Multiterminal HVDC for Offshore Windfarms – Control Strategy

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Abstract—The use of HVDC for submarine power transmission is well known to increase the transmission capacity and decrease transmission losses. But so far this technology has been limited to interconnecting only two terminals as there was little or no serious demand for multi-terminal HVDC systems. With many researches going on to develop offshore wind farms in the North Sea and trends to electrify the offshore oil/gas platforms by HVDC connection from onshore, multiterminal HVDC (MTDC) could be a competitive solution for interconnecting offshore windfarms and other offshore systems into the onshore national grid. This paper discusses proposed control strategy for such a system. Voltage source converter (VSC) was selected for its suitability for MTDC system and for its flexibility in control. An equivalent circuit of the VSC in synchronous d-q reference frame has been established and decoupled control of active and reactive power was developed. A four terminal MTDC using VSCs was modeled and simulated in EMTDC/PSCAD software. A modified mix of voltage-margin-method and DC-voltaged-droop control has been used for reliable operation of the HVDC system avoiding the need for communication. Simulation results show that the proposed MTDC control system was able to maintain the DC voltage with in desired range during load switchings, step changes in power demand and was able to secure power to passive loads during loss of a DC voltage regulating converter terminal without the use of communication between terminals.

Index Terms—Multi-terminal HVDC, MTDC, EMTDC/PSCAD, Voltage Source Converters, vector control

I. INTRODUCTION

The North Sea has a vast potential for generation of green energy from high-energy content offshore wind as well as from tidal and wave energy available in the area. With some of the sites with high energy per area ratio located as far as 100-300 km from onshore, transmitting the generated power to onshore grid would be a challenge [1]. Due to the large capacitive currents associated with long distance ac power transmission, the use of HVDC transmission for integrating offshore wind farms to inland grid system would excel other alternative solutions. On the other hand Norwegian oil/gas platforms in the North Sea use electricity from gas fired turbines located at offshore sites. These gas turbines have much lower efficiency than onshore generation of electricity and also release large amounts of green house gases. Therefore supplying the platforms with power from onshore transmitted by HVDC would result in benefits both from economic and environmental protection perspectives. Given these two interests for HVDC in the Norwegian offshore and the North Sea, the use of Multiterminal HVDC (MTDC) is a potential solution for the integration of the windfarms and oil/gas platforms into the onshore grid system.

An interconnection between the offshore windfarms, the oil and gas platforms and onshore grid can result in reduced operational costs, increased reliability and reduced CO_2 emissions. An MTDC network will then be the core of such an interconnection system. MTDC can also open new power market opportunities and result in better utilization of transmission lines [2].

The advent of voltage sourced converters (VSC) in high voltage range has created the possibility of constructing true MTDC grid which has been difficult with the use of current sourced converters. Some of the main reasons for this are due to the complicated control structure with thyristor based converters, the limitations of thyristor based HVDC to one quadrant operation while used in multiterminal topology and the need for supply of commutating voltage at each converter terminal.

This paper discusses proposed control strategy of a VSC based MTDC transmission system for offshore wind energy harvesting application. The proposed control strategy results in robust and reliable control of terminal parameters in such a way that active/reactive power, ac voltage and frequency are controlled locally and the DC grid voltage is controlled by coordination of the DC-voltage-vs-power characteristic curves of several terminals.

One way to do so is by slave-master configuration where there is one master-terminal dedicated for the dc bus voltage regulation and others are set for constant power control mode. In this control scheme the functionality of the whole MTDC link always depends on the presence of the master-terminal in the grid leading to breakdown of the whole system during failure of the master terminal. An alternative solution to avoid this problem is the use of dc voltage regulation by voltage droop control at several terminals. In this paper a modified version of the dc voltage droop control is proposed and simulated. The modification imposes movable upper and

lower power limits on the droop characteristic curve so that the control mode of a terminal can be easily changed between constant P and constant DC voltage operations.

II. EQUIVALENT CIRCUIT OF VSC IN SYNCHRONOUS D-Q REFERENCE FRAME

A. Voltage Source Converter

A schematic view of voltage source converter is shown in Figure 1. The series inductance on the ac side, also called ac reactor, smoothens the sinusoidal current on the ac network and is also useful for providing the reference point for ac voltage, current and active and reactive power measurements. The shunt connected capacitors on the DC network side are used for DC voltage source and harmonic attenuation.
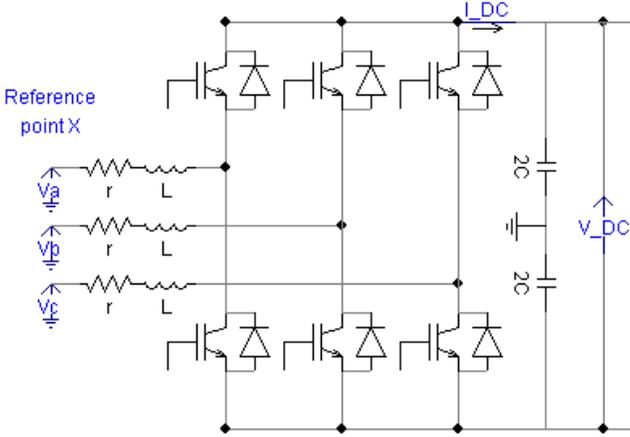
Figure 1. Schematic of VSC

A VSC terminal works with one or more of the four control modes namely: constant active power control, constant DC voltage control, constant DC current control and constant AC voltage control. Constant AC voltage control is applied when the converter is connected to either weak grid or passive AC system. In this paper active power control, DC voltage control and AC voltage control will be used at different terminals to establish an MTDC network.

B. Single line diagram and mathematical model of VSC

A single line diagram of a VSC is shown below in Figure 2.
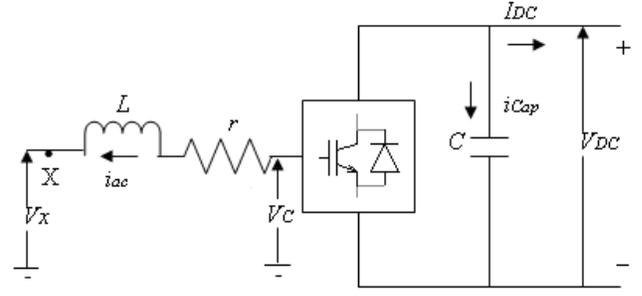
Figure 2. Single line diagram representation of VSC

The reference point for measuring active power, reactive power, and voltage is point X in Figure 2.

Voltage across the ac reactor in *abc* reference frame is given by:

$$V_{Cabc} - V_{xabc} = L\frac{di_{abc}}{dt} + ri_{abc} \qquad (1)$$

In order to decouple the active and reactive power controls, the synchronously rotating d-q reference frame will be used for developing the controllers. The d-q transformed equivalent of equation (1) is given by:

$$V_{cdq} - V_{xdq} = L\frac{di_{dq}}{dt} + j\omega Li_{dq} + ri_{dq} \qquad (2)$$

The detailed deduction of equation (2) from equation (1) is referred to [3], [4].

The Phase Lock Loop (PLL) that provides with the angle for abc→dq/dq→abc transformation blocks is phase locked with phase a voltage of point X. Moreover, the synchronous d-q reference frame is chosen in order to align the d axis with that of the voltage phasor of phase-a at reference point X in stationary abc reference frame. This results in $V_{Xq}=0$ and $V_{Xd}=V_X$. Thus, from equation (2) we get the following expanded relation.

$$\begin{pmatrix} sL+r & 0 \\ 0 & sL+r \end{pmatrix}\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} V_{Cd} \\ V_{Cq} \end{pmatrix} - \begin{pmatrix} V_{Xd} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 & \omega L \\ -\omega L & 0 \end{pmatrix}\begin{pmatrix} i_d \\ i_q \end{pmatrix} \qquad (3)$$

From equation (3) the equivalent circuit of the VSC in the synchronized d-q reference frame can be shown as in Figure 3.
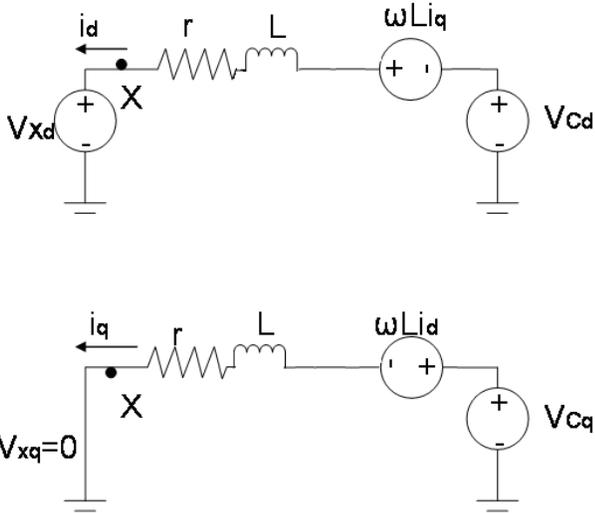
Figure 3. Equivalent circuit diagram of VSC in synchronous d-q reference frame

III. CONTROL OF LOCAL PARAMETERS

A. Inner Current Controllers

The inner current controller can be developed based upon equation (3) that describes the circuit. Figure 4 shows the d-axis and q-axis current controllers of the inner current loop.

The converter has a delay of $e^{-T_w S} \approx 1/(1+T_w s)$ due to the sinusoidal pulse width modulator and $T_w = 1/2f_s$ where f_s is the switching frequency of the converter. Proportional integral (PI) controllers are used for closed loop control and the zeroes of the PI controllers are selected to cancel the dominant pole in the external circuit. For a typical VSC, the time constant $\tau = L/r$ is much higher than T_w and hence will be the dominant pole to be canceled.

The cross coupling currents in equation (3) are compensated by feed forward terms in the controllers as in Figure 4.

i_d^* and i_q^* are reference currents for the d-axis and q-axis current controllers respectively.
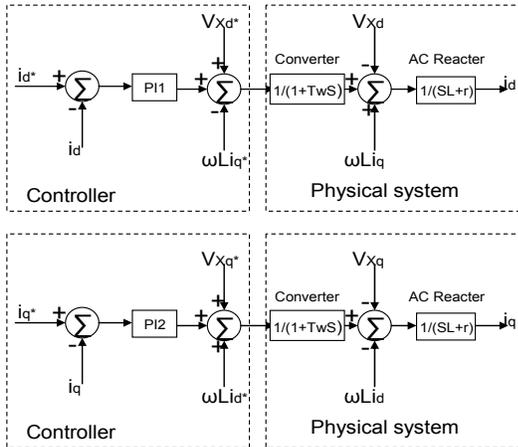
Figure 4: Inner current controllers

B. Outer Controllers

The outer controllers constitute one or more of DC voltage control, active /reactive power control and AC voltage control. From the d-q equivalent circuit and observing from reference point X, the apparent power injected by the VSC in to the AC network is given by:

$$S = \frac{1}{2}\left(V_{Xd} + j0\right)\left(i_d - ji_q\right) \tag{4}$$

And hence active and reactive powers are given by:

$$P = \frac{3}{2}V_{Xd}i_d \tag{5}$$

$$Q = \frac{-3}{2}V_{Xd}i_q \tag{6}$$

And a small change in the DC voltage can be approximated as:

$$\Delta V_{DC} = \frac{\Delta q_{cap}}{C} = \frac{1}{C}\int i_{cap}dt \tag{7}$$

Where C is the shunt capacitance of the VSC, q_{cap} is the charge of the capacitor and i_{cap} is the current going in to the DC capacitor bank as shown in Figure 2. The direction of the currents in the power calculations strictly refer to Figure 2.

From the law of conservation of energy (power),

$$\frac{3}{2}V_{Xd}i_d + V_{DC}i_{cap} + V_{DC}I_{DC} = 0 \tag{8}$$

From equations (7) and (8),

$$\frac{d\Delta V_{DC}}{dt} = \frac{-3V_{Xd}}{2CV_{DC}}\left(i_d + \frac{2V_{DC}I_{DC}}{3V_{Xd}}\right) \tag{9}$$

For the sake of simplicity, it is assumed that the converter terminal is connected to a stiff AC network implying that V_{Xd} is a constant quantity. With such consideration, it can be seen from equations (5), (6) and (9) that active power and DC voltage are correlated with i_d and reactive power with i_q. The resulting control structures are shown in Figure 5.
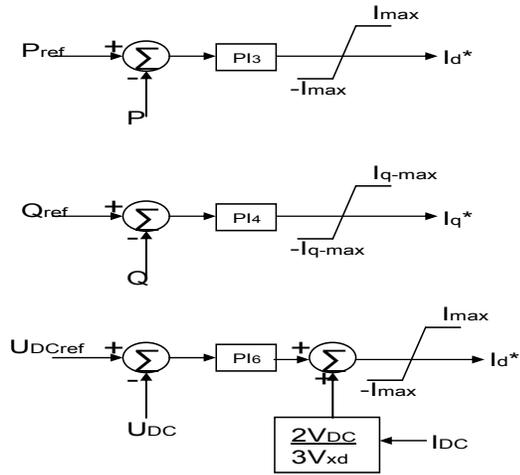
Figure 5. Outer controllers

The DC current beyond the capacitor bank is feed forward compensated in the DC voltage controller (Figure 5).

In VSC, the maximum current limit of the converter must not be exceeded at any moment of the operation. On the other hand, priority is given to transfer active power than reactive power. Hence i_d is limited to the maximum current capacity $+/-I_{max}$ and i_q is limited in such a way that the total current will not exceed the rating of the valves. Hence these limits can be given by:

$$I_{\max} = I_{rated} \tag{10}$$

$$I_{q\max} = \sqrt{\left(I_{rated}^2 - I_d^2 \right)} \tag{11}$$

Figure (6) shows the complete assembly of the inner and outer controllers of a VSC terminal.
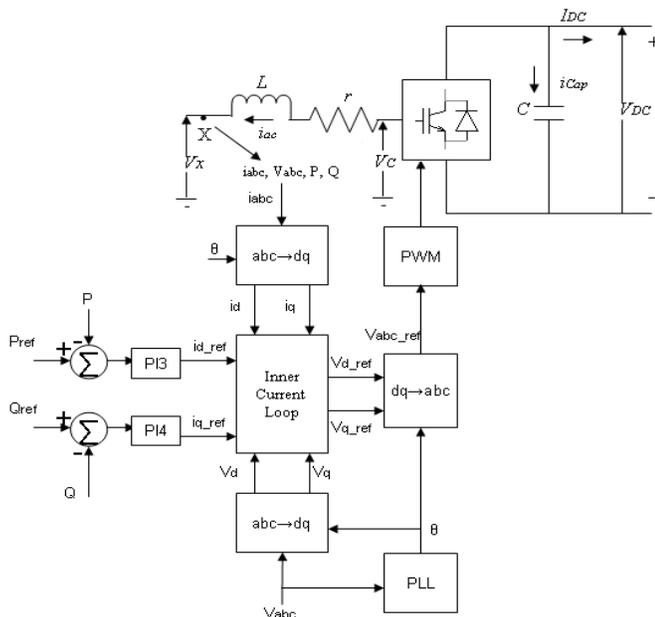
Figure 6. Block diagram of the inner and outer controllers

IV. MULTITERMINAL HVDC CONTROL BY VOLTAGE MARGIN METHOD

VSC based MTDC consists of three or more VSC terminals with the different control objectives aforementioned before. A four terminal MTDC connecting an offshore windpark, a platform and an onshore grid is proposed and analyzed in this paper. The schematic diagram of the proposed MTDC is shown in Figure 7.
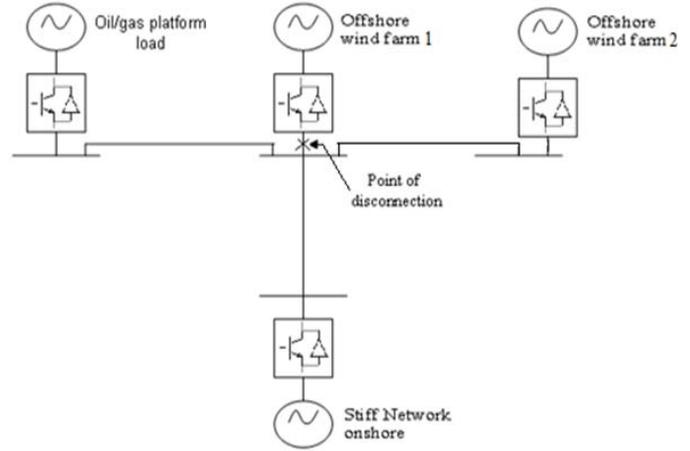
Figure 7. Schematic of interconnection of platform, offshore wind farm and onshore grid

It is assumed that the offshore wind farms will supply power both to the platform and to onshore grid. When power from the wind park terminal is not available or not sufficient, the onshore grid should be able to secure power supply to the platform without the need to communicate between terminals. The platform is assumed to consist of passive loads. A control scheme called voltage margin method can result in the desired performance characteristics of the MTDC system [5].

According to the voltage margin method, each converter will regulate the DC voltage as long as the power flow through it is within the upper and lower limits and the reference DC voltages of the terminals are offset from one another by a certain voltage margin. These characteristics are shown in Figure 8 and Figure 9.
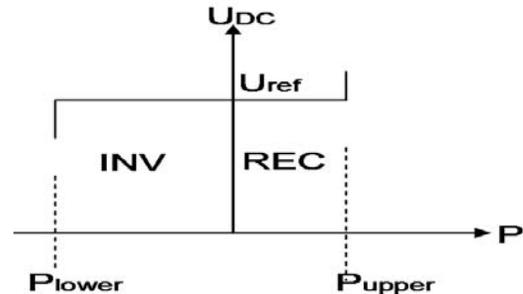
Figure 8. P, U_{DC} characteristic of a converter connected to an active system

When the upper or lower limit is passed, the terminal starts to act as a constant power terminal. The operating DC voltage will be at the point where the following relation is satisfied.

$$P_A + P_B + P_C + \cdots = 0 \qquad (12)$$

Where A, B and C refer to onshore grid, offshore wind farm and oil/gas platform respectively.

This point lies in a horizontal line section of the P-U curve of one of the VSC terminals as can be seen in Figure 11. This voltage determining terminal will act as a dc slack bus and will compensate for variations in power flow.
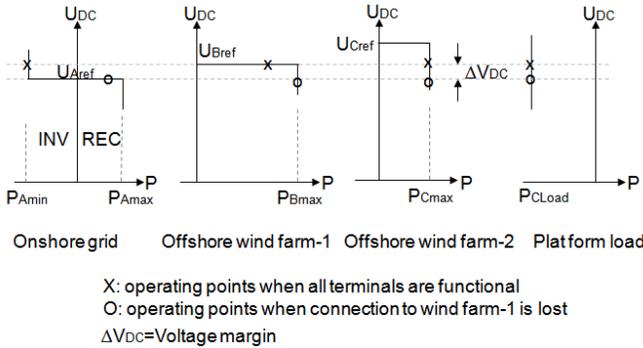
Figure 9. U-P characteristics and operating points of terminals

It can be observed from Figure 9 that the onshore grid has operating range maximum rectified power (P_{Amax}) to maximum inverted power P_{Amin}). This is to ensure that this terminal evacuates the extra power when the windfarms generate in excess and to supply the offshore loads (oil/gas platforms) when generated power from offshore windfarms is not sufficient. On the other hand the offshore windfarms always operate in rectifier mode, neglecting the small amount of power needed to operate the windfarms. The offshore load behaves differently from the other terminals. This is because this load has only one source of AC voltage, i.e. the VSC-HVDC converter and hence the active power flow towards the load should be kept constant irrespective of the variation in DC voltage. If the DC voltage is too high or too low the converters will be disconnected from the DC mesh and this are indicated by the end points of the DC voltage vs power characteristic curves.

By allowing small DC voltage margins between the different terminal voltage controllers it is possible to make a back up of DC voltage control during disconnection of DC-voltage–regulating terminal.

The DC voltage margin is given by:

$$U_{B\_ref} - U_{A\_ref} = U_{m\arg in} = \Delta V_{DC} \qquad (13)$$

The DC voltage margin should be sufficient enough to avoid interaction of the DC voltage controllers of terminal A and B during DC voltage disturbances while all the terminals are in operation.

By changing the DC voltage and active power control references it is possible to configure a terminal to rectify or invert a fixed amount of power or regulate the DC voltage of the DC mesh.

V. MODIFIED MTDC CONTROL WITH DC VOLTAGE DROOP

The voltage margin method gives reliable way of controlling MTDC without the need for communication between terminals and is capable of keeping the steady state voltage with in preset limits even after load switchings and disconnection of some converter terminals. But on the other hand this method implies allocation of only one terminal at a time for the regulation of DC voltage and the other terminals do not experience significant change during changes in power flow of the DC network. This puts a lot of stress on the terminal regulating the DC voltage at the instance considered. In addition the transition from one voltage level to another during disconnection of voltage regulating terminal is so abrupt that this results in added stress in the system.

In order to tackle these problems, a modified control of MTDC with DC voltage droop characteristics is suggested. The suggested modification results in the DC voltage vs power characteristic curve is observed in Figure 10.
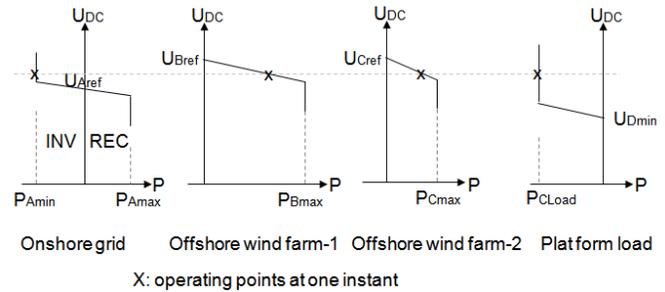
Figure 10: Modified voltage vs power characteristics of the different terminals in the DC mesh system

As Figure 10 shows, the two offshore windfarm terminals have overlapping DC voltage droop characteristics. The overlapping results in sharing of changes in power flow of the DC grid and smother increment/decrement of the DC link voltage. As opposed to this method, in the voltage margin

control method the operating DC voltage levels are discrete and are limited to the preset DC voltage reverences of the terminals controllers. The DC droop control is achieved by using P controller in the DC voltage controller of the converter terminal. The higher the value for the P controller, the less droop would be attained for the terminal and this forces the terminal to respond more to changes in DC voltage variations of the DC mesh system.

The DC droop control in the offshore load terminal has entirely different purpose. When the DC voltage goes to very low level, the converter connected to the passive load may go to over-modulation resulting in unacceptable performance which may require disconnection of the converter. To avoid an abrupt disconnection of the converter at a critical voltage level, AC voltage degradation can be used beginning from some level higher than the critical DC voltage level. This voltage degradation corresponds to the DC voltage droop at lower DC voltage levels. An example for the realization of the modified control scheme (for the offshore windfarms) is shown in Figure 11.
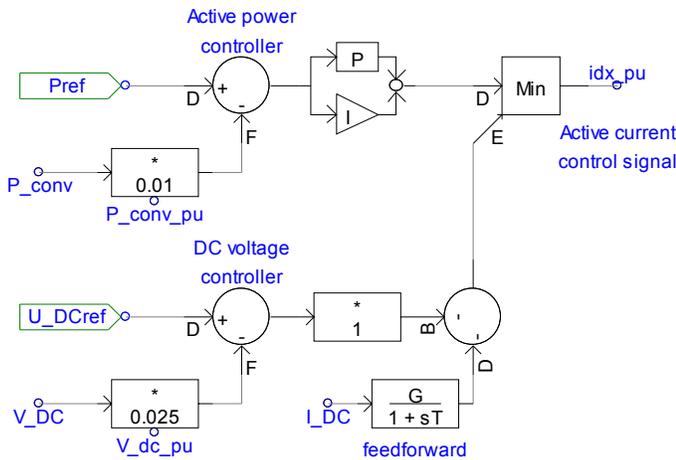
Figure 11: Example implementation of the modified MTCD voltage controller

VI. SIMULATION RESULTS

To corroborate the proposed control scheme for the multi-terminal HVDC system, the four terminal MTDC connections, shown in Figure 7, was modelled and analyzed using PSCAD/EMTDC simulation software. For all converters *r=0.06 Ω, L=0.0048 H* and *C=400 uF* were used. The switching frequency in all the three cases was set to *5 kHz*. DC cables were represented by series resistances of $R_{ab}=R_{bc}=R_{bd}=0.01\ \Omega$.

The following reference values were used for the simulation analysis.

Table 1. Reference value settings for controllers

Terminal	Pmax	Pmin	Uref
1. Offshore windfarm-1	60 MW	0 MW	50 KV
2. Oil/gas platform load	5,25,30 MW	5 MW	40 KV
3. Onshore grid connection	40 MW	-60 MW	44 kV
4. Offshore windfarm-2	40 MW	0 MW	50 kV

The inner current controllers in all converters were set to *P=4* and *T=0.0133* sec while the power controllers were adjusted to P=0.43 and *T=0.0267* sec. The DC voltage controllers for windfarm-1 and windfarm-2 were set to *-2* and *-1* respectively.

Table 2 indicates the list of events chosen for analysis of the simulation study.

Table 2. Description of simulated events

Time (sec)	Events
0	System start up
4	25 MW Load disconnection at platform
10	Onshore grid power reference changed from 20 MW to 40MW power
15	Connection to Offshore wind farm-2 lost

Figure 12: Power variations at the different terminals and the resulting dc link voltage variation

platform and also maintained a new constant DC voltage level in the MTDC system. One can see the similar patterns of the power plots from the two offshore wind farms. It is observed that when both terminals were connected to the Dc mesh, they were sharing the power imbalance of the system due to a change in power conversion of the other terminals. It is also clear to see that the DC voltage variation serves as a natural "communication signal" between the terminals to detect changes in power flow of the multiterminal system. The power supplies to the passive loads at the platform and to the onshore grid connection were not affected by the loss of connection to one of the wind farms, as it was desired originally.

CONCLUSION

In this paper a control strategy, using a mix of voltage margin control and DC voltage droop, for offshore wind farm connected MTDC system was suggested. The control strategy was tested with simulation of a four terminal MTDC connecting two offshore wind farms, oil & gas platform load and onshore grid systems. The proposed control technique, i.e. voltage margin control method with modified droop characteristics, was used to control the MTDC system for a stable steady state and dynamic performance. An important feature of the controller is the ability to maintain operation of the MTDC system during sudden loss of a converter terminal without the need for communication between terminals. Simulation results have confirmed that the proposed control results in satisfactory steady state and dynamic performance.

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Figure 12 shows that the DC voltage of the MTDC was kept within the desired range even after load switching, changes in power references and disconnection of rectifying terminal. The plots show that load switching at platform (at $t=4$ sec) and change in power reference at onshore grid (at $t=10$ sec) have caused only minor oscillations on the DC voltage and these oscillations are effectively attenuated quickly. It is also seen that when connection to the wind farm terminal was lost, the onshore grid instantly started to supply the load demand at the