MMC based Multi-terminal HVDC Subsea Power Transmission System with the Integration of Offshore Renewable Energy

Rajesh Sapkota, Sandeep Kolluri, Jeevan Adhikari and Sanjib Kumar Panda
Department of Electrical and Computer Engineering
National University of Singapore, Singapore 117580
Email: elersk@nus.edu.sg,

***Abstract*—Typical 2-level and 3-level converters are still widely implemented in offshore renewable and deep-water oil and gas applications due to their simplicity and maturity in these fields. However, it is difficult for these converters to operate in higher dc bus voltage due to the switching transients, large voltage stress on each switches and large losses. Therefore, Modular Multilevel Converter (MMC) has been gaining popularity over these converters in the field of high voltage and high power applications such as HVDC. In this paper, control of MMC based multiterminal HVDC transmission system for offshore wind energy integration and subsea oil and gas application are presented. Different strategies to regulate the DC link voltage, active and reactive power flow and AC grid voltage of the passive subsea grid in a 3-terminal offshore HVDC grid have been presented.**

***Keywords*: MMC-HVDC transmission, Subsea Power Systems, PSCAD/EMTDC**

I. INTRODUCTION

The increase in power transmission distance and the power demand at the distant offshore oil and gas platforms have made the power supply to these facilities ever so challenging. The limitations of the HVAC and the necessity of HVDC subsea cable transmission system to supply distant offshore oil and gas processing have been discussed in [1]–[5]. Conventional offshore oil and gas floating production system generates electricity from gas fired turbines installed at its own floating platforms. Issues related to these platforms such as limitation in the turbine-generator size and weight, low efficiency of the gas turbines and generation of large amount of greenhouse gases at the already fragile marine ecosystem needs to be redressed with a suitable solution. Furthermore, wind energy densities in the offshore regions are higher as compared to the land. This energy can be tapped by the offshore wind farms and integrated to the HVDC transmission system supplying distant oil and gas facilities and thereby reducing the overall carbon footprint. Therefore supplying the platforms with power from onshore generating station with HVDC subsea power transmission will result in benefits both from economic and environmental protection perspectives.

Given these two interests for HVDC in the subsea power transmission, implementation of Modular Multilevel Converter (MMC) based Multiterminal HVDC (MTDC) is a potential solution to integrate offshore wind farms and oil/gas platforms with the onshore grid. With its advantages over 2 level or other multilevel converters in terms of scalability and modularity, low $\frac{dv}{dt}$, low harmonics, improved reliability and lower switching losses resulting in improved efficiency, elimination of DC bus capacitor, MMCs have proved to be a superior alternative [6], [7].

In this paper MMC based 3 terminal HVDC transmission system model is developed and tested in PSCAD/EMTDC tool. The Detailed Equivalent Model (DEM) of the MMC, proposed in [8], is implemented to reduce the simulation time without compromising the accuracy. Frequency Dependent model for the subsea cable have been developed and implemented for accurate observation during transients.

The internal control techniques of MMC for balancing the submodule capacitor voltages and circulating current control have been already discussed in a number of literatures in the past [8]–[10], and hence they have not been discussed in this paper.

Control fo MMC based Multiterminal HVDC system for offshore wind power application have been presented in [12], [13] but does not focus on power supply to subsea passive grid.

This paper focuses on the external control loops i.e. DC link voltage control for the onshore converter, AC voltage control for the offshore converter supplying passive subsea load and PQ control techniques for the converter employed at offshore wind farm are discussed. The paper ends with the analysis of the simulation results.

Fig.1 shows the schematic diagram of MMC based multiterminal HVDC subsea power transmission system with the integration of offshore wind energy into the HVDC grid. Purpose of each converter and their corresponding control strategy have been explained in Section II. Simulation results of MMC based Multiterminal HVDC system and the effectiveness of each control loops for tracking the control references of each converter terminal have been discussed in Section III. Section IV represents the conclusion based on the simulation results regarding the effectiveness of the implemented control methods for MMC based Multiterminal HVDC system.

Several literatures on MMC based back-to-back HVDC transmission system for connecting two different active AC grids can be found among [6], [7], [9], [10]. In addition there are a few literatures discussing the VSC based Multiterminal

978-1-5386-4950-3/17/$31.0

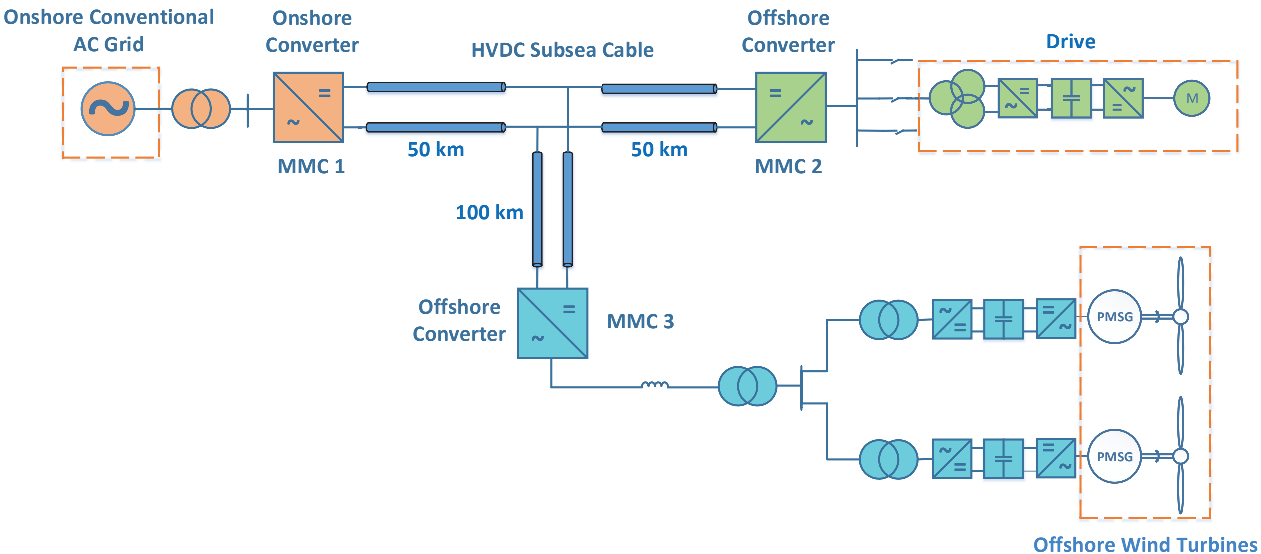

Fig. 1: MMC based Multiterminal HVDC with offshore wind energy integration

HVDC for interconnecting grids of various types [11] . But non of the papers focus on the MMC based Multiterminal HVDC for supplying deepwater oil and gas facilities with offshore wind energy integration. This paper aims to present the control method for MMC based multiterminal HVDC for both applications.

II. CONTROL STRATEGY OF MMC BASED MULTITERMINAL HVDC SYSTEM

For a typical point-to-point HVDC transmission system connecting two active AC grids, the Active Front End (AFE) converter controls the DC link voltage and the Rear End converter acts as the Power Dispatcher. However, if one of the grid is passive in nature (eg. subsea oil and gas platforms), then its AC voltage and frequency needs to be regulated. Power flow with this grid is solely based on the AC grid voltage and the load parameters. Hence, independent control of active and reactive power is not possible in this case.

For the MMC based Multiterminal HVDC transmission system, shown in Fig. 1, supplying power to the passive subsea loads along with integration of offshore wind energy, each terminals are independently controlled such that

1) AFE converter (MMC 1) connected to the onshore AC grid regulates the DC link voltage.
2) Converter connected to the offshore subsea load (MMC 2) regulats the AC voltage and frequency in the subsea passive network.
3) Converter connected to the offshore wind turbine (MMC 3) controls the power injection from the offshore wind farm to the HVDC grid thereby reducing the power demand from the onshore grid.

The control method of each terminal of the MMC based HVDC are explained in the following sections.

A. *Control of Sub-module Capacitor Voltage and Circulating Current*

Maintaining the sub-module capacitor voltage to the nominal level and controlling the negative sequence circulating current are of main challenges of the MMC control. Without sub-module voltage balancing control, the sub-module capacitors of top and bottom of the arm are stressed more as they share major portion of the DC bus voltage as compared to the mid capacitors. Although the average voltage across the sub-module capacitors is equal, the ripple component across the sub-module capacitor creates different instantaneous voltages among the three phases. This consequently causes second-order harmonic in circulating current that flows through the DC source and the phase leg. And also causes circulating currents to flow among the three phases due to the phase parallel configuration.

To rectify this issue, both, the individual submodule capacitor voltage as well as the average submodule capacitor voltage of the each phase, should be balanced. Fig. 2 shows the block diagram of the PI based internal controller used for the individual sub-module voltage balancing as well as the the average voltage balancing across each phase for circulating current control. (v_{cj}) represents the reference for the individual submodule capacitor voltage, (i_{Pa}) and (i_{Na}) represent the upper and lower arm phase current of MMC and (v_{csum}) represents the average voltage of the SM capacitors of each phase. (V_{con_cap}) and $(V_{control})$ are the control signals from the submodule voltage balancing loop and circulating current contol loop respectively.

These internal control signals are added to the the reference signals obtained from the external control loop to get the final modulating signals for each half bridge sub-module.

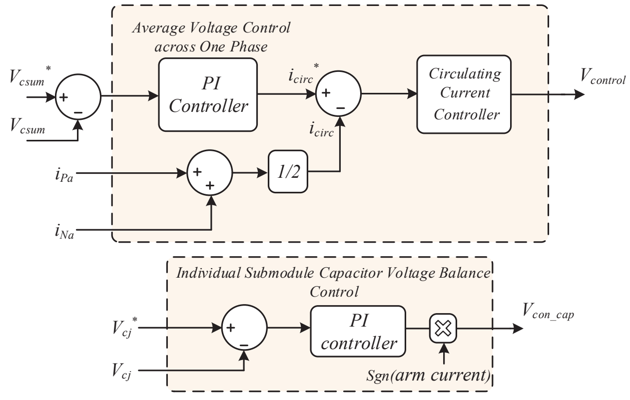

Fig. 2: Internal Controller Block for Sub-module Voltage Balancing and Circulating Current Contol

B. Control of Onshore Active Front End Converter (MMC 1)

As mentioned above, the task of onshore MMC is to regulate the DC link voltage throughout the HVDC grid. PI controller is used to track the DC link voltage reference given by the grid operator. The block diagram of the DC link voltage controller is shown in Fig. 3.

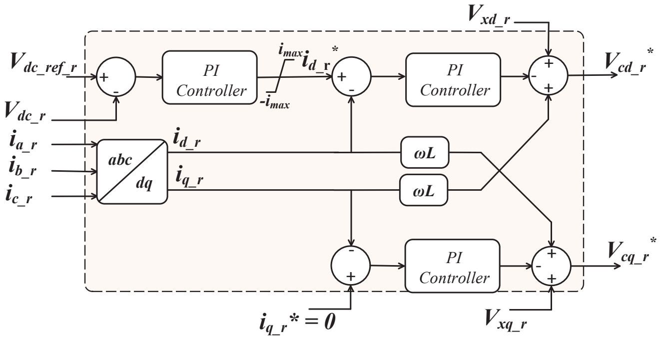

Fig. 3: DC link voltage control loop for Active Front End Converter

The DC link voltage ($V_{dc\_ref\_r}$) is compared to the reference value and the error signal is given to the PI controller. The output of the PI controller generates the current reference (i_{dr}). The $d-q$ axes decoupling and the feed-forward components are implemented to enhance the performance of front-end converter during load and supply voltage disturbances. Generated dq voltage references are converted to the stationary reference frames, normalized with the DC reference voltage to obtain the ac reference signals. These reference signals are then added to the internal control signals for MMC (voltage balancing loop for each loop and circulating current control for each leg) to obtain the modulating signals for the MMC.

C. Control of Offshore Converter (MMC 2) for Subsea Grid

In addition to controlling power flow between two ac networks, VSC-HVDC systems can supply weak (low short-circuit ratio) and even passive networks. MMC-HVDC connected to passive network has to maintain constant rms phase voltages for all line currents ranging from no load to full load. Reference AC signals are compared to the grid voltages in dq reference frame and the error signal is given to the PI controller. The output of the PI controller gives the reference signals for modulation (m_{abc}). These reference signals are then added with the control outputs of submodule capacitor voltage balancing and circulating current control loops and are fed to the PWM generators.

The control diagram with reference signal generators for the AC voltage control has been shown in Fig.4

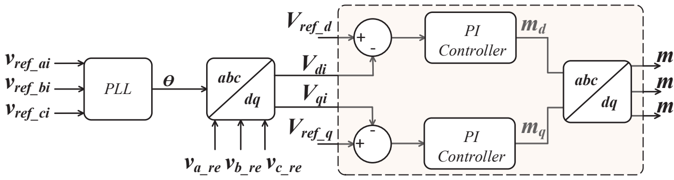

Fig. 4: AC voltage control loop for passive subsea network

D. Control of Offshore Converter (MMC 3) for Offshore Wind Farm

As mentioned in earlier section, the converter connected to the offshore wind turbine regulates the power injected into the HVDC grid. The reference for the power control loop for MMC 3 converter is obtained form the Maximum Power Point Tracking (MPPT) algorithm. The MPPT algorithm determines the optimum rotor speed for the available wind speed such that the maximum power can be extracted from the each wind turbine. Since the offshore wind farms contains the hundreds of these wind turbines, implementation of MPPT is not discussed here. Instead, the main focus here is the study of the power dispather control loop for the overall wind farm. The block diagram for the Power Controller is shown in Fig.5.

Similar with the previously described controllers, the final output references of the controller are added to the output of the submodule voltage balancing loop and the circulating current reduction loop.

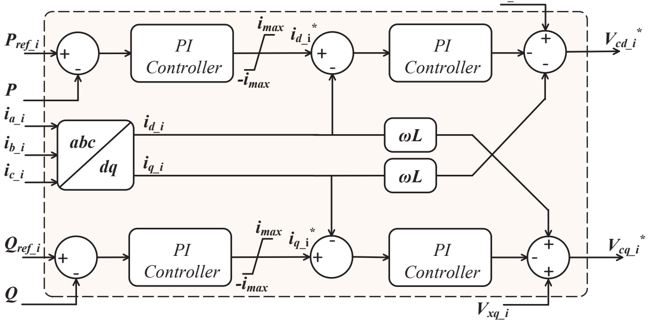

Fig. 5: Power Control loop for dispatching power from the Offshore Wind Farm to the HVDC Grid

III. SIMULATION RESULTS FOR MMC BASED MULTITERMINAL HVDC

Simulation of MMC based Multiterminal HVDC transmission system supplying 100 MW power to the passive subsea network situated at a distance of 100 km from the onshore converter station is carried out in PSCAD/EMTDC tool. The DC link voltage for the subsea transmission is kept at 80 kV.

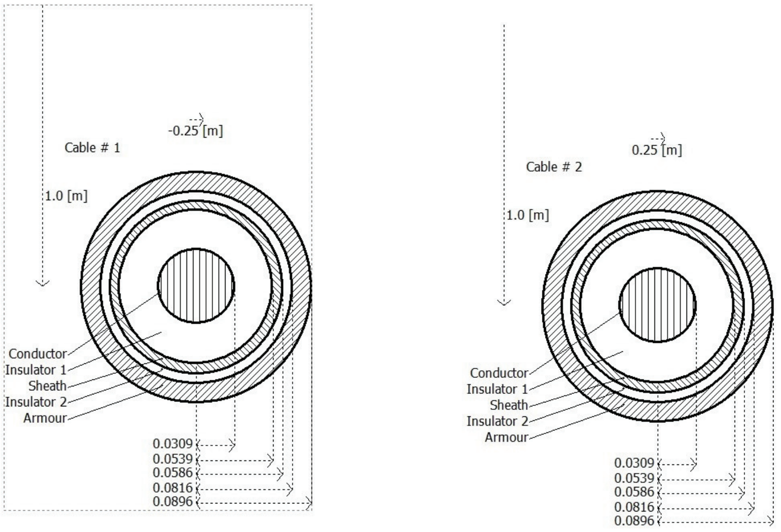

Fig. 6: Frequency dependent modelling of Subsea Cable with PSCAD/EMTDC

TABLE I: Simulation parameters for MMC based Multi-terminal HVDC Transmission System

Parameter	Symbol	Value
DC link voltage (kV)	Vdc	80
No of SMs in each arm		22
Submodule Capacitor (uF)	Csm	3000
Arm Inductor (mH)	Larm	2
Arm Resistance (Ohm)	Rarm	0.1

The selection of the DC voltage, transmitted power and the subsea cable length is chosen to be similar to the Troll A Offshore Gas Field Platform, Norway [4].

Simulation of 3 terminal MMC based HVDC subsea transmission system, depicted in Fig1, has been performed in PSCAD/EMTDC tool. An onshore AFE converter (MMC 1) has been connected to the MMC 2 with offshore passive subsea load with a subsea cable of 100 km. Offshore wind energy is tapped and is connected to the HVDC transmission system at the mid-point of the subsea cable (50km) from MMC 1 station. The length of the subsea cable for the offshore wind integration itself is taken as 50 km from the offshore converter MMC 3 to the point of connection. Frequency dependent modelling of the subsea cable has been performed instead of the lumped circuit model in order to achieve the more accurate waveforms during transients.

The physical parameters and the dimensions of the subsea cable used for frequency dependent modelling has been shown in Fig.6 [14]. The electrical parameters of the subsea cable transmission system are internally computed by the PSCAD/EMTDC tool. Similarly, the parameters for each of the three MMCs has been listed in Table I.

A. *Power Flow Control*

The simulation result of the power flow control and load sharing is shown in Fig. 7. 100 MW subsea load is shared among Offshore Wind Farm (OWF) and the onshore grid with the OWF contributing 25 MW and the rest is taken up by the onshore grid. At t=1.0 second, power from the OFW has suddenly increased by 10 MW and reached 35 MW. It can be observed that the power from the onshore grid reduces by the same amount so as to maintain the load sharing with the OWF. At t=2.0 second, power from the OWF further ramps up to 50 MW and the power dispatched from the onshore grid also decreases by the same rate. Similarly, at t=3.5 second, there is a sudden load change at the offshore grid to 125 MW. Since 50 MW power is being dispatched from the OWF, remaining power is balanced by the onshore grid. At t=5.0 second, the entire subsea load is taken up by the onshore grid as the OWF is completely cut off from the grid.

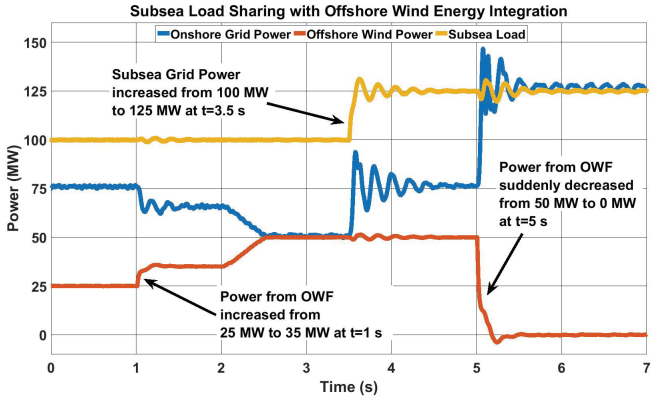

Fig. 7: Subsea load sharing among all three converters with the increase in power from Offshore Wind Farm

Fig. 8 shows the DC link voltage and the current at the onshore converter (MMC 1) station. Since the AC voltage across the subsea loads at MMC 3 is fixed, the power dispatched into this passive AC grid is also fixed.

During steady state, the power dispatched from the onshore terminal and the OWF balances the power dispatched at the subsea loads along with the losses at the converter stations and the transmission cable. This stabilises voltage profile of the grid so that the the DC link voltage remains stable. However, at t=1.0 second, the sudden injection of extra power from the MMC 3 results in the power imbalance in the HVDC grid.

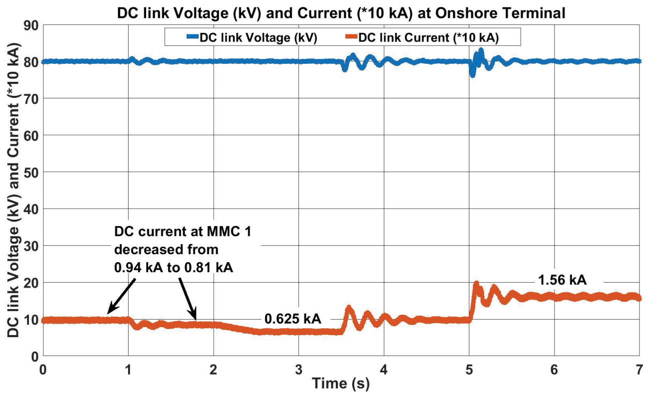

Fig. 8: DC link voltage and current profiles at onshore converter station (MMC 1) during the increase in power injection from OWF

This sudden surge of power is reflected in the voltage profile of the transmission cable. The additional energy is stored in the submodule capacitors of the MMC stations resulting in the rise of voltage profile of HVDC transmission cable.

Fig. 9 shows the AC currents in the onshore AC grid during the increase in power from OFW. The line currents are plotted in dq reference frame for better understanding. It can be seen that at t=1.0 second, the active current, i_d is decreased from 1.6 kA to 1.2 kA. The i_q remains 0 during the transient, confirming the unity power factor throughout the simulation.

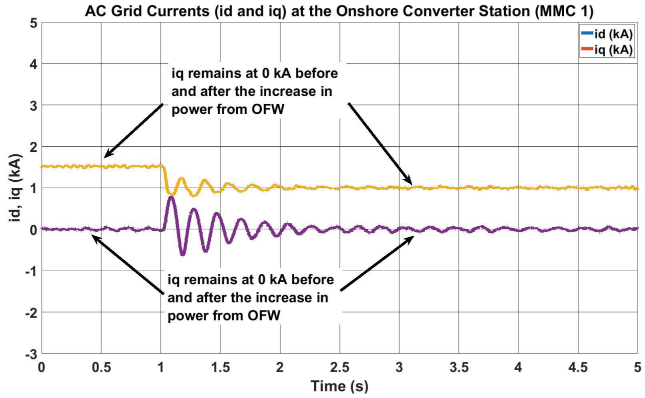

Fig. 9: AC grid currents (i_d and i_q) at the onshore AC grid

B. DC Link Voltage Control

As discussed in Section II, the DC link voltage in this HVDC grid is controlled by the onshore AFE converter. Fig.10 shows the voltage tracking of the MMC based Multiterminal HVDC system. The reference voltage is decreased by 10% from 80 kV to 72kV at t=1.0 seconds. The line to line grid voltage on the passive AC subsea load remains at 44 kV even during the change in the DC link voltage as the increase in modulation index compensates the effect of decrease in the DC link voltage thereby stabilising the AC voltage of the passive grid as well we the power flow. Fig. 11 shows the power flow during the decrease in DC link voltage.

It is to be noted that the power generated from the offshore grid is fixed, given the power reference from the MPPT is fixed and the power injected into the passive subsea grid is constant is also constant for a given AC voltage. Therefore the decrease in DC link voltage ultimately results in increase of DC current from MMC 1 so that it will keep on dispatching its share of power from the onshore grid. Fig. 11 shows the DC link voltage and current during the decrease in DC link voltage.

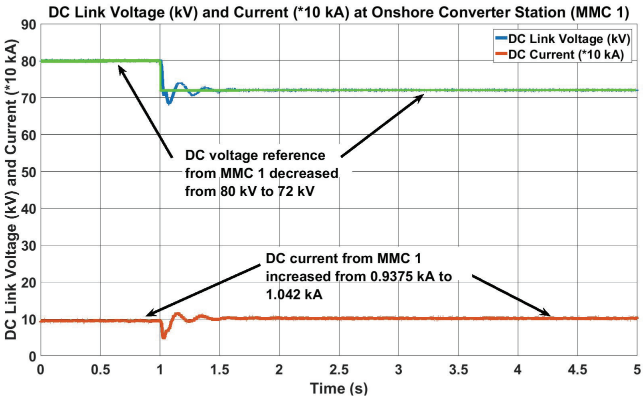

Fig. 10: DC link voltage and current profiles at onshore converter station (MMC 1) with the decrease in DC voltage reference

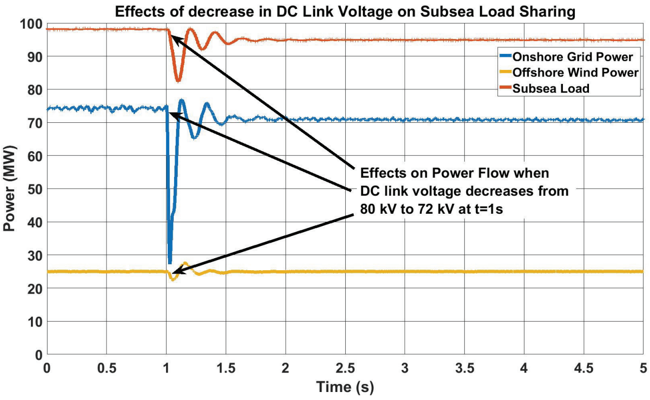

Fig. 11: Effect of decrease in DC link voltage on Subsea load sharing

C. Voltage Control of Passive AC Grid

The AC voltage control mechanism for the passive subsea grid has been explained in Section II. In this section, simulation results demonstrating the AC voltage control is presented. The line-to-line voltage at the subsea AC grid is maintained at 44 kV. As shown in Fig. 12, the voltage on this passive grid is suddenly changed to 33 kV at t=1.0 seconds

Since the load at the oil and gas platform are passive in nature, the power consumption solely depends on the converter line to line voltage. As the line voltage decreases from 44 kV to 33 kV, the line current too decreases with similar proportions. This overall change in the voltage and current results in decrease in power consumption at the subsea loads as shown in Fig.13.

Its effect on the dc link voltage and the dc currents at MMC 1 and MMC 3 are shown in Fig. 14. It is observed that because of the sudden decrease in power consumption at the subsea load, the DC bus voltage of the HVDC grid increases before settling down to the reference value (80 kV). The dc current from the OFW settles to a value of 0.32 kA, corresponding

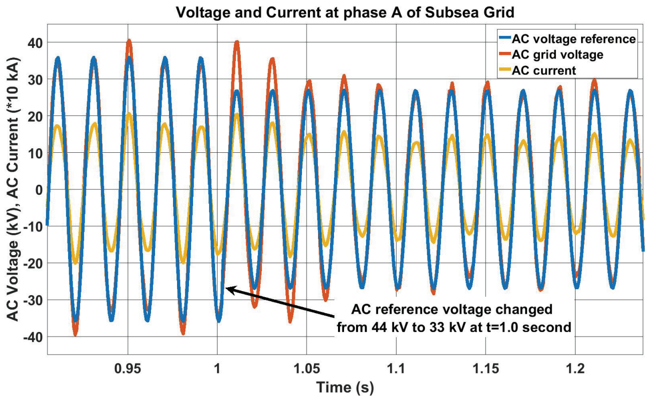

Fig. 12: AC voltage control at Subsea AC grid

to the power reference of 25 MW, where as the DC current from the onshore grid decreases to 0.45 kA where the power supplied from the onshore grid and the OWF finally balances the power consumed at the subsea load and the line losses.

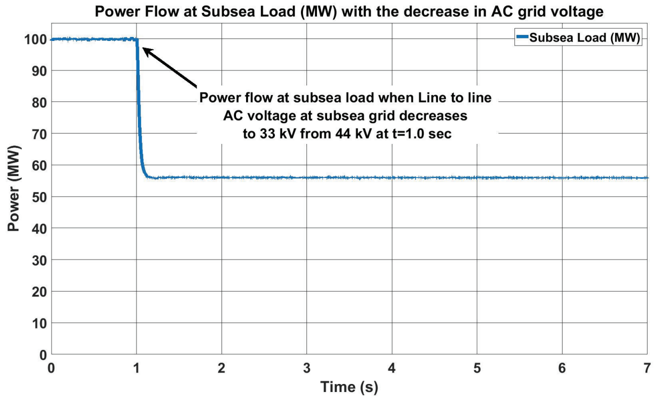

Fig. 13: Power flow at the subsea load with decrease in the AC grid voltage

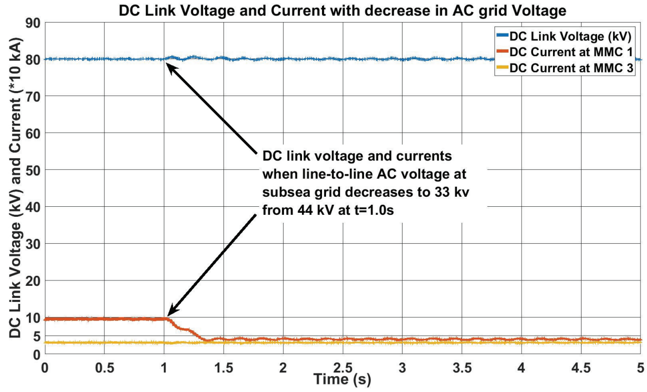

Fig. 14: DC voltage and Current at Terminal 1 and 3 with the decrease in AC grid Voltage

IV. CONCLUSIONS

In this chapter the control method for 3 terminal MMC based HVDC transmission system is explained. A control method is proposed where the onshore converter controls the DC voltage of the HVDC grid, offshore converter connected to the OWF controls the power injection from the wind turbines and the converter connected to the subsea loads controls the ac voltage of the passive grid. Simulations of a 3 MMC based 5 level converters are performed in PSCAD/EMTDC tool. Frequency dependent modelling of the subsea cable is done to ensure the accurate results during transients in various parameters. All three control methods are collectively applied to the corresponding converters so that the overall response of the sysetm is analysed. It has been found that control system performs adequately maintain the system stability during the changes in DC link voltage, power fluctuations in the OWF and grid voltage changes in the subsea passive network.

V. ACKNOWLEDGEMENT

This research was supported by Singapore Maritime Institute.

REFERENCES

[1] Z. E. Al-Haiki and A. N. Shaikh-Nasser, “Power transmission to distant offshore facilities,” *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1180–1183, 2011.

[2] J. Song-Manguelle, R. Datta, M. H. Todorovic, R. Gupta, D. Zhang, S. Chi, L. Garcs, and R. Lai, “A modular stacked dc transmission and distribution system for long distance subsea applications,” in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2012, pp. 4437–4444.

[3] S. Gilje, L. Carlsson, ”VALHALL RE-DEVELOPMENT PROJECT, POWER FROM SHORE,” ENERGEX 2006

[4] P. Jones, L. Lars Stendius, ”The Challenges of Offshore Power System Construction Troll A,Electrical Power Delivered Successfully to an Oil and Gas Platform in the North Sea,” EWEC 2006, Athens

[5] S. Kolluri, P. Thummala, R. Sapkota, S. Kumar Panda and D. Rendusara, ”Subsea power transmission cable modelling: Reactive power compensation and transient response studies,” 2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL), Trondheim, 2016, pp. 1-6. doi: 10.1109/COMPEL.2016.7556718

[6] A. Beddard, M. Barnes, ”Modelling of MMC-HVDC Systems An Overview,” Energy Procedia, Volume 80, 2015, Pages 201-212, ISSN 1876-6102

[7] A. Nami, J. Liang, F. Dijkhuizen, and G. D. Demetriades, “Modular multilevel converters for hvdc applications: Review on converter cells and functionalities,” *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 18–36, Jan 2015.

[8] U. N. Gnanarathna, A. M. Gole and R. P. Jayasinghe, ”Efficient Modeling of Modular Multilevel HVDC Converters (MMC) on Electromagnetic Transient Simulation Programs,” in IEEE Transactions on Power Delivery, vol. 26, no. 1, pp. 316-324, Jan. 2011. doi: 10.1109/TPWRD.2010.2060737

[9] S Li, X. Wang, Z. Yao, T. Li, Z. Peng, ”Circulating Current Suppressing Strategy for MMC-HVDC Based on Nonideal Proportional Resonant Controllers Under Unbalanced Grid Conditions,” in *IEEE Transactions on Power Electronics*, Volume: 30, Issue: 1, Jan. 2015 pp. 387-397

[10] J. Wang; J. Liang; C. Wang; X. Dong, ”Circulating Current Suppression for MMC-HVDC under Unbalanced Grid Conditions,” in IEEE Transactions on Industry Applications , vol.PP, no.99, doi: 10.1109/TIA.2017.2675992

[11] Magne Lorentzen Kolstad ”Integrating Offshore Wind Power and Multiple Oil and Gas Platforms to the Onshore Power Grid using VSC-HVDC Technology” MSc thesis in Electric Power Engineering, Norwegian University of Science and Technology

[12] P. Wang, X. P. Zhang, P. F. Coventry and R. Zhang, ”Start-Up Control of an Offshore Integrated MMC Multi-Terminal HVDC System With Reduced DC Voltage,” in IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 2740-2751, July 2016. doi: 10.1109/TPWRS.2015.2466600

[13] L. Zeni,T. Haileselassie, G. Stamatiou, A. G. Eriksen, J. Holbll, O. Carlsson, K. Uhlen, P. Srensen, N.A. Cutululis, ”Start-Up Control of an Offshore Integrated MMC Multi-Terminal HVDC System With Reduced DC Voltage,” Chalmers University, Sweden-2011.

[14] T. H. Lee, J.W. Choi, E.H. Jung, J.H. Nam, J.N. Kim, I.H. Lee, S.I. Jeon, D.H. Kim, H.S. Park and J.W. Kang, ” Development of the HVDC 80kV XLPE Cable System and Construction of Test-bed in KOREA,” 21, rue dArtois, F-75008 PARIS, CIGRE 2012.