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North Sea Offshore Modelling Schemes with VSC-HVDC Technology: Control and Dynamic Performance Assessment

K. Nieradzinska[1a*], J. C. Nambo[1], G. P. Adam[1], G. Kalcon[2], R. Peña-Gallardo[3], O. Anaya-Lara[1], W. Leithead[1], a[*]

[1]Department of Electronic and Electrical Engineering, Institute for Energy and Environment, University of Strathclyde, Royal College Building, 204, George Street, G1 1XW Glasgow, UK,
[2]Sudan University of Science and Technology, Sudan
[3]Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí, México

Abstract

The present thinking and trend for connection of large offshore wind farms, dispersed over wide areas, is to use multi-terminal HVDC networks rather than point-to-point DC transmission systems. The aim behind this approach is to improve the security of supply and minimise the loss of generation during scheduled maintenance or unexpected disturbances in any part of the power network. This paper describes various models of multi-terminal HVDC networks connecting offshore wind farms to a number of mainland AC grids which have been developed in MATLAB-Simulink with the main objective of facilitating numerous studies such as steady-state power flow, optimal power dispatch analysis, transient stability, and provision of ancillaries.

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VSC-HVDC; Multi-terminal VSC-HVDC; Power pool; droop control

1. Introduction

The growing global population and potential future energy crisis has brought about a favourable interest in renewable energy sources. Wind power appears to be a promising option, as there is a growing interest in this industry which has shown a rapid growth over the last decade [1]. Offshore wind farms seem to be well suited for large-scale power generation, however, the control requirements and dynamic performance of these systems, comprised of a wide variety of technology and complex network arrangements, may be

[*] kamila.nieradzinska@strath.ac.uk

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significantly different from conventional (and comparatively simpler) existing power networks. This presents huge challenges that need to be addressed.

The use of an AC transmission option results in a synchronous connection where any large disturbance in the mainland grid may propagate to the offshore wind farm and disturb power production [2]. Therefore, DC transmission is seen by many experts and utility companies as the best option that may minimise the impact of grid disturbances on power production offshore. This will result in an asynchronous connection (offshore wind farm network and onshore grid are decoupled), reduce wind intermittency effects on power quality, and will allow to use onshore converter stations in the provision of additional services to the onshore grid. The present thinking for connection of large offshore wind farms, dispersed over wide areas, is to use multi-terminal VSC-HVDC networks rather than point-to-point DC transmission systems [3-6]. The aim behind this approach is to improve the security of supply and minimise the loss of generation during scheduled maintenance or unexpected disturbances in any part of the power network.

In this paper, the main objective is to show steady-state power flow, optimal power dispatch analysis, and transient stability for multi terminal VSC-HVDC networks. Several models have been developed in MATLAB-Simulink to comply with current Grid Codes and to ensure a safe operation of the proposed connections.

2. Control of VSC-HVDC

A generic controller of a converter station in a VSC-HVDC is shown in Figure 1 [8]. Using Pulse-Width Modulation and vector control it is possible to control active and reactive power flow across the HVDC link, the DC link voltage and the AC voltage at both sides of the HVDC link.

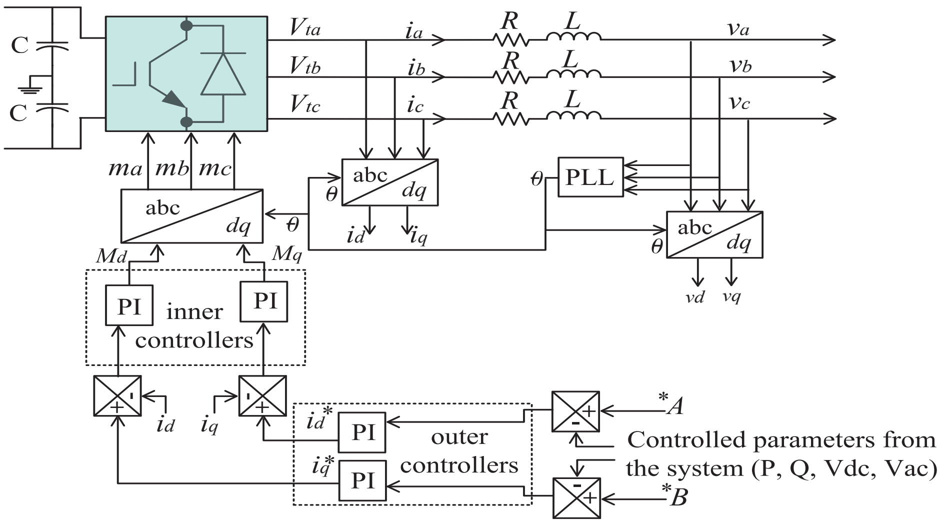

Figure 1 Schematic of a VSC-HVDC control configuration.

The modulation index M, and converter angle δ, can be adjusted independently by the VSC controller to give any combination of voltage and phase shift [7]. By controlling these two variables, the converter can control active power and reactive power using the rectifier on the wind farm side, and the inverter can maintain DC voltage and AC voltage at the point of connection with the onshore grid.

2.1. Inner control loop and outer controllers

Figure 2 shows the inner current controller loop for a VSC converter. The design of the inner current controller loop is based on the following equations:

$$V_{cd1} = u_{d1} - \omega L_{iq1} + V_{sd1} \quad (1)$$
$$V_{qd1} = u_{q1} + \omega L_{id1} + V_{sq1} \quad (2)$$

where u_d and u_q regulate the dq-axis current:

$$u_d = R_{id} + L\frac{d_{id}}{dt} \quad (3)$$
$$u_q = R_{iq} + L\frac{d_{iq}}{dt} \quad (4)$$

A control signal is then derived from the proportional-integral (PI) controller:

$$u_d = k_p(i_d^* - i_d) + k_i \int (i_d^* - i_d)dt \quad (5)$$
$$u_q = k_p(i_q^* - i_q) + k_i \int (i_q^* - i_q)dt \quad (6)$$

where k_p and k_i are the proportional and integral gains of the PI controller.

The outer controller is responsible for providing the inner controller with the reference values, (where different controllers can be employed), such as active/reactive power, and AC and DC voltages.

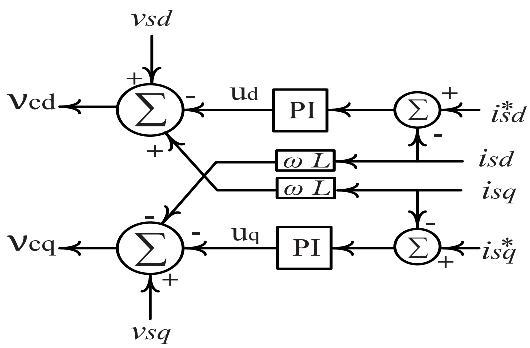

Figure 2. Current control loop for VSC-HVDC.

3. Multi terminal VSC-HVDC connection scenario 1

The multi-terminal VSC-HVDC network shown in Figure 3 is implemented to investigate system behaviour in the event of an AC fault, and also during a sudden loss of the converter/DC link cable. The four-terminal VSC-HVDC comprises of two offshore wind farms (WF1&WF2) connected to two onshore AC networks with an auxiliary DC cable connecting the wind farms' converters. WF1 and WF2 inject 1200 MW into the DC network, whereas AC network 1 and AC network 2 withdraw 1200 MW each.

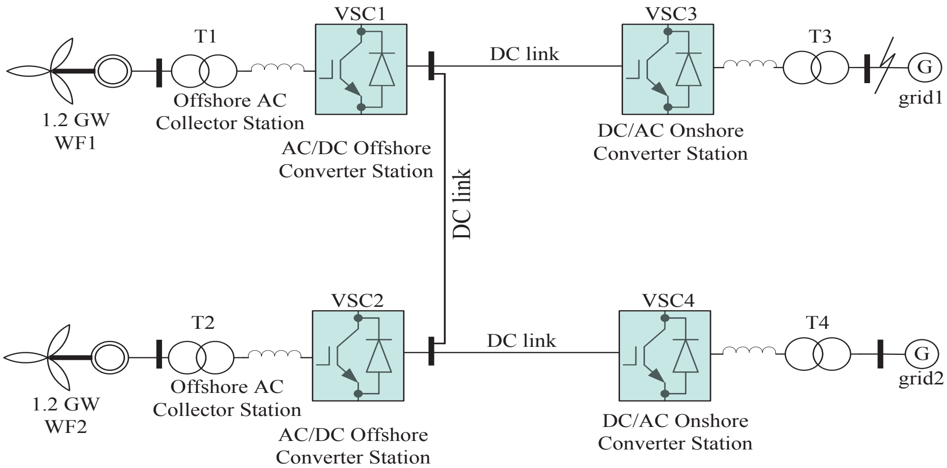

Figure 3 Simplified four-terminal transmission system

In this model, converters VSC1 and VSC2 control active power flow and AC voltage control, and converters VSC3 and VSC4 control DC and AC voltages. The control system for converter VSC1 is shown in Figure 4 and that for VSC2 is shown in Figure 5. The DC voltage is maintained at 300 kV and the AC voltage at 1pu.

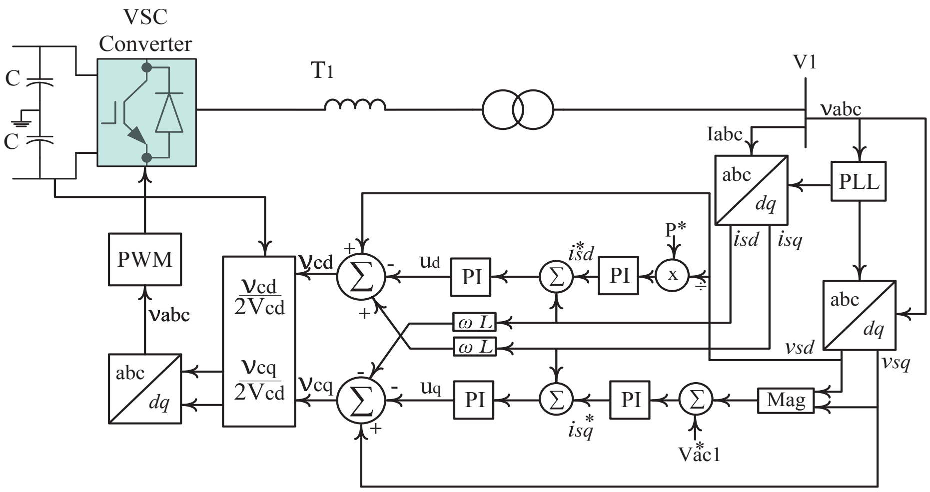

Figure 4 Control system converter VSC1.

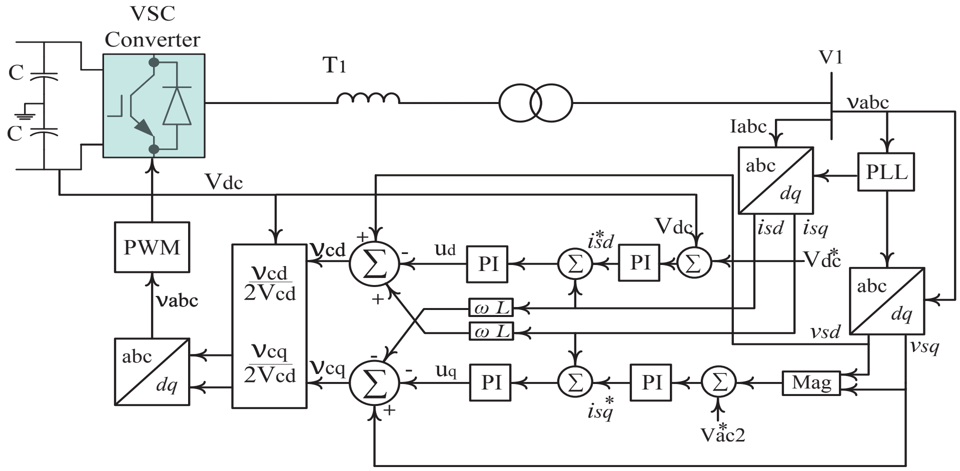

Figure 5 Control system for converter VSC2.

In this simulation, the AC Grid1 has been subjected to a three-phase fault at t=1s with a duration of 100ms to show the transient behaviour of the multi-terminal VSC-HVDC network during major system disturbances. It can be seen in Figure 6 that the AC voltage at Grid2 (and at the receiving-end converter) is less sensitive than the AC fault in Grid1. This improves the AC fault ride-through capabilities by enabling decoupled operation: and the wind farm is isolated from the grid. Also noticeable is that the loss of AC Grid1 has no significant effect on the transient stability of the whole system.

Active power mismatch during a fault, shown in Figure 7, is handled by the slack-bus AC Grid2. The regional network should have enough reserve to take additional power to account for any mismatches in the DC network as shown in the figures below. Figure 7 shows active power being transferred to the AC Grid2 where there is no fault, via the auxiliary DC cable.

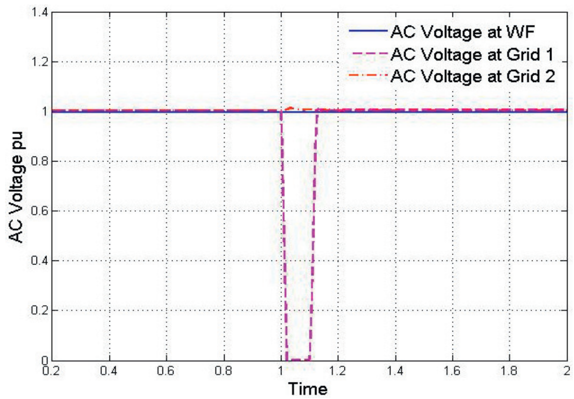

Figure 6 AC voltages at WF and Grids

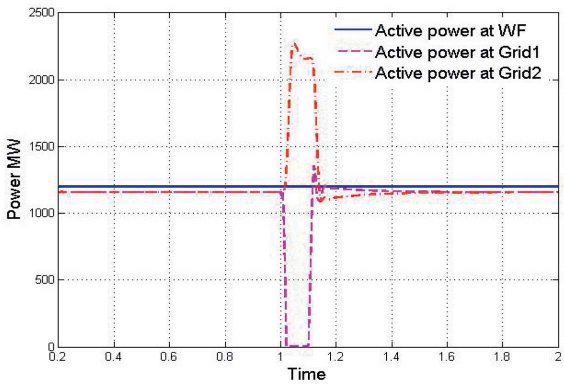

Figure 7 Active power at WF and Grids

Figure 8 shows the DC voltage increase during a fault, which occurred in the AC site. However, the change in the DC voltage is not to a level that would damage the converter equipment.

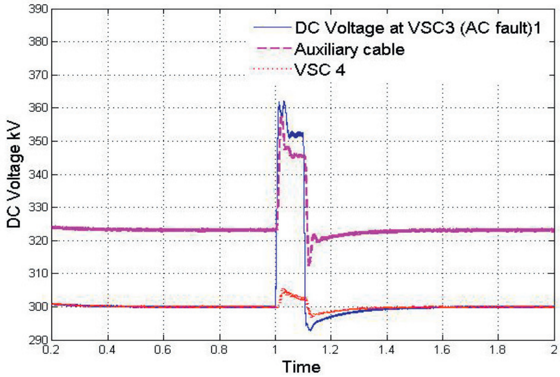

Figure 8 DC voltage at VSC3, VSC4 and auxiliary cable

4. Power exchange in a multi-terminal VSC-HVDC

A multi–terminal power pool is shown in Figure 9. All converters in this network control active power between system terminals excluding VSC3 which maintains DC voltage [9]. In this case, VSC3 is a slack-bus, which supports power balancing in the system shown in Figure 9. The central control system is used in this DC network to coordinate power exchange between VSC converter stations.

To show steady-state power flow during changing loads, the multi-terminal model has been implemented and simulated in Simulink. During any change in power schedule, VSC3 will adapt to the new situation and will import or export power. The power delivered to, or withdrawn from, the slack bus converter to keep the balance in the network is calculated by:

$$P_{slack\ bus,VSC3} = P_{VSC1} + P_{VSC2} + P_{VSC4} + P_{Losses} \qquad (7)$$

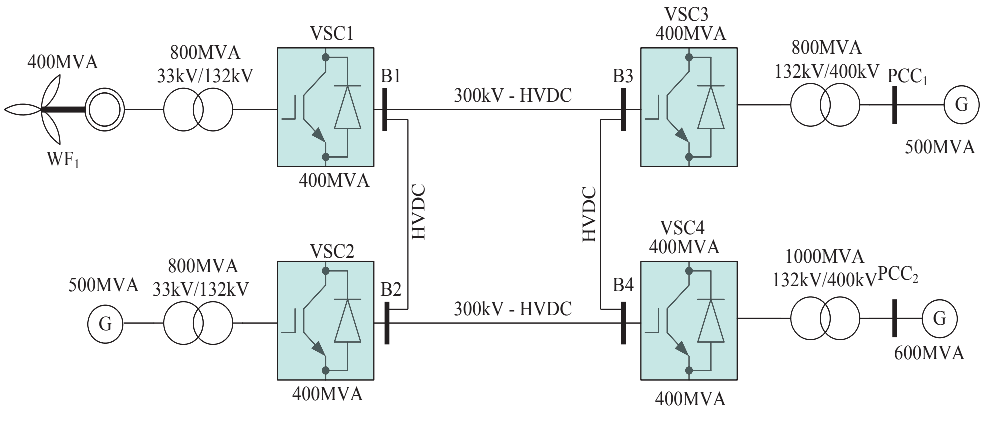

Figure 9 Multi-terminal VSC-HVDC for power exchange analysis.

To demonstrate the viability of using a VSC-HVDC power pool to accommodate large amounts of wind power the network is adapted to include one offshore wind farm and three onshore AC networks. At the start the wind farm converter VSC1 and AC network converter VSC2 are injecting 300MW and 200MW in to the power pool, respectively. Converters VSC3 and VSC4 are importing 300MW and 200MW from the power pool. Table 1 shows the results obtained from this simulation event of power sharing between converters. The power variation of the wind farm and VSC converter can clearly be seen in Figure 10 and Figure 11. Figure 10 shows the power variation in converters VSC1 and VSC2, and Figure 11 shows the power variation of the converters VSC3 and VSC4.

Table 1 Power sharing between converters

Time (sec)	0.0-2.0	2.0-4.5	4.5-6.0	6.0-8.0
VSC1 (wind farm)	+300 MW	+400 MW	+200 MW	+200 MW
VSC2	+200 MW	+100 MW	-100 MW	-100 MW
VSC3	-300 MW	-200 MW	+100 MW	+200 MW
VSC4	-200 MW	-300 MW	-200 MW	-300 MW

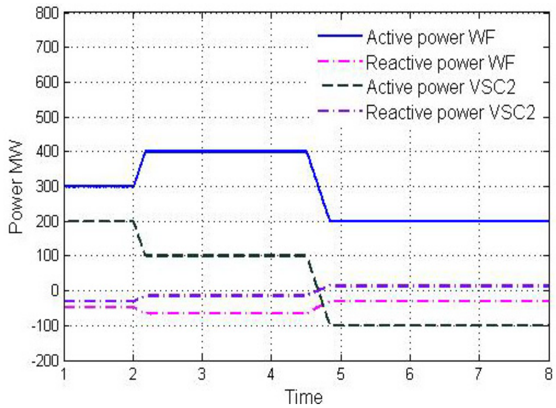

Figure 10 Active and reactive power at WF and VSC2

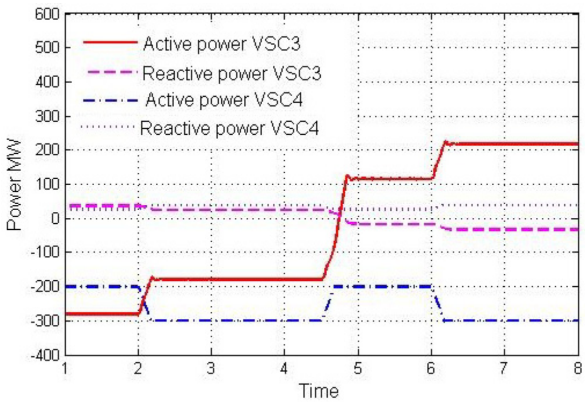

Figure 11 Active power and reactive power at VSC3 and VSC4

Figure 12 shows the variation of DC voltage during changes in the power exchange between regional AC networks. The VSC3 converter is responsible for maintaining the DC voltage at 300kV during power exchange in the multi-terminal network.

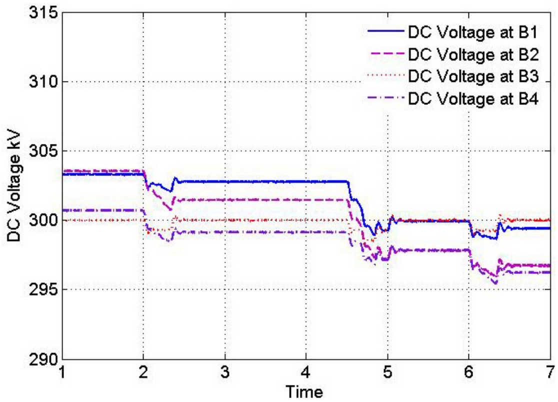

Figure 12 DC link voltages

5. Multi-terminal VSC-HVDC with DC voltage droop control

A generalised DC voltage droop control is presented to control the power flows to the onshore networks [7]. The validity of this droop control is tested in steady-state operating conditions.

A five-terminal VSC-HVDC system as shown in Figure 13 has been implemented in Simulink to represent a generic connection scenario for two wind farms located in a distant offshore wind site. These two wind farms are connected to three different onshore grids with three onshore converter stations. It can also be connected to the three different onshore grids.

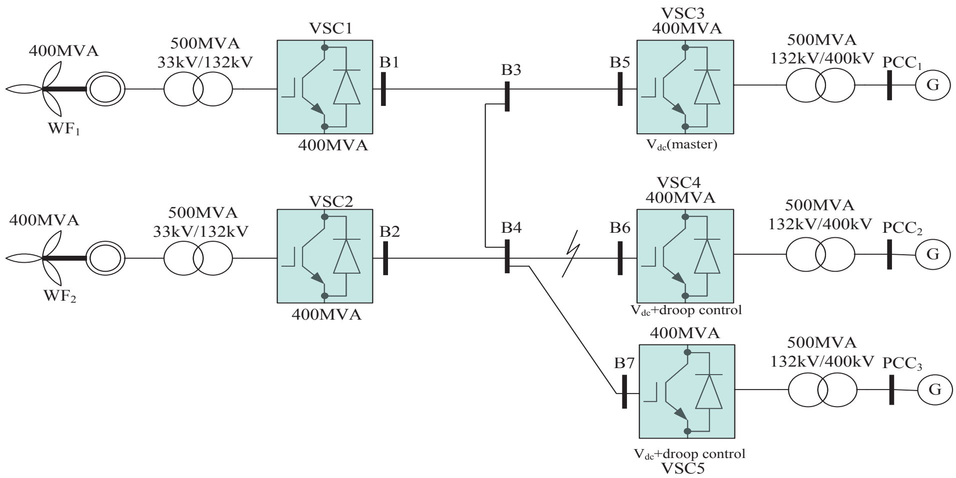

Figure 13 Multi-terminal VSC-HVDC with droop control.

5.1. DC voltage droop control

A generalised droop control is proposed in this section to facilitate the power dispatch (sharing) in a multi-terminal HVDC system connecting two offshore wind farms to three mainland grids as shown in Figure 13. Droop control has been also investigated in [7, 10].

The droop control presented exploits the current split concept to enable power dispatch at the onshore grid-side converters according to arbitrary current ratios $N_1{:}N_2{:}N_3{:}\ldots.N_n=I_1{:}I_2{:}I_3\ldots I_n$, where n is the number of onshore grid-side converter terminals; N_1 to N_n are the ratios at which the total power transmitted from the offshore wind farms is shared between the onshore grid-side terminals; and I_1 to I_n are the DC currents corresponding to each converter terminal. This paper also shows the power management and performance when one of the onshore grid-side converters is lost (this simulates either a fault in the converter, or a fault in the DC cable connecting this converter).

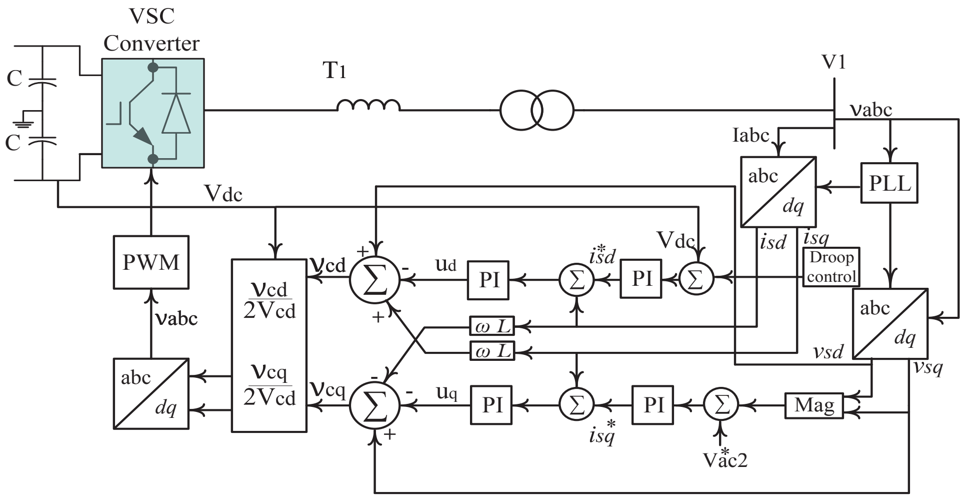

Figure 14 Block diagram illustrating the implementation of the proposed DC voltage droop control in an onshore grid-side converter.

The proposed DC droop control is implemented in VSC4 and VSC5, in order to facilitate the power sharing between onshore grid-side converters. The proposed DC voltage droop controls the amount of power according to the needs of the onshore AC grids. Figure 14 shows that the proposed droop control provides a reference voltage to the DC voltage controller *'i'* taking into account the voltage at the support node ,*'j'*, as shown in equation (8):

$$V_{dci} = \frac{1}{2}V_{dcj} + \frac{1}{2}\sqrt{V_{dcj}^2 - 4R_{ji}P_i} \qquad (8)$$

Introducing the DC voltage droop characteristic into the control system of VSC4 and VSC5 will allow control of the power share between VSC3-VSC5 converters.

Figure 15 shows the DC voltage in the DC network. Figure 16 shows the power sharing between the onshore grid-side converters where the DC voltage droop control has been introduced. At time 1.5s the droop control has been activated and injects 180MW of additional power to the VSC3 master converter. The additional power flow is from VSC4 (75MW) and VSC5 (105MW).

At time 3s, the power command has been changed and additional power has been injected into VSC4 and VSC5. At time 4.5s, the droop control has been deactivated and each converter shares power equally around 255MW. At time 6s, the droop is activated to decrease the power flow in VSC3 (master converter) and split the power decrease between VSC4 and VSC5. Additional power decrease in VSC3 is simulated at time 7.5s. The power injected into the system by VSC1 and VSC2 remains the same at 400MW each during the simulation period.

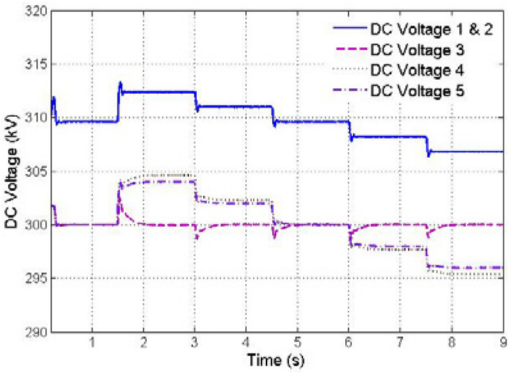

Figure 15 DC voltages in the converters

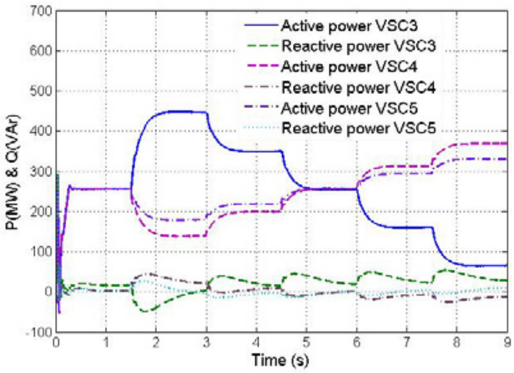

Figure 16 Active and reactive power at buses B5-B7

6. Conclusions

This investigation shows three possible connections for power management between different scenarios of multi-terminal wind farm connections. The first configuration shows the connection between groups of wind farms delivering power to two different points of a network, where the DC transmission lines are interconnected by a DC auxiliary link. This kind of configuration is suitable for re-scheduling the DC power transfer within the HVDC connection in the case of presence of fault or required maintenance. The four-terminal pool VSC-HVDC configuration allows the connection between wind farms and different network systems, where the power exchange can be bi-directional and one of the systems is responsible to balance the power demanded by the rest of them.

The last model presents a generalised DC voltage droop control which facilitates power management in a multi-terminal DC network connecting two offshore wind farms to three different onshore power networks. The results illustrate that multi-terminal VSC-based networks provide significant advantages in terms of power flow controllability when they are fitted with suitable control loops such as the droop introduced here. This can prove to be very advantageous for connection of variable wind generation and assist in the power balancing of interconnected networks. Each of these controls provides some different controllability properties, giving the option to select which of them is the most suitable depending on the required properties in which a multi-terminal connection is required.

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