 4) there is no commutation failure problem; 5) start-up capability, i.e., does not need an external commutation voltage for its operation. In spite of all the above advantages, the VSC has higher power losses and is more expensive compared to an LCC solution. Transmission losses, at 500 MW, are about 4.5% for a three-level VSC and about 1.8% for LCC as reported in [4]. Also, the losses for a multilevel modular converter (MMC) HVDC are estimated to be about 1% per station as was reported in [5], i.e., the VSC transmission losses are approaching the LCC losses. The LCC stations
are cheaper than three-level VSC as was reported in [4], and it is expected to be still cheaper than a MMC-HVDC. In addition, LCC-HVDC is very suitable for very high power levels, and the reliability and availability of LCC-HVDC has been demonstrated for many years [3].

This paper is focused on investigating the feasibility of using a conventional LCC-HVDC in combination with a VSC through a dc cable to integrate OWF, is schematically shown in Fig. 1. The proposed configuration has the benefits of both VSC and LCC i.e., 1) the reduction in the investment cost, considering that many LCC-HVDC are in operation or planned; 2) the reduction in the power losses, the configuration has a single VSC which has less losses compared to the point-to-point option using VSC; and 3) a more reliable power supply, the VSC and the LCC rectifier can work in a complementary manner to ensure the supply of the nominal power. The proposed configuration deals with a hybrid HVDC. The hybrid consists of an LCC connected to a VSC through a dc cable. A feature of the hybrid is that the power reversal cannot be carried out without stopping operation. This is because LCC requires the reversal of the dc voltage while maintaining the dc current unchanged, VSC requires the opposite [7]. Therefore the power reversal can only be done with discharge of the dc link and reconnections.

Figure 1. Proposed Hybrid HVDC for Integration of OWF

The paper is organized as follows. Section II presents the details of the proposed configuration and the respective control strategy for both the HVDC and the wind farm. The Section III deals with two important aspects to this concept: the start-up and the response to faults in the LCC inverter. In Section IV, MATLAB/Simulink simulation results are provided to illustrate the performance of the system under normal conditions, such as changes in wind speed, and abnormal conditions, such as an onshore ac fault in the LCC inverter. Finally some concluding remarks are presented in Section V.

II. SYSTEM DESCRIPTION AND CONTROL DESIGN

The proposed configuration is shown in Fig.1. Ac systems are considered weak grids to provide greater degree of difficulty for the dc control. Each LCC converter consists of two twelve-pulse bridges. Both ac filters, tuned to the characteristic harmonics, and reactive compensation are considered in each LCC. A large offshore wind farm is connected to the LCC HVDC through a two-level VSC. Each turbine of the wind farm consists of full-converter using a permanent magnet synchronous generator (PMSG). To reduce the simulation time, an aggregated model has been used to represent the entire wind farm. The controllers design is divided into four parts: the LCC rectifier, the LCC inverter, the VSC, and the offshore wind farm. The control objectives and strategy for each system element are described below:

A. Control of LCC Rectifier

The LCC rectifier (rLCC) has the function of controlling the power extracted from one grid to another. In normal operation, the LCC rectifier operates in a constant dc current mode. Its objective is to regulate the dc current (i*DCr) toward its reference (iDCr). Basically, the firing angle (α1) is obtained using a proportional and integral (PI) controller that compares (iDCr) and (i*DCr). The reference value is set using the voltage dependent current order limiter (VDCOL) and the power generated by the OWF. The controller is shown in figure2.

Figure 2. Block diagram of the LCC rectifier controller.

B. Control of LCC Inverter

The LCC inverter (iLCC) control objective is to regulate the dc link voltage of the HVDC to its reference. In normal operation, the firing angle is produced using a PI whose inputs are and as shown in the Fig. 3. During disturbances, such as ac faults, the controller changes the operation mode to assist the regulation of dc current using a scheme similar to rLCC but reduced by the margin current as shown in the
Fig. 3. Here the inputs of the PI are the dc current to the inverter and its corresponding reference. The reference is adjusted using both the VDCOL and the measurement of the dc current coming from the OWF. 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. 3.

C. Control of VSC for Hybrid HVDC

The VSC function is to support the offshore ac voltage and to regulate the offshore ac voltage and frequency. The idea is to emulate an infinite bus, so all the power in the OWF can be absorbed automatically toward the HVDC. Here in this paper a controller that is able to mitigate the effects of fluctuating power due to the nature of wind is introduced. Also the controller uses a closed-loop structure for the frequency. Also the controller uses a closed-loop structure for the frequency.

To facilitate the design of the controller, the dynamics of the capacitor \( C \) and inductor \( L \) are expressed in terms of a synchronous reference frame (SRF) or the called d-q reference frame.

\[
C_f \frac{d}{dt} \mathbf{v}_{Gdq} = \mathbf{i}_{OWFdq} - \mathbf{i}_{dq} - \omega \mathbf{J} \mathbf{C}_f \mathbf{v}_{Gdq} \tag{1}
\]

\[
L \frac{d}{dt} \mathbf{i}_{dq} = \mathbf{v}_{Gdq} - \mathbf{v}_{dq} - \omega \mathbf{J} \mathbf{L} \mathbf{i}_{dq} \tag{2}
\]

Where \( \mathbf{v}_{Gdq} \) represent the offshore ac voltages, \( \mathbf{i}_{OWFdq} \) is the current coming from the OWF, \( \mathbf{i}_{dq} \) represents the currents flowing into the VSC, \( \mathbf{v}_{dq} \) represents the voltages at the input of the VSC and \( \mathbf{J} \) is the skew-symmetric of the \( 2 \times 2 \) identity matrix. From (1), \( \mathbf{v}_{Gdq} \) can be regulated by controlling \( \mathbf{i}_{dq} \). For simplicity, it is considered that the dynamics (1) and (2) are decoupled. Therefore, the design is divided into an inner and an outer loop. The purpose of the inner loop is to regulate the current toward its reference \( i_{dq}^* \).

Hence \( \mathbf{v}_{dq} \) is calculated as:

\[
\mathbf{v}_{dq} = \mathbf{v}_{Gdq} - \omega \mathbf{J} \mathbf{L} \mathbf{i}_{dq} + \left( k_p + \frac{k_i}{s} \right) \tilde{\mathbf{i}}_{dq} \tag{3}
\]

Where \( \tilde{\mathbf{i}}_{dq} \triangleq \mathbf{i}_{dq} - \mathbf{i}_{dq}^* \) and \( \mathbf{i}_{dq}^* \) the reference of is \( k_p \) and \( k_i \) are design parameters.

The system (2) in closed loop with the controller (3) guarantees the regulation of \( \mathbf{i}_{dq} \) toward \( i_{dq}^* \). For the design of the outer loop, it is considered that \( \mathbf{i}_{dq} \) has reached its reference, i.e., \( \mathbf{i}_{dq} = 0 \). Then the dynamic (1) can be written as follows:

\[
C_f \frac{d}{dt} \mathbf{v}_{Gdq} = \mathbf{i}_{OWFdq} - \mathbf{i}_{dq}^* - \omega \mathbf{J} \mathbf{C}_f \mathbf{v}_{Gdq}.
\]

Solving for \( \mathbf{i}_{dq}^* \), and adding damping with a PI controller, yields the following expression:

\[
\mathbf{i}_{dq}^* = \mathbf{i}_{OWFdq} - \omega \mathbf{J} \mathbf{C}_f \mathbf{v}_{Gdq} - \left( k_p + \frac{k_i}{s} \right) \tilde{\mathbf{v}}_{Gdq}
\]

Where \( \tilde{\mathbf{v}}_{Gdq} \triangleq \mathbf{v}_{Gdq} - \mathbf{v}_{Gdq}^* - \mathbf{v}_{Gdq} = \left[ \mathbf{v}_{Gdq}^* \mathbf{v}_{Gdq}^* \right]^T \); are the voltage references? \( k_p \) and \( k_i \) are design parameters. The system (1) in closed loop with the controller (4) ensures the regulation of \( \mathbf{v}_{Gdq} \) toward its respective reference \( \mathbf{v}_{Gdq}^* \) since the controller is represented in a SRF, a phase locked loop (PLL) is required. In the SRF-PLL approach, the angle is found by forcing \( \mathbf{v}_{Gdq} \) to zero using a PI controller. As \( \mathbf{v}_{Gdq} \) goes to zero, the regulation of voltage magnitude can be carried by \( \mathbf{v}_{Gdq}^* \), since \( \mathbf{v}_{Gdq}^* = \sqrt{\mathbf{v}_{Gdq}^2 + \mathbf{v}_{Gdq}^2} \), and the angular frequency \( \omega \) can be regulated to its reference \( \omega^* \) using a proportional (P) control as shown in figure 4.

D. Control of Offshore Wind Farm

The OWF uses an aggregate model, i.e., the behavior of a single turbine represents the entire farm. The equivalent turbine is equipped with two back-to-back IGBT converters and a permanent-magnet synchronous generator (PMSG). The controller design of the turbine can be divided into three parts: the generator side controller (GSC), the ac grid side controller (AGCC) and the pitch controller. Below each part of the turbine controller is explained in detail.

1. Generator Side Controller: The objective of GSC is to control the rotor speed to achieve the maximum power of the wind at low wind conditions. The GSC is based on the steady-state characteristic of the wind turbine, which is a typical three-blade horizontal-axis design. To illustrate the mechanism, figure 6 shows the generator power \( p \) versus the rotor speed \( \omega \), in the turbine without pitch control action, \( p \)-\( \omega \) curve.

From figure 5, for a given \( \omega \), and for each wind speed \( v_{\text{in}} \), there is a point of maximum power. To design the controller, the dynamical model of the PMSG in a SRF is written as:
for the proper operation of the back-to-back converter. The dynamical model of the converter connected to offshore ac grid in the SRF is given by:

$$L_G \frac{d\tilde{i}_{Gd}}{dt} = u_{Gd} - R_G \tilde{i}_{Gd} - v_{Gd} - \omega L_G \tilde{i}_{Gq}$$  \hspace{1cm} (8)$$

Where $v_{Gd}$ represents voltages coming from the ac offshore grid; $i_{Gd}$ is the currents flowing into the ac side; $L_G$, $R_G$ are the inductance and resistance coupling the converter and the offshore ac grid; $u_{Gd}$ represent the voltages at the input of the converter; and $\omega$ is the angular frequency of the offshore ac grid.

In the above (8), the $d$-axis is aligned with offshore ac voltage. Under these conditions active power and reactive power are decoupled. Again, the control design is divided into two loops. The inner loop has the same objective of regulating the currents, as shown in the following:

$$u_{Gd} = \omega L_G \tilde{i}_{Gd} + v_{Gd} + \left( k_{p3} + \frac{k_{i3}}{s} \right) \tilde{v}_{Gd}$$  \hspace{1cm} (9)$$

Where $\tilde{v}_{Gd}$ are the current references. $k_{p3}$ and $k_{i3}$ are design parameters. Outer loop regulates the dc voltage $v_{dc}$ in the dc link of the back-to-back converter, setting the $d$-axis reference current $i_{Gd}$.* This ensures instantaneous transfer of active power between the generator converter and inverter connected to the offshore ac grid. Given the decoupling of active and reactive power, the controller is able also to provide reactive support. Outer loop regulates the reactive power setting the $q$-axis reference current $i_{Gq}^*$. Both $i_{Gd}^*$ and $i_{Gq}^*$ are given as follows:

$$i_{Gd} = \left( k_{p4} + \frac{k_{i4}}{s} \right) \tilde{v}_{dc}$$  \hspace{1cm} (10)$$

$$i_{Gq} = \left( k_{p4} + \frac{k_{i4}}{s} \right) \tilde{q}$$  \hspace{1cm} (11)$$

Where $\tilde{v}_{dc}$ and $\tilde{q}$ are the references of the dc voltage and reactive power, respectively. $k_{p4}$ and $k_{i4}$ represent the parameters of the PI controller.

3. Pitch Controller: It limits the rotor speed in high wind conditions. If the turbine is operating above the rated wind speed, the actuator system must change the pitch angle $\beta$, and thus reduce the power coefficient $C_p$. Modifying $C_p$ it can keep the turbine operating at a rated power, and avoid overloading and damaging both the generator and converter. Above the nominal wind speed, $\beta$ is kept at a constant value, an optimum, and the $p-\omega$ curve drives the turbine to the maximum power point. A schematic diagram of the controllers of the OWF is shown in the figure6.
PMSG Based Offshore Wind Farm Grid Integration by VSC-HVDC with LCC-HVDC Transmission and improvement in Dynamic Stability using STATCOM

III. HYBRID HVDC OPERATION

Two issues related to the operation of the hybrid HVDC are: a) start-up or black start capability and b) ac faults in the LCC inverter.

A. Start-up

The start-up of the hybrid HVDC is similar to the VSC HVDC[3], except for the dc link. A LCC inverter needs holding current to operate, this current usually is a low or long pulse. With the holding current, the inverter LCC is able to ramp up the dc voltage to its [18]. The process of start-up is explained below, initially, with the offshore VSC disabled, the LCC HVDC is started in the conventional manner, i.e., both dc current and dc voltage ramp up using the VDCOL. After the dc voltage has reached its nominal value, the offshore VSC is enabled and ramped up to its nominal value. Since the power flows from the LCC-HVDC to the VSC, a small amount of power is used to supply the losses in the offshore equipment. Afterwards, the ACGC at each turbine is enabled and synchronized with the offshore ac voltage. The dc links of each turbine are able to charge. Finally, the GSC is enabled and the output power increases and is automatically transmitted to onshore ac grid via iLCC. As the power of the OWF increases the power delivered by the rLCC decreases.

B. AC Faults in the LCC Inverter

If a significant voltage dip occurs at the iLCC, the reduction in the commutation voltages will lead to a commutation failure. The failure causes an abrupt reduction in the dc voltage. The collapse in the dc voltage rises suddenly the dc current at the iLCC. This current increases abruptly by the current from both the rLCC and the VSC. The dc current of the rLCC can be minimized using the VDCOL scheme, but the dc current of the VSC cannot be minimized by the controller action if a commutation failure occurs. This is because during the failure, the dc current flows through the anti-parallel diodes of the VSC and the semiconductors are unable to operate. The diodes become the most exposed component to over-current damage. The over-current at the iLCC may prolong the recovery time. Simulations show the behavior of the system to ac faults.

IV. STATIC SYNCHRONOUS COMPENSATOR

A STATCOM is a controlled reactive-power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks. Using the controller, the VSC and the coupling transformer, the basic model of STATCOM is shown in Figure 6. It is a regulating device used on an ac electricity transmission networks. It is based on power electronics voltage source converter and can act as either a source or sink of reactive power to an electricity network. It also support network that has poor power factor and voltage regulation.

Figure 6. Schematic diagram of the controllers of the OWF with STATCOM.

Figure 6a. Basic Model of a STATCOM.

Figure 6b. Simulation model of Hybrid HVDC for integration of offshore wind farm with STATCOM.
The HVDC system, shown in Fig. 1, has been implemented using MATLAB/Simulink to illustrate the performance of the proposed controllers. 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 200 km. The dc uses a distributed model. At the rLCC side, the ac voltage is 345 kV at 50 Hz with a short circuit ratio (SCR) of 2.5. At the iLCC side, the ac voltage is 230 kV at 50 Hz with SCR of 2.5. The VSC is connected via a 50 km dc cable at the midpoint of the other cable. The switching frequency of the VSC is 1 kHz. The OWF is simulated using an aggregate model, i.e., a single unit of 500 MW. The wind farm is connected to the VSC through a step-up transformer 0.69/230 kV. The Appendix lists the most important parameters of the PMSG. The simulations were conducted under different conditions to investigate the operating characteristics of the proposed system. These conditions include variations in the wind speed, start-up procedure, and ac faults.

A. Start-up

Fig. 8 presents the start-up process. From s to s, iLCC ramps up the dc voltage as shown in Fig. 8(c). Fig. 8(d) illustrates the dc currents of the rLCC, the iLCC, and the VSC, respectively. At the same time, the VSC is enabled and the ac voltage ramps up to its nominal value as shown in Fig. 8(a). Once the ac voltage reaches the nominal value, it is possible to connect the turbines. At s, in each turbine theACGC is enabled, allowing the synchronization with the offshore ac voltage, and each dc link of the back-to-back converters is charged. At s, the GSC is enabled and the output power of the OWF increases as shown in Fig. 7(b). Fig. 7(d) shows that as the dc current coming from the OWF increases the dc current from rectifier decreases. The dc current to the iLCC is the nominal current as it was expected.
B. Response to Change in the Wind Speed:
To study the response of the system to change in the wind speed, the OWF is tested under various conditions as shown in figure 8. From t= 0s to t= 1.5s, the wind speed is \( v_w = 10 \text{m/s} \), the nominal wind speed is \( v_n = 12 \text{m/s} \). After t=0.1s, a ramp begins that increases at a rate of 4 m/s for t= 30s. At t= 1.5s, a wind speed gust occurs which decreases amplitude 3m/s with 10s duration. Finally, the wind speed is set at \( v_w = 15 \text{m/s} \). During all the simulations the wind is noisy. Noise wind data are the following: number of noise component 250, random seed number 50, time interval for random generation 0.35 s, and noise amplitude controlling parameter 10 rad/s. From t=0.5s to t= 1.5s, the behavior of the turbine is below nominal wind speed.

Figure 8(b) shows that the output power of the (PMSG) tracking the maximum power point. Also, the pitch angle is very small as was expected. At t= 4s, the gust occurs and the abrupt change in the wind is minimized due the inertia of turbine. After that gust, the wind speed begins to increase gradually to a value above the nominal wind speed. The pitch angle starts to increase to prevent overload in the rotor as shown in figure 8(e). It can also be seen that the output power of the PMSG remains at the nominal value. The noise introduced by the wind is not reflected in the active power due to the inertia of the rotor. Figure 8(d) shows that the dc-link voltage is regulated to its reference; the reference is set at 1.2 p.u.

Figure 9 illustrates the response to the wind condition. Figure 9(a) presents the rms voltage at the rLCC, the iLCC and the VSC. It is observed that all ac voltages are maintained at their nominal values. Figure 9(b) shows the active power at the input of the VSC, at the input of the rLCC and the output of the iLCC. The figure 9(b) shows that the power fluctuations of the VSC are complemented by changing the set point of the rLCC, in order to provide rated power at the output of the iLCC. Figure 9(c) presents the dc voltages at the terminals of VSC, the rLCC, and the iLCC. It is noted that dc voltages are regulated satisfactorily to their references even with the power fluctuations at the VSC and rLCC. Figure 9(d) gives the dc currents at the VSC and the rLCC and iLCC, it is again observed the complementarity between the dc current in the VSC and the rLCC. The system requires communication between stations, a communication delay of 100 ms has been introduced to emulate a more realistic case.

C. AC Faults at the LCC Inverter
Fig 10. Illustrates the performance of the system during three phases to ground fault. The fault was applied on the ac
side of the LCC inverter at t=3.5s and was cleared after 100 ms. Fig.10(a) shows that the rms voltage at the LCC inverter is reduced to zero during the fault. As a result, a commutation failure occurs that causes an abrupt decrease in the dc voltage as shown in Fig.10(c). The failure causes that the dc currents, both from the rLCC and the VSC, rise rapidly as shown in Fig.10(d). During the fault, the IGBTs are blocked for their own protection. The dc current from the rLCC can be decreased by the action of the VDCOL. However, the dc current from VSC must be absorbed by the iLCC prolonging the recovery time as shown in the simulations. To assist the iLCC during fault, the controller changes from constant dc voltage to constant dc current mode. Both ac voltage and dc voltages recover after the fault is cleared as seen in Fig.10.

Figure10. Proposed system response during three-phase to ground fault at LCC inverter: a) ac voltages, (b) active powers, (c) dc voltages, and (d) dc currents at the LCC rectifier (blue solid line), LCC inverter (green dotted line), and VSC (red dashed line), respectively.

Fig.11 shows the performance during three-phase to ground fault. The fault was applied at ac side of the LCC rectifier at t=3.5s and was cleared after 100 ms. Fig. 11(a) shows that the rms voltage at rLCC reduced to zero during the fault. As a result of the sudden voltage drop, the power at VSC (from the wind farm), drops to zero as shown in Fig. 12(b). The power unbalance is reflected in the dc current of the VSC, as shown in Fig.12(d). Also Fig.12(d) shows that the dc current of the rLCC rises, as result of the change in the set point of rLCC. As it can be observed in the Fig. 12(c), there is a drop in the dc voltage. Note that the system is capable of providing power to the iLCC during the fault. The system is able to recover successfully after the fault is cleared as seen in Fig. 12.

Figure11. Proposed system response during three-phase to ground fault at LCC rectifier: a) ac voltages, b) active power, c) dc voltages, and (d) dc currents at the LCC rectifier (blue solid line), LCC inverter (green dotted line), and VSC (red dashed line), respectively.

Fig. 12(a) shows that the rms voltage at VSC is reduced during the fault, a circuit breaker is activated and isolates the fault. As a result of the sudden voltage drop, the power at VSC (from the wind farm), drops to zero as shown in Fig. 12(b). The power unbalance is reflected in the dc current of the VSC, as shown in Fig.12(d). Also Fig.12(d) shows that the dc current of the rLCC rises, as result of the change in the set point of rLCC. As it can be observed in the Fig. 12(c), there is a drop in the dc voltage. Note that the system is capable of providing power to the iLCC during the fault. The system is able to recover successfully after the fault is cleared as seen in Fig. 12.

Figure12. Proposed system response during three-phase to ground fault at VSC: a) ac voltages, b) active powers,
PMSG Based Offshore Wind Farm Grid Integration by VSC-HVDC with LCC-HVDC Transmission and improvement in Dynamic Stability using STATCOM

c) dc voltages, and d) dc currents at the LCC rectifier (blue solid line), LCC inverter (green dotted line), and VSC (red dashed line), respectively.

Figure 14 shows the ac and dc terminal voltages of the STATCOM. At t=1.5 sec, a three phase to ground fault occurs at the load bus. The voltage at the fault bus drops depending on the fault location. This initiates the operation of the STATCOM. The drop in the terminal voltage determines the amount of reactive power needed. The STATCOM can operate at full capacity even at low voltages. The STATCOM in this case supplies its rated reactive power to support the load bus voltage. From t=1.7 sec when the fault has been cleared to the point where the system completely recovers, the STATCOM helps to return to full operation.

VI. CONCLUSION

This paper examines the feasibility of a hybrid configuration that combines the conventional LCC-HVDC with the VSC for the integration of offshore wind farm through a dc cable. This work contains the design of the control strategy for the entire system. Two major events of the model have been exposed. The performance of the system using the proposed controller has been tested under various conditions using MATLAB/Simulink. A start-up strategy has been presented and verified. An aggregate model of an offshore wind farm was implemented to study the system response to changes in wind speed. It is observed that the power transferred by the rectifier is reduced by adding the output from the VSC, i.e., from the wind farm. Three cases of ac faults have been simulated, at the terminals of the LCC inverter, at the LCC rectifier, and the VSC. It was shown that ac faults in the rectifier and the VSC can be overcome relatively easily. This paper also investigates the use STATCOM along with wind farms for the purpose of stabilizing the grid voltage after grid-side disturbances such as a three phase short circuit fault, temporary trip of a wind turbine and sudden load changes. The dynamic performance of wind farms in a power grid is improved by the application of a STATCOM. This work intends to set the basis for considering hybrid HVDC as an option in the offshore wind farm integration and can be used for further research on hybrid HVDC.

APPENDIX

| TABLE I  |
|---|---|---|
| Most Important Parameters of the PMSG |  |  |
| Parameters | Values | Units |
| Rated Power | 500 | MW |
| Rated Voltage | 0.69 | kV |
| Base Frequency | 50 | Hz |
| L_{sd} | 0.5 | p.u. |
| L_{sq} | 0.51 | p.u. |
| R_{s} | 0.61 | p.u. |
| Magnet Flux | 1.2 | p.u. |
| Inertia constant | 3 | s |

VII. REFERENCES


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