An Enhanced Fault Ride-Through Capability for MTDC Systems Using Vector Current Control and Inherent Energy of Submodules of MMC

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***Abstract*—Modular multi-level converter (MMC) has been recognized as the most prominent topology in building the multi-terminal direct current (MTDC systems) due to its numerous advantages over other converter topologies. The primary concern for the operation of such advanced MTDC grids is to ensure the reliability and safety of the electrical equipment during dynamic and transient conditions following standard grid codes. This research work proposes a combination of different control strategies developed for MMC based MTDC systems to promote fault ride-through capability during three-phase transients and voltage dips. The proposed control architecture contains inner and outer control loops for MMC stations. Along with the different control strategies, the inherent energy available in the capacitors of submodules MMC has also been utilized, which ensures constant power delivery to the load system during three-phase transients & voltage dips and provides power oscillation damping (POD) with quick post fault recovery operation. The energy dimensions required for capacitors of each MMC station are calculated. The proposed control strategies have been validated with an experimental setup of a four-terminal MMC based MTDC system developed in the simulation environment. The proposed control strategies envision a robust fault ride-through capability with reduced oscillations and total harmonic distortion (THD). Such a method is more reliable for an MTDC system than the classical solutions, which are based on drawing increased current from the grid or using additional circuitries. Moreover, the proposed control strategies can work efficiently for any MTDC system as compared to previously presented solutions, which are restricted to two-terminal HVDC systems.**

Keywords—Modular Multi-level Converter (MMC), Multi-terminal direct current (MTDC), Fault ride-through (FRT), Droop control and Power oscillation damping

I. INTRODUCTION

Word wide integration of renewable energy resources for electricity generation is increasing day by day [1]. With this rapid development, the demand for a secure and reliable high power transmission system is emerging [2]. High voltage direct current (HVDC) transmission system has been identified as the most reliable and economical solution to transmit the electric power [3]. Modular multi-level converter (MMC) has got much attention in recent years [4] due to its numerous advantages such as modularity, scalability, improved efficiency, reduced total harmonic distortion (THD) and fault blocking capability [5-7,33]. Today, several MMC based HVDC projects are commissioned globally, whereas some future projects are also under consideration [8]. China has started implementing MMC-based MTDC systems for the interconnection of offshore and asynchronous power systems [9]. It is expected that soon, China will emerge as the global leader of the MMC based MTDC systems.

There has been a long history of research work carried for AC faults in the power transmission system. For the MTDC systems, the protection against DC side faults has remained a significant focus area for researchers [10]. For the AC fault ride-through capability of the MTDC systems, various researchers, such as in [11-16], have proposed different control and protection strategies. The driving force behind these challenges is the strict requirement of fault ride-through for the safe operation of the grid during transients with minimum power outages [17]. However, in case of a fault, the associated risk of this requirement may be severe, including the power imbalance and increase of the DC bus voltage which can cause damage to the DC cable in case of symmetrical and asymmetrical faults [10]. In such conditions, fast control actions can compensate the imbalance in the DC voltage and the power [18]. Additionally, an MTDC system requires a high power quality supply with reduced THD when passive loads are fed from DC buses using inverters. A transient voltage dip, either single or three-phase, may cause severe damage to electrical equipment [19, 20].

There are two possible methods to control the DC bus voltage, i.e. the centralized DC voltage control and the distributed droop control. The centralized method requires a fast communication medium, while the droop control does not [13, 21]. The stability of the DC grid can be quickly achieved by the droop control because it can maintain the dc voltage at multiple converter stations [13]. The problems of DC voltage regulation and power oscillations in transients and voltage dips can be easily solved using the inherent property of power oscillation damping (POD) present in MMC converters [20, 22]. The energy stored in MMC converters can be utilized to mitigate such oscillations. Each arm of an MMC contains submodules connected with capacitors, which are suitable for releasing or absorbing the fluctuating active power [22]. In literature [23-27], different methods have been proposed for POD using the internal energy storage of an MMC. In [22], a detailed analysis for POD using MMC has been presented and validated. In [20], a control strategy was proposed to mitigate the transient voltage dips for a back-to-back MMC based HVDC system. The idea was to support the passive loads with the constant power using internal energy of the submodule capacitors of MMC in case of any transient voltage dip at the grid side. In [28], a VSC based MTDC system was analyzed to supply the high power demand with high quality. The idea was to allow higher currents flow during voltage transient dips. In [29], it was proposed that allowing two times the nominal current; a VSC based HVDC network can be protected during transient voltage dips. Several methods have been proposed in the literature to maintain the DC bus voltage and the power flow in HVDC systems during faults, but all those methods require additional circuitries [10, 30]. All these methods show good performance for power flow control when the fault occurs after inverter stations. However, they are slow to compensate the fault when it occurs at the ac side of the rectifier station. Additionally, there has been very little work carried out to mitigate the voltage dips for passive loads in HVDC systems. The solutions provided are usually based on drawing an increased current from the grid during fault to maintain the DC bus voltage. This intends to design an overrated converter, which is not an economical solution. In [20], the submodule capacitors are designed according to dedicated energy calculations required to mitigate the voltage dips. However, such a system is only limited for a back-to-back HVDC system, and only scenarios for voltage dip are analyzed.

To overcome the above-mentioned issues, in this article, the overall control architecture for rectifier and inverter stations has been proposed which is based on the decoupled control strategy. The proposed control architecture includes various control loops to provide DC voltage control and power oscillation damping. To test the reliability of the proposed control architecture, an MTDC system has been developed in a simulation environment using the average value model (AVM) of MMC [31]. The nearest level modulation (NLM) with N+1 level modulation strategy has been used for each MMC station [32]. The developed control architecture provides excellent fault ride-through capability for the MTDC systems. Additionally, it provides quick post fault recovery, following grid codes in case of grid side and load side deviations such as three phase transients and voltage sags. The utilization of inherent energy of submodules of MMC in the proposed solution reduces the overall cost and size of MMC as compared to previously presented classical solutions. In addition, the proposed solution ensures constant power delivery to the passive loads in an MTDC system with very low total harmonic distortion (THD), for output voltage and current of inverter stations.

The rest of the paper is organized as follows: Section II presents the development of control architecture for the MTDC system. In Section III, the reliability of the proposed control system has been tested under various transient conditions. Finally, section IV concludes the outcomes of the paper.

II. Development of the Proposed Control Architecture

The developed control architecture contains inner and outer control loops for the MMC rectifier and inverter stations, which are working as remote end converters to control and shape voltages and currents. The block diagrams for the developed control systems for the rectifier and the inverter stations are shown in fig. 1 and fig. 2, respectively.

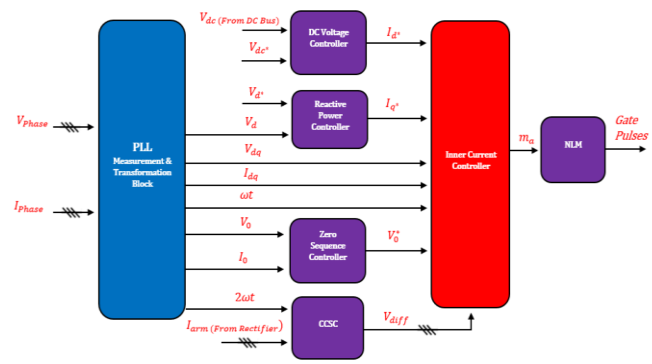


Fig. 1. Control system for rectifier station.

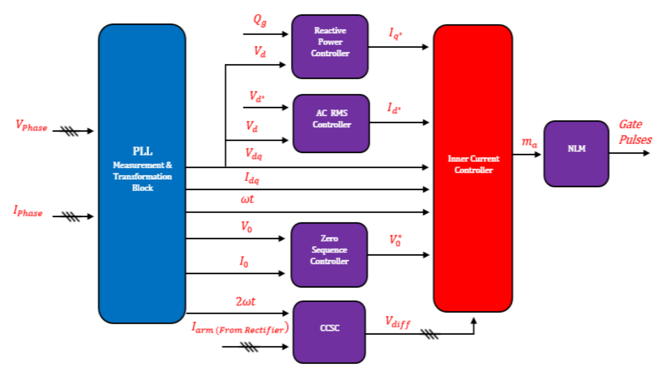


Fig. 2. Control system for inverter station

A. Vector Current Control

In this research work, a vector current control scheme has been adopted to provide the independent decoupled control of active and reactive power. The vector current control is a widely accepted control scheme for VSC based HVDC systems [37]. The vector current control scheme is simply referred as the current controller for the MMC. Hence, it finds core importance in the MMC control system. Following mathematical relationships are used to implement a vector current control [38]:

$$P_g = V_g^d I^d \tag{1}$$

$$Q_g = -V_g^d I^q \tag{2}$$

From equations (1) and (2), it is clear that the active power can be controlled using the d component of the current while the reactive power can be controlled using the q component of the current. This provides an independent decoupled control of the active and the reactive power in an MMC based MTDC system. The block diagram for the complete current controller (CC) is shown in fig. 3.

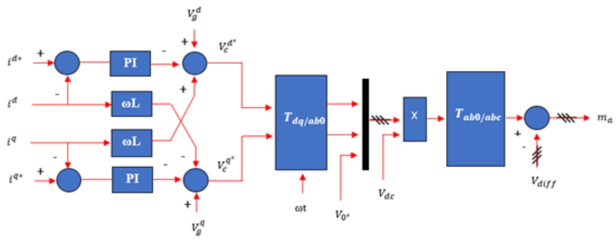


Fig. 3. Inner current controller.

B. *Energy Dimensioning of Submodules of MMC*

The MMC inhibits the internal submodule capacitors, which can exchange energy between the rectifier and the inverter station. The energy of submodule capacitors can be optimized for a safe discharge during transients to ensure constant power delivery to the loads. In industries, MMC converter stations are designed to have a total energy capacity of 30-40 kJ/MVA per converter station [36]. During the fault period, the converter should ensure nominal dc bus voltage with constant power delivery to the load. This can be realized by supplying the energy available in the capacitors of submodules of MMC. In this research work, the energy required to maintain the dc bus voltage is provided by the energy available in submodule capacitors. Energy dimensioning of submodule capacitors depends on the appropriate selection of capacitors so that the converter stations should not undergo over modulation in the worst case. To ensure the satisfactory operation of the HVDC system during transients, the submodule capacitance is increased to maintain the DC bus voltage at 0.8 p.u [45].

1) *Analysis of transients*

The analysis of various voltage dips in an HVDC system is presented in [19, 20]. Where, the dip severity for the recorded voltage dips is shown in a histogram with a distribution function, which is commonly used in statistics for random events and financial analysis. It is concluded from the data presented in [19, 20] that the most severe transient condition in the electrical grid is considered as the three-phase dip of 50 percent in voltage magnitude that lasts for 75 milliseconds. Based on the data presented for voltage dips in [19, 20, 45], the different voltage dip scenarios have been analyzed for a back-to-back MMC based HVDC system. It is suggested that considering the worst case of voltage dips i.e. 50 per cent dip in voltage magnitude for a duration of 75 milliseconds, the designed converter stations can also mitigate the effects of other three-phase transients located in the upstream network of converter stations. However, no such analysis has been provided in the results.

Considering the worst case of voltage dips as suggested by [19, 20] for converter energy dimensions, in this research work two types of transient conditions are analyzed for an MTDC system i.e. a three-phase dip at the grid side and a three-phase short circuit fault at the load side. The proposed energy dimensions for converter stations along with different control strategies have been tested for a four-terminal MMC based MTDC system.

2) *Energy required from submodule capacitors*

The product of the magnitude of dip and duration of dip is called dip severity.

$$Dip\ Severity = V_{dip} \times t_{dip} \tag{3}$$

The energy for any electrical system is calculated by

$$E = p \times t = I \times v \times t \tag{4}$$

Substituting equation (3) into equation (4) will give the relationship for missing energy in the system, which must be compensated by the submodule capacitors of MMC.

$$E_{missing} = I_{dip} \times V_{dip} \times t_{dip} \tag{5}$$

Using equation (5), the missing energy caused by any transient can be calculated. Considering the worst-case i.e. a three-phase dip of 50 percent in magnitude, which lasts for 75 milliseconds, knowing the fact that the rectifier, will draw nominal current i.e. 1 p.u from the grid during any transient the missing energy in p.u will be

$$E_{missing} = 1 \times 0.5 \times 0.075 = 0.0375\ p.u \tag{6}$$

The energy of every submodule is given by

$$E_{Supplied\ by\ capacitors} = \frac{1}{2} cv^2 \tag{7}$$

The amount of energy required from capacitors of submodules of MMC depends upon the safe operation of the converter without going in over modulation. This is decided by the steady-state modulation index of the inverter, which is 0.8 p.u. While maintaining a modulation index of 0.8 p.u, the inverter would allow DC voltage to be dropped up to 0.8 p.u without disturbing the power quality [20]. Thus, the capacitors can discharge from 1 p.u to 0.8 p.u to supply the required amount of energy. From equation (7), it can be concluded that the energy supplied from 1 p.u to 0.8 p.u of the DC voltage is 36% of the available energy in the capacitors.

$$E_{missing} = 0.36 \times E_{Supplied\ by\ capacitors} \tag{8}$$

From equation (8), the required amount of energy from capacitors of submodules can be calculated as:

$$E_{supplied\ by\ capacitors} = E_{missing}/0.36 = 2.77 E_{missing} \tag{9}$$

From equation (9), it is clear that to provide a sufficient amount of energy, the installed energy capacity must be 2.77 times the missing energy caused by the transient. This requires that the submodule capacitors of the converter station be designed to have an energy supply capability of 0.103875p.u (2.77×0.0375). With this, the total energy supply required for a 1 MVA converter station should be 104kJ/MVA [20]. Following this standard, the submodule capacitors inside each converter station in this research work is designed to have a total energy supply capability of 22.8 MJ/MVA. With this, the total energy required from submodule capacitors to provide efficient energy support for a four-terminal MMC based MTDC system becomes 91.2 MJ/MVA.

III. Results and Discussions

A. *Experimental Setup*

In this research work, a four-terminal MMC based MTDC system based on parallel connection is simulated as an experimental case to analyze the performance of the developed control architecture. The parallel connection is the most popular one due to its simplicity, reliability and expandability [35]. The simulated system consists four MMC converter stations connected with two AC grids and two passive load centers. The single line diagram of the developed system is shown in fig. 4, where the passive loads are simulated using linear and non-linear loads. Parameters of the MTDC system are shown in table I.

TABLE I. Parameters of MTDC System

Quantity	Value
Arm Inductance	0.15 p.u
Arm Resistance	0.03 ohm
Submodule Capacitance	10.4 mF
DC Bus Voltage	135 kV
Frequency	50 Hz
X/R Ratio of Grid	14.28
Transformer 1 & 3 (Y-Y)	220 MVA
Transformer 2 & 4 (Y-D)	220 MVA
MMC Stations	220 MVA

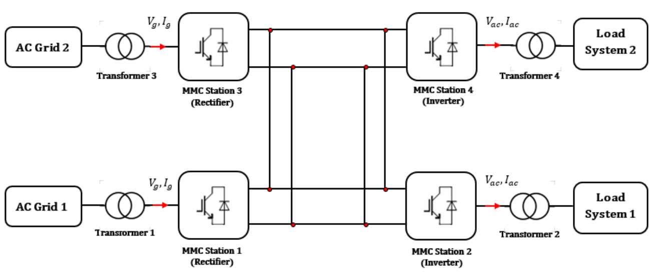
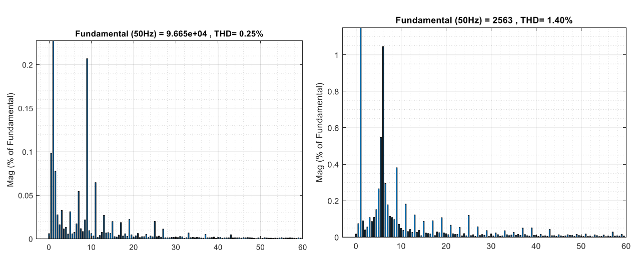


Fig. 4. Layout for proposed experimental setup.

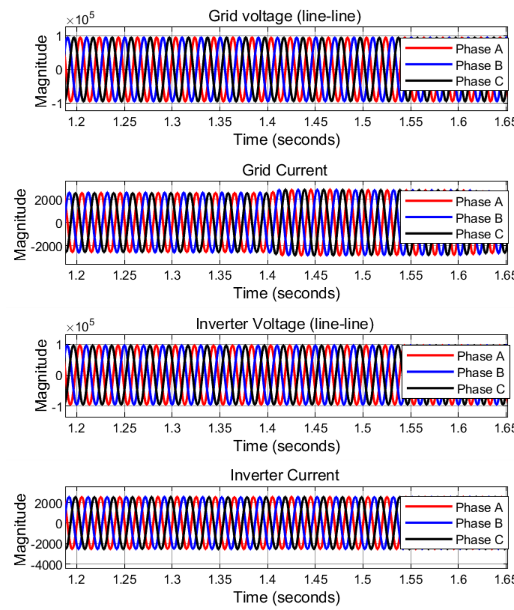


(a) (b)

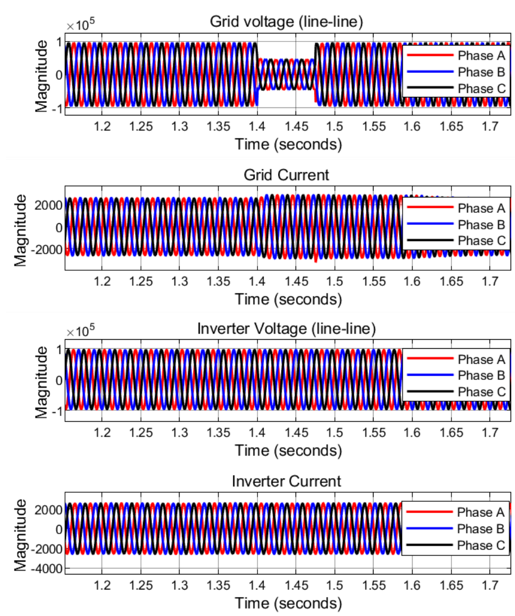
Fig. 5. Results for THD (a) Output voltage (b) Output current.

In the developed control architecture, all controllers are designed so that the MTDC system reaches in steady-state condition by 1 second approximately. In this research work, the simulation results are discussed in detail for the two cases, (I) three-phase dip applied at the grid side converter and (II) three-phase fault applied at the load side converter. However, the behaviour of the developed system for the steady-state condition can be observed in the simulation results presented in section B before applying the fault condition. After reaching steady-state condition, the active power and the DC bus voltages for all converter stations are set to 1 p.u with a modulation index of 0.8 p.u. The THD for output voltage and current for MMC stations working as inverters is measured as 0.25% and 1.40 %, respectively, which is shown in fig. 5, ensuring IEEE standards.

B. *Case I: Simulation Results for Three Phase Dip at AC Grid 2 Connected to MMC 3*



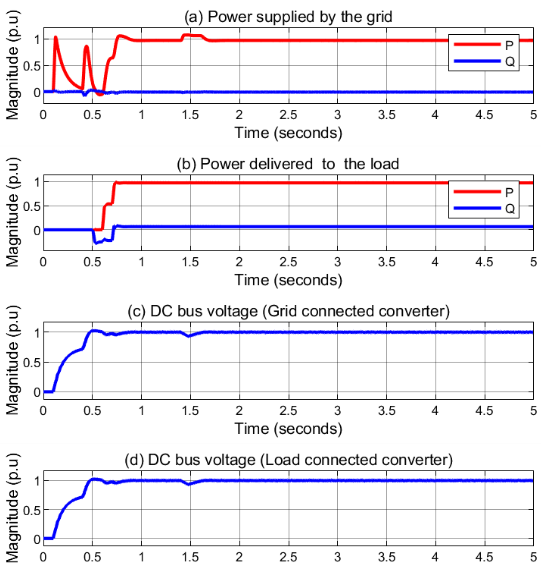
(a)



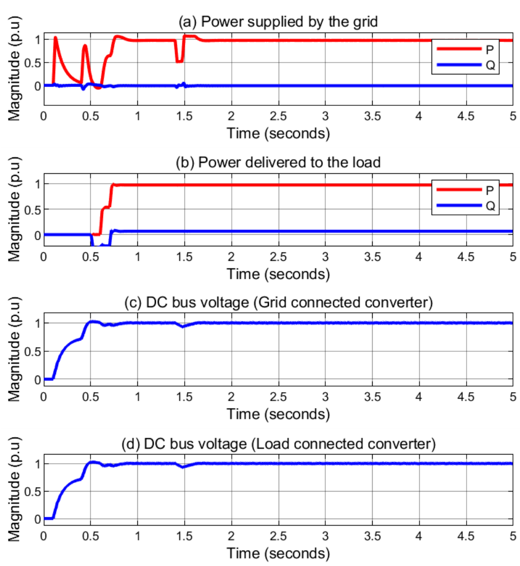
(b)

Fig. 6. Sinusoidal voltages and currents for all MMC stations (a) MMC 1 and MMC 2 (b) MMC 3 and MMC 4.

In this section, a three-phase voltage dip has been applied at the AC grid 2 to analyze the performance of developed control architecture. The three-phase dip is switched at t = 1.4 seconds and it lasts over 75 milliseconds with a magnitude of dip = 0.5 p.u. Fig. 6 shows the simulation results for the sinusoidal voltages and the currents for all MMC stations. It can be observed that only MMC 3, which is connected to the AC grid 2, is affected with a 50 percent decrease in its voltage magnitude and a slight increase of 0.05 p.u in its current. Such slight increment can be easily handled by the converter station. The sinusoidal voltages and currents of MMC 1, MMC2 and MMC 4 are not affected by the presence of dip at MMC 3.



(a)

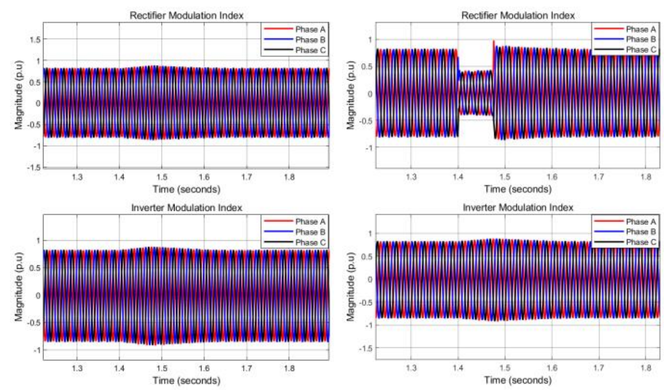


(b)

Fig. 7. Power and DC bus voltages for all MMC stations (a) MMC 1 (b) MMC 2 (c) MMC 3 (d) MMC 4

Fig. 7 shows simulation results for the active & reactive power and DC bus voltages for all MMC stations. It can be observed that during the dip, the active power delivered by MMC 3 is reduced to half, which causes a small drop of 0.2 p.u in the DC bus voltages of all MMC stations. This ensures that converters are dimensioned properly maintaining a DC bus voltage of 0.8 p.u during the dip. During this period, the energy available in the capacitors of MMCs is discharged to maintain the constant power delivery to both load systems, which are connected to MMC 2 and MMC 4.

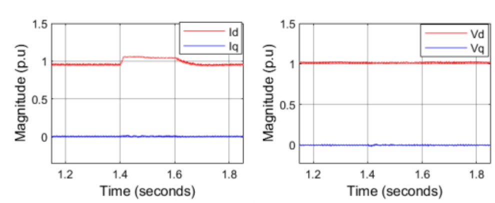
Fig. 8 shows the simulation results for the modulation index of all MMC stations. It can be observed that the modulation index for MMC 3 is reduced during the dip, which ensures that the MMC station is trying to draw the nominal current from grid during dip. While other converter stations have a small increase of 0.1 p.u in their modulation index, which does not contribute significantly in the submodule voltages and currents. However, in post fault recovery operation, all converter stations achieve the modulation index of 0.8 p.u.



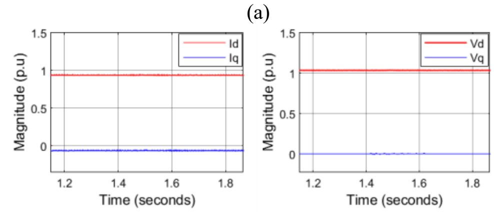
(a) (b)

Fig. 8. Modulation index for all MMC stations (a) MMC 1 and MMC 2 (b) MMC 3 and MMC 4.

Fig. 9 shows the results for the voltages and currents for all MMC stations transformed into dq quantities. Fig. 9 (b) and (d) show simulation results for the voltages and currents for MMC 2 and MMC 4 respectively. It can be observed that they are not affected by the presence of dip and ensure smooth delivery of power to the connected load systems. From fig. 9 (a) and (c) it can be observed that during dip converters extract maximum energy from both grids to charge their submodules and maintain DC bus voltages to 1 p.u in post fault recovery operation, which can be witnessed in fig. 7.



(a)



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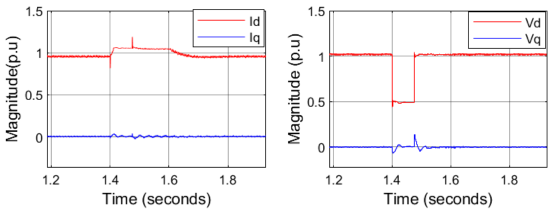

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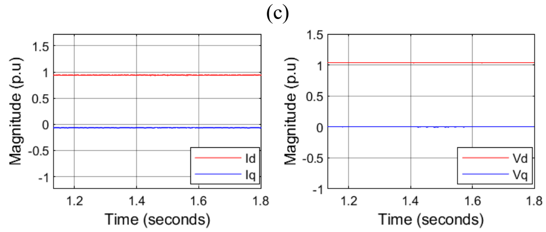
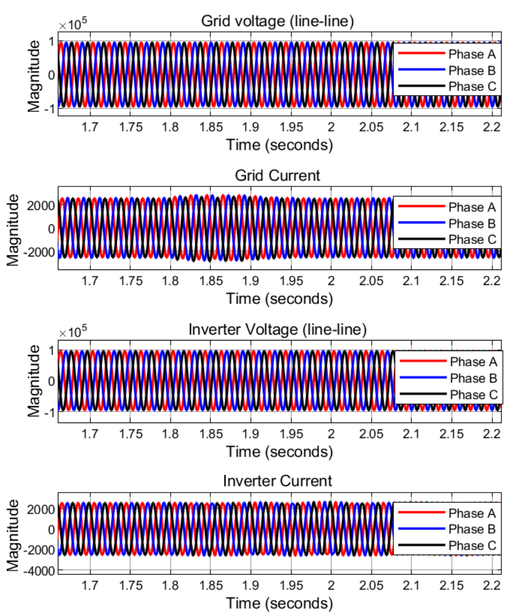


(d)

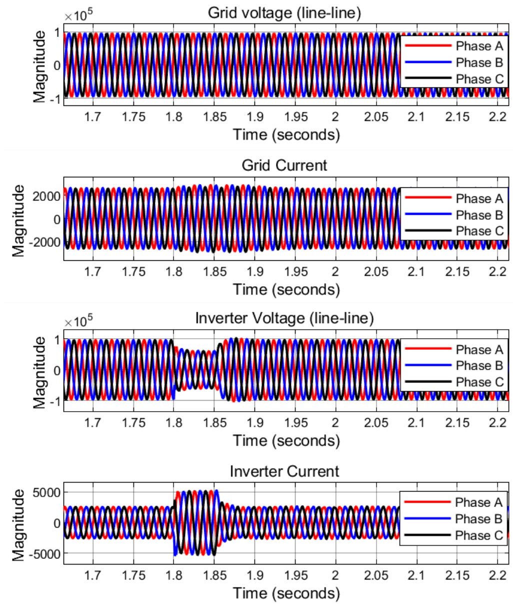
Fig. 9. Currents and voltages in dq axis for all MMC stations (a) MMC 1 (b) MMC 2 (c) MMC 3 (d) MMC 4

C. *Case II: Simulation Results for Three-Phase Fault at Load System 2 Connected to MMC 4*

To analyze the performance of the developed system w.r.t the load side deviations, a three phase symmetrical fault has been simulated at the load system 2 in this section. The duration of the simulated fault is 50 milli seconds. As compared to previously simulated dip at the grid side converter, the scenario for the load side fault is bit different. Fig. 10 show the simulation results for the sinusoidal voltages and currents for all MMC stations, where the available voltage at MMC 4 reduces with an increment in its sinusoidal current. However, MMC 2 ensures smooth power delivery to the load system 1 with no dip in its sinusoidal voltage and current. The sinusoidal voltages and currents for MMC 1 and MMC 3 ensures smooth delivery of power from both grids irrespective of the fault present at MMC 4.



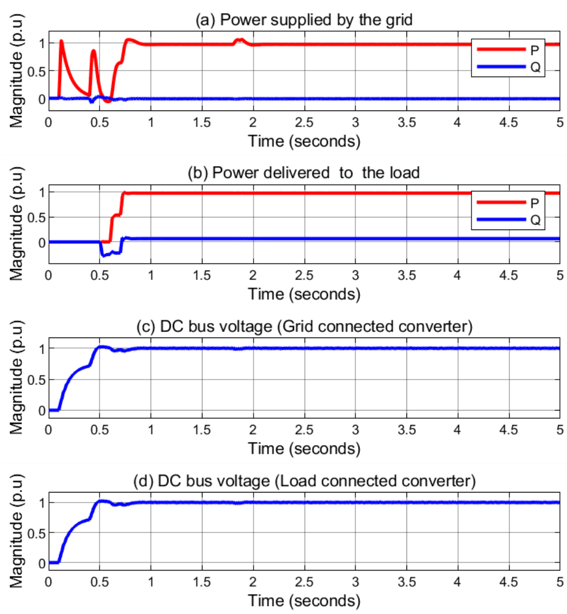
(a)



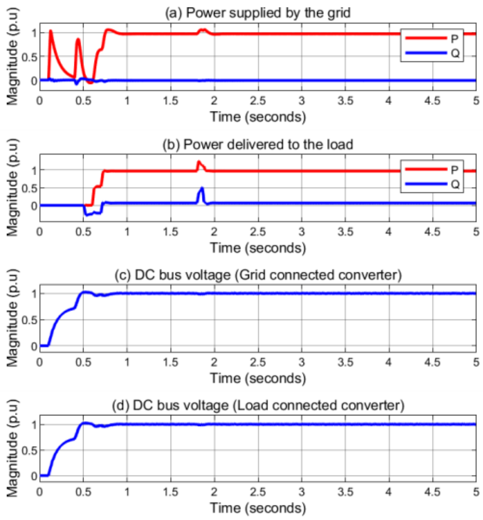
(b)

Fig. 10. Sinusoidal voltages and currents for all MMC stations (a) MMC 1 and MMC 2 (b) MMC 3 and MMC 4

Fig. 11 shows the simulation results for the active & the reactive power and the DC bus voltages for all MMC stations. It can be observed that the DC bus voltages for all MMC stations doesn't have any significant effect during the load side fault and contain a small deviation of 0.05 p.u. Moreover, the power delivered to the load system 1 through MMC 2 remains constant irrespective of the fault present at the MMC 4. During the fault period, the active power supplied by AC grid 1 and AC grid 2 through MMC 1 and MMC 3 slightly increases which in turn helps to maintain the DC bus voltage to 1 p.u in post fault recovery operation.



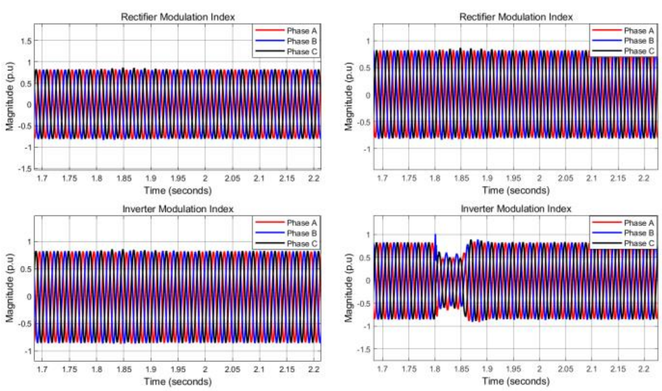
(a)



(b)

Fig. 11. Power and DC bus voltages for all MMC stations (a) MMC 1 and MMC 2 (b) MMC 3 and MMC 4.

The modulation index for all MMC stations as shown in fig. 12 ensures the safe operation of MMC 1, MMC 2 and MMC 3 during the fault condition, maintaining a modulation index of 0.8. However, the modulation index of MMC 4 slightly decreases adopting the fault and retains to its normal value in post fault recovery operation.

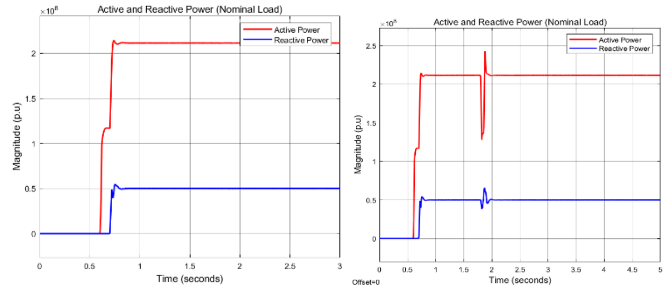


(a) (b)

Fig. 12. Modulation index for all MMC stations (a) MMC 1 and MMC 2 (b) MMC 3 and MMC 4.

As discussed in section 3, each load system contains linear and non-linear loads. The simulation results for active and reactive power of the loads connected to MMC 2 and MMC 4 are shown in fig. 13.

It can be observed from fig. 13 (a) that the active and reactive power delivery to the load connected to MMC 2 remains constant irrespective of the fault present at MMC 4. However, due to the presence of the fault, the active and reactive power delivery to the load connected to the MMC 4 is affected as seen in fig. 13 (b). During the fault period, MMC 1 and MMC 3 tries to extract maximum energy from both grids. This in turn recovers the system in stable condition in post fault operation and maintains the active and reactive power delivery to both load systems as per their requirement.



(a) (b)

Fig. 13. Results for active and reactive power for load (a) P & Q for load connected to MMC 2 (b) P & Q for load connected to MMC 4.

From the above-detailed discussions, it is clear that the developed system possesses excellent fault ride -through capability, maintaining a dc bus voltage of 0.8 p.u using droop control. The proposed solution ensures constant power delivery to the loads in case of transients, without taking any excessive current from the grid. This leads to designing MMC stations as per normal operating conditions without using additional circuitry. The proposed solution envision robust performance by maintaining the lowest THD values. The classical solutions based on energy utilization of submodule capacitors of MMC are only limited to a particular number of terminals in an HVDC system. However, the proposed control strategies can effectively work for any MTDC system maintaining a modulation index of 0.8 p.u for all converter stations.

IV. Conclusion

This research work develops a decoupled control strategy to address the reliability and safety concerns of the MMC based MTDC systems. The performance of the developed control strategies has been tested in a four-terminal MTDC system under various operating scenarios such as three-phase transients and voltage dips. More specifically, the simulation results show that the developed control strategies can effectively control the DC bus voltage, ensuring constant power delivery to the connected loads during AC side faults. Moreover, the paper explores the possibility of utilization of internal energy of submodules of MMC to reduce the power oscillations to the connected AC grids in case of transients & voltage dips and ensures quick post fault recovery operation. In future studies, such system will be extended and tested with the integration of renewable energy resources. In the future, the performance of proposed control strategies will be analyzed in hardware in loop setup.

References

[1] European Wind Energy Association. Pure power-wind energy targets for 2020 and 2030 (2011) European Wind Energy Association Report. Brussels; [online]. Available at: http://www.ewea.org

[2] Liu M, Li Z, and Yang X (2020) A universal mathematical model of modular multilevel converter with half-bridge. Energies, 13(17), p.4464.

[3] Moreira, CL and Silva B (2014) Operation and control of multiterminal HVDC grids for AC Fault Ride Through compatibility. In 2014 IEEE International Energy Conference (ENERGYCON) (pp. 287-294). IEEE.

[4] Liu, C, Lin X, Li H, et al (2014) Sub-module component developed in CBuilder for MMC control and protection test in RTDS. International Journal of Electrical Power & Energy Systems, 56, pp.198-208.

[5] Raju MN, Sreedevi J, Mandi RP, et al (2019) Modular multilevel converters technology: a comprehensive study on its topologies,

modelling, control and applications. IET Power Electronics, 12(2), pp.149-169.

[6] Kouro S, Malinowski M, Gopakumar K, et al (2010) Recent advances and industrial applications of multilevel converters. IEEE Transactions on industrial electronics, 57(8), pp.2553-2580.

[7] Debnath S, Qin J, Bahrani B, et al (2014) Operation, control, and applications of the modular multilevel converter: A review. IEEE transactions on power electronics, 30(1), pp.37-53.

[8] Qin B, Liu W, Zhang R, et al (2020) Review on short-circuit current analysis and suppression techniques for MMC-HVDC transmission systems. Applied Sciences, 10(19), p.6769.

[9] Qin B, Li H, Zhou X, et al (2020) Low-voltage ride-through techniques in DFIG-based wind turbines: a review. Applied Sciences, 10(6), p.2154.

[10] Tzelepis D, Rousis AO, Dyśko A, et al (2017) A new fault-ride-through strategy for MTDC networks incorporating wind farms and modular multi-level converters. International Journal of Electrical Power & Energy Systems, 92, pp.104-113.

[11] Xin Y, LouW, Li G, et al (2021) AC fault ride-through coordinated control strategy of LCC-MMC hybrid DC transmission system connected to passive networks. International Journal of Electrical Power & Energy Systems, 131, p.107076.

[12] Shah R, Islam S, et al (2020) Impact of MMC-HVDC Control Parameter Selection on the Dynamic Performance of AC System. In 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD) (pp. 1-2). IEEE.

[13] Malanda, SC, Davidson, IE and Adam GA, (2020) Comparison of DC voltage Control Strategies for Multi-terminal HVDC Network during AC Faults. In 2020 International SAUPEC/RobMech/PRASA Conference (pp. 1-6). IEEE.

[14] Luscan B, Bacha S, Benchaib A, Bertinato A, et al (2020) A vision of HVDC key role towards fault-tolerant and stable AC/DC grids. IEEE Journal of Emerging and Selected Topics in Power Electronics. (Early access version)

[15] Zhou Z, Chen Z, Wang X, Du D, et al (2019) AC fault ride through control strategy on inverter side of hybrid HVDC transmission systems. Journal of Modern Power Systems and Clean Energy, 7(5), pp.1129-1141.

[16] Cheng F, Yao L, Xu J, et al (2021) A new AC fault ride-through strategy for HVDC link with serial connected LCC-VSC hybrid inverter. CSEE Journal of Power and Energy Systems. (Early access version)

[17] Tsili M and Papathanassiou S (2009) A review of grid code technical requirements for wind farms. IET Renewable power generation, 3(3), pp.308-332.

[18] Wang H, Wang Y, Duan G, et al (2017) An Improved Droop Control Method for Multi-Terminal VSC-HVDC Converter Stations, Energies, vol. 10, no. 7, p. 843,.

[19] Slettbakk, TE (2018) Development of a Power Quality Conditioning System for Particle Accelerators. PhD dissertation, Norwegian University of science and Technology,.

[20] Hoehn T, Slettbakk TE, Blanquez F, et al (2019) Back-to-Back HVDC Modular Multilevel Converter for Transient Voltage Dip Mitigation in Passive Networks. In 21st European Conference on Power Electronics and Applications (EPE'19 ECCE Europe) (pp. P-1). IEEE.

[21] Malanda SC, Davidson IE and Adam GA, (2020) Comparison of DC voltage Control Strategies for Multi-terminal HVDC Network during AC Faults. In 2020 International SAUPEC/RobMech/PRASA Conference (pp. 1-6). IEEE.

[22] Taffese Abel A, Atsede G, Salvatore D'Arco, et al (2020) Power oscillation damping with virtual capacitance support from modular multilevel converters. IET Renewable Power Generation 14, no. 5: 897-905.

[23] Barker CD, Whitehouse RS, Adamczyk AG, et al (2017) Low frequency active power oscillation damping using a MMC-VSC HVDC link'. 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Manchester,UK, pp. 1–6

[24] Taffese AA, Tedeschi E and de Jong E (2017) A control scheme for utilizing energy storage of the modular multilevel converter for power oscillation damping. IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL), Stanford, CA, USA, 2017, pp. 1–8

[25] Taffese AA and Tedeschi E (2018) Coordination of modular multilevel converter based HVDC terminals for ancillary services. 2018 Power Systems Computation Conf. (PSCC), Dublin, Ireland, pp. 1–7

[26] Freytes J, Akkari S, Rault P, et al (2018) Dynamic analysis of MMC-based MTDC grids: Use of MMC energy to improve voltage behavior. IEEE transactions on power delivery, 34(1), pp.137-148.

[27] Trinh NT, Erlich I and Teeuwsen SP (2014) Methods for utilization of MMCVSC- HVDC for power oscillation damping'. 2014 IEEE PES General Meeting | Conf. Exposition, National Harbor, MD, USA, 2014, pp. 1–5

[28] Lu W and Ooi BT (2005) Premium quality Power Park based on multi-terminal HVDC. IEEE Transactions on Power Delivery, 20(2), pp.978-983.

[29] Du C, Bollen MH, Agneholm E, et al (2007) A new control strategy of a VSC–HVDC system for high-quality supply of industrial plants. IEEE Transactions on Power Delivery, 22(4), pp.2386-2394.

[30] Feltes C, Wrede H, Koch FW, et al (2009) Enhanced fault ride-through method for wind farms connected to the grid through VSC-based HVDC transmission. IEEE Transactions on Power Systems, 24(3), pp.1537-1546.

[31] Peralta J, Saad H, Dennetière S, et al (2012) Detailed and averaged models for a 401-level MMC–HVDC system. IEEE Transactions on Power Delivery, 27(3), pp.1501-1508.

[32] Hu, Pengfei, and Daozhuo Jiang (2014) A level-increased nearest level modulation method for modular multilevel converters, IEEE Transactions on Power Electronics 30, no. 4 : 1836-1842.

[33] Khan SS and Tedeschi E (2017) Modeling of MMC for fast and accurate simulation of electromagnetic transients: A review. Energies, 10(8), p.1161.

[34] Gomis-Bellmunt O, Liang J, Ekanayake J, et al (2011) Topologies of multiterminal HVDC-VSC transmission for large offshore wind farms, Electric Power Systems Research, vol. 81, no. 2, pp. 271-281.

[35] Meng X, Li KJ, Wang Z, et al (2015) A hybrid MMC topology with DC fault ride through capability for MTDC transmission system, Mathematical Problems in Engineering. Hindawi, vol. 2015, pp. 1–11, 2015.

[36] Jacobson B, Karlsson P, Asplun G, et al (2010) VSC-HVDC transmission with cascaded two-level converters. In CIGRE session (pp. B4-B110).

[37] Harnefors L, Bongiorno M and Lundberg S (2007) Input-admittance calculation and shaping for controlled voltage-source converters. IEEE transactions on industrial electronics, 54(6), pp.3323-3334.

[38] Stamatiou G (2016) Analysis of VSC-based HVDC systems, PhD thesis, Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden..

[39] Harnefors L (1997) On analysis, control and estimation of variable-speed drives, Ph.D. dissertation, Royal Institute of Technology, Stockholm, Sweden.

[40] Ji H, Chen A, Liu Q, et al (2017) A new circulating current suppressing control strategy for modular multilevel converters. In 2017 36th Chinese Control Conference (CCC) (pp. 9151-9156). IEEE.

[41] Li S, Wang X, Yao Z, et al (2014) Circulating current suppressing strategy for MMC-HVDC based on non-ideal proportional resonant controllers under unbalanced grid conditions. IEEE Transactions on Power Electronics, 30(1), pp.387-397.

[42] Tu Q, Xu Z, and Xu L (2011) Reduced switching-frequency modulation and circulating current suppression for modular multilevel converters. IEEE transactions on power delivery, 26(3), pp.2009.

[43] Ma K, Chen W, Liserre M, et al (2014) Power controllability of a three-phase converter with an unbalanced AC source. IEEE Transactions on Power Electronics, 30(3), pp.1591-1604.

[44] Colmenero, M., Blanquez, F.R. and Kahle, K., 2020, September. Transient Voltage Dip Mitigation System Based On Hybrid Modular Multilevel Converters. In 2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe) (pp. P-1). IEEE.