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Offshore Integrated MMC Based HVDC System

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Abstract: The modular multilevel converter (MMC) provides promising development for high-voltage direct current(HVDC) applications, including multi terminal HVDC (MTDC) and renewable energy integration. This paper, considering an offshore wind farm (OWF) integrated MMC MTDC system, investigates its start-up process with three main developments: 1) it further develops the mathematical model of MTDC with active networks and proposes a hierarchical start-up control scheme; 2) for the terminal which connects the OWF, it proposes a reduced dc voltage control scheme of mitigating the current surges with deblocking the converter at zero voltage difference on submodules (SMs) and proposes an overall sequential start-up control scheme for the offshore integrated MTDC; and 3) it analyzes and compares different start-up control schemes. To evaluate the proposed sequential start-up control scheme, an offshore MMC HVDC system is established on the RTDS. The simulation results verify effectiveness of the proposed scheme on the MMC MTDC system with two control paradigms, i.e., master–slave control and droop control, respectively. In comparison with different start-up control schemes, the superiority of the mitigation of voltage spikes and current surges are shown using the proposed scheme with less complexity and easier implementation.

Keywords: Droop Control, Master–Slave Control, Modular Multilevel Converter (MMC), Multiterminal HVDC (MTDC), Offshore Wind Farm (OWF), Sequential Start-Up Control.

I. INTRODUCTION

Now it is fully confidential that there is no exaggeration to say that HVDC technology was introduced as a response to the need of having a more efficient and flexible transmission system. This need became more important especially due to increase in electricity demand and number of the renewable energy sources connected to the grid such as wind power sources. HVDC system has been conventionally used to interconnect two AC power systems working either at two different frequencies or at the same frequency but without being synchronized. It is also used as a way of delivering electric power between two distant points through overhead transmission lines or submarine cables. Another feature of HVDC systems which made them to be put into service in parallel with the AC transmission systems is capability of rapidly control on the transferred power. Alternating Current(AC) system suffer so call called line losses that can range from 10-15%, but HVDC line losses are closer to just 2 %. HVDC system are 100% controllable the power will only go where you want it to go, where as AC systems flow sometimes in unpredictable ways, an attribute that contributes to rolling blackout or brownouts. In this way, HVDC systems can act like firewells, limiting grid disturbance to small geographical area. The small short circuit ratio of wind farms and fast power flow reversal requirement lead to use transistor-based converters commonly named Voltage Source Converters (VSC) instead of conventional thyristor-based Line Commutated Converters.

Modular Multilevel Converter (MMC) structure is a recent advance in the field of HVDC power transmission, which consists in a VSC using a modular approach. It will definitively push VSC topology to the best alternative. The term multi-terminal HVDC mainly refers to an HVDC topology in which the DC buses of three or more HVDC converters are connected to a common DC grid regardless of whether the associated AC grids are synchronous or not. Similar to AC power grids, the intention of establishing HVDC grids, which is multi-terminal DC grids, will naturally emerge when the technology of HVDC grows to a high maturity. This is because in comparison with the traditional 2-terminal HVDC link, MTDC has higher utilization of DC lines, higher reliability of power supply and the DC network becomes more flexible. For example, when a permanent fault occurs in an MTDC grid, with effective control and protection actions, the unfaulted terminals may keep operation without interruption. However, for the same fault occurring in a 2-terminal HVDC grid, it may cause the interruption of the whole HVDC network. In comparison with the LCC technology, the VSC technology is more appropriate for the applications of MTDC. This is due to its flexible control characteristics and the fact that the power flow reversal can be easily achieved by reversing the direction of DC currents without the need to change the polarity of the DC voltage. Compared with the traditional VSC, the use of MMC is considered to be more attractive for MTDC applications, due to its inherent characteristics and low failure rates.

In a three-terminal MMC HVDC system based on a real application was investigated, and a control procedure of starting the system was proposed in detail. However, these

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procedures were obtained as a conceptual approach, which was based on the analysis at systematic level. There was no analysis on the dynamics of the SMs in the MMC with no comprehensive simulation results. Different sequential startup control was compared in while most comparisons were based on simulations and the analysis was not comprehensive with no mathematical derivations. Hence, the startup control including the startup sequence of MMC MTDC systems deserves our study and exploration. This paper investigates the start-up process of an OWF integrated MMC MTDC system with the main contributions given as follows. 1) Regarding an MMC MTDC system with active ac networks, the mathematical model before and after the deblocking of the converter is further developed on into a second-order circuit with the consideration of the converter arm inductor. A hierarchical start-up control scheme is proposed. Considering the fact that an OWF is a passive ac network before the completion of its start-up, a start-up control strategy for the converter connecting with the OWF with deblocking the converter at zero voltage difference on SMs is proposed; 2) A four-terminal MMC HVDC system is established on the RTDS with one terminal connecting with an OWF. The effectiveness of the proposed sequential start-up control scheme is verified by the simulation results. The superiority of the proposed scheme, in terms of mitigating the voltage spikes and current surges, than other control schemes is compared, and the easy implementation of the proposed scheme is presented; 3) The proposed start-up control scheme is validated on the MMC MTDC system with master–slave control and droop control, respectively.

II. SYSTEM MODELING

Fig1 shows a single-line schematic diagram of an MMC MTDC system with the integration of an OWF. Both the offshore and onshore MMCs connect to the ac power sources, either the OWF or ac utility grids, through a three-phase transformer. The MTDC network can be in either radial or meshed arrangement. For the sake of simplicity, the MTDC investigated in this paper is in radial connection only.

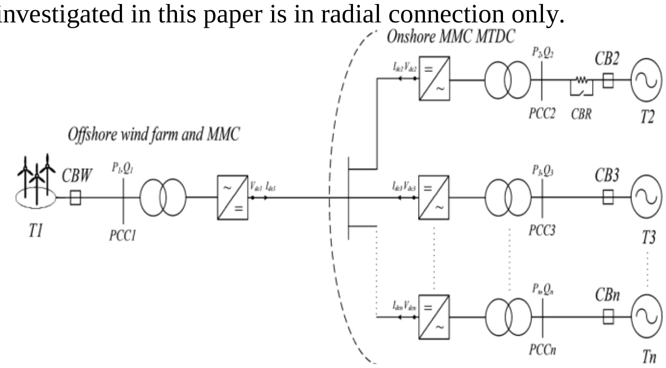


Fig. 1. MMC MTDC system with the integration of an OWF.

Fig. 2 depicts the structure of one MMC and one SM within the MMC. Each MMC consists of three parallel-connected phase units where each phase unit comprises two arms. Each arm is composed of one arm inductor and series-connected, identical half-bridge SMs. The arm inductor is designed to provide current control and limit the circulating current within the arm and to limit fault currents. A SM has three switching states, block (BLK), ON, and OFF. The SM is blocked either in the standby mode or under fault conditions. Under nominal conditions, each SM is either switched ON or OFF. In the ON state, the upper IGBT (S1) is switched on and the lower one (S2) is switched off, the voltage of the SM equals to the capacitor voltage. In the OFF state, S1 is switched off and S2 is switched on, the capacitor is bypassed. At the initial stage before the start-up of the system, the MMC is in standby mode with all SMs being blocked.

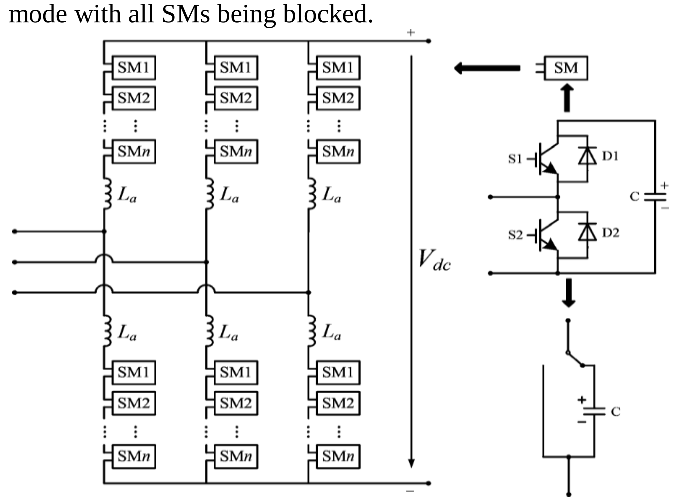


Fig. 2. Structure of one MMC and a SM.

Controlling the direct voltage inside a MTDC transmission system is equivalent to controlling the frequency in ac networks. A well-controlled direct voltage on a HVDC transmission network means the power is balanced amongst all nodes. Usually, the control of point-to-point HVDC transmission systems is arranged as follows: one terminal controls the dc network voltage, whereas the other operates in current or power regulation mode. This control philosophy of having only one converter controlling the direct voltage can also be extended to MTDC networks, as in the voltage margin method. However, as the MTDC network grows in size and complexity, having only one terminal responsible for voltage regulation makes it increasingly difficult to guarantee the power balance in the network. Hence, for large MTDC networks, it is not recommended to control the direct voltage at a sole terminal. A more suitable control strategy is to have several terminals responsible for controlling the direct voltage inside the MTDC network. This increases reliability by adding redundancy and provides the possibility to control the dc power flow. The distributed voltage control (DVC) method assigns each dc-voltage-controlling VSC terminal with a specific voltage set-point. In this way, the MTDC network voltage control is distributed amongst several nodes and any feasible load-flow scenario can be accomplished. In addition, no single converter assumes alone the responsibility of balancing the power inside the transmission system.

The MTDC investigated in this paper is a four-terminal MMC HVDC system. For the offshore terminal, T1, the active power transferred is determined by the control of the DFIG-based OWF. Hence, MMC-1 applies ac voltage and frequency control to stabilize the voltage magnitude and frequency at PCC1. For the onshore MTDC terminals, the MMCs are connected with active AC networks which can provide stable ac voltage at the PCC and active power to the connected MMC. The well-known dq decoupled control is applied. For MMC MTDC systems, two main control paradigms, i.e., master–slave control and droop control, are generally used. For the master–slave control, one terminal is operated as the master terminal with constant dc voltage control, while the other terminals are operated as slave terminals with constant active power control. For the droop control, active power can be shared among different HVDC terminals. The following analysis on the start-up control will be conducted based on the system with master–slave control in which T2 is operated as the master terminal, while the other three terminals are operated as slave terminals. Reactive power control is applied by T2, T3 and T4 to control the reactive power at 0. The control strategy of each terminal is shown in Table I. The proposed start-up control will be validated on the system with master-slave control and droop control, respectively, in the case studies. At the initial state, all of the capacitors within the MMCs are not charged and the voltage of the MTDC system is not established. During the period from the initial state to the steady state, in order to realize the start-up of the MTDC with small voltage spikes and current surges, the start-up process is divided into several stages rather than starting all terminals simultaneously.

TABLE I: Control Strategy Of The MTDC With Master–Slave Control

Offshore MMC	**Control Strategy**	
MMC-1	V_{ac}, f	
Onshore MMC	***d*-axis**	***q*-axis**
MMC-2	V_{dc}	Q
MMC-3	P	Q
MMC-4	P	Q

For T1, the start-up of the OWF necessitates a stable nominal AC voltage at PCC1. The establishment of the AC voltage relies on the inverted control of MMC-1 of the DC voltage. Hence, the start-up of T1 should be initiated after the start-up of T2 with a well-stabilized MTDC voltage. As for T2, it not only stabilizes the MTDC voltage, but also acts as a dc slack bus to balance the active power of the MTDC system. The active power transferred at T2 should be within its maximum rating. If the active power flow is not well regulated during the start-up period and is significantly over its transfer capability, it may affect the stabilization of the DC voltage controlled at T2 and there will be subsequent impact on the system performance. In addition, T1 with OWF is a weaker network compared with T3 and T4 with active ac networks. Hence, the coordinated start-up sequence plays a significant role in the start-up of the system and needs to be comprehensively investigated. Based on the previous analysis, a hierarchical start-up control scheme for the MMC terminal with active ac network is proposed.

Step 0: Initially, set the dc voltage reference to

Step 1: close the ac circuit breaker and charge the voltage of the SM capacitor;

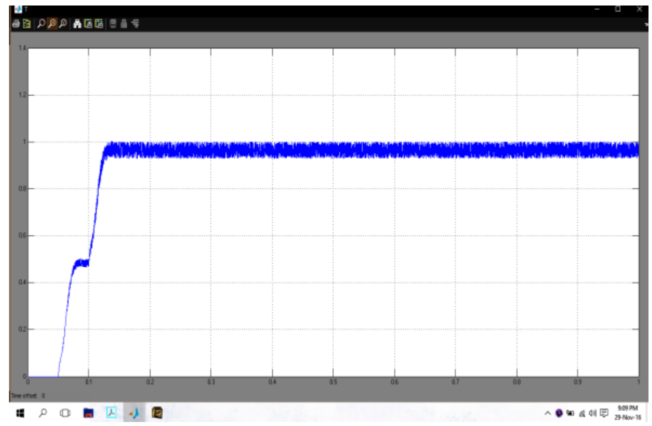
Step 2: deblock the MMC;

Step 3: When the dc voltage is stably controlled, ramp the dc voltage reference to the nominal value to complete the start-up.

If the wind farm connected MMC is deblocked directly, there must be a current surge due to the SM voltage difference at the deblocking instant. Therefore, in order to reduce the voltage difference at the deblocking stage, the controlled dc voltage is regulated to a reduced value, which is named as reduced dc voltage control scheme.

III. SIMULATION RESULTS

In order to verify the effectiveness of the proposed scheme, a four-terminal MMC HVDC system with one terminal connected with an OWF is established on the RTDS.



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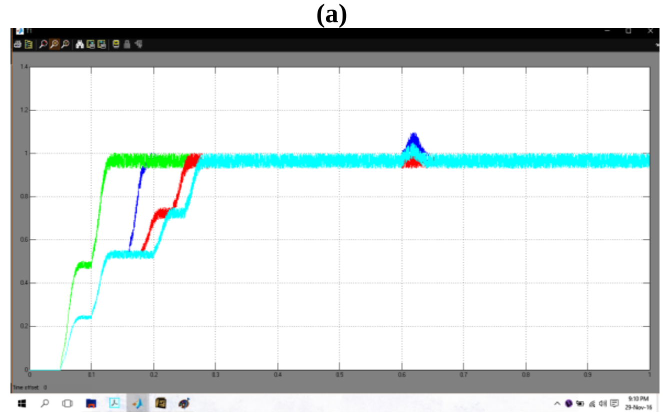

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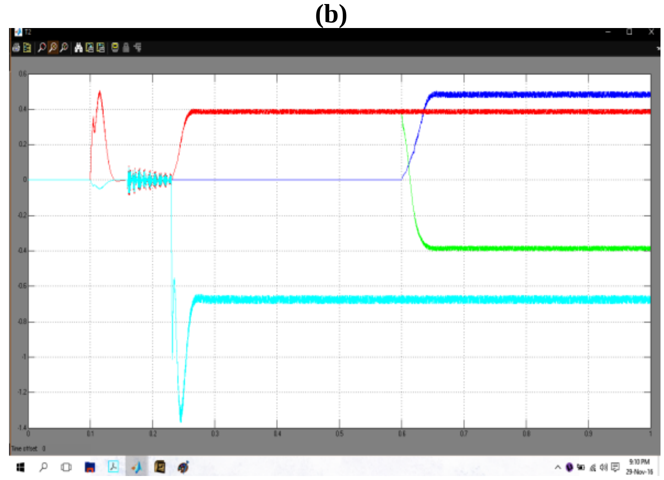

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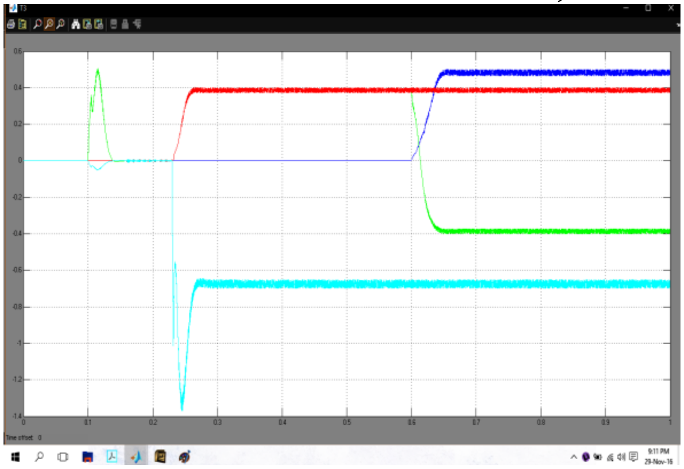

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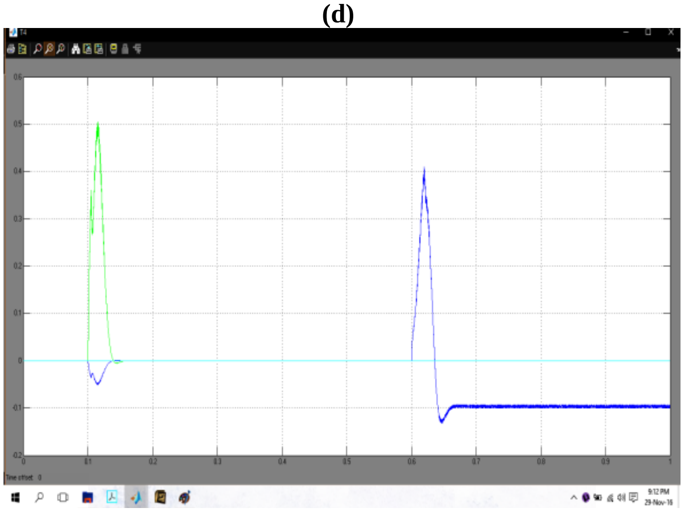
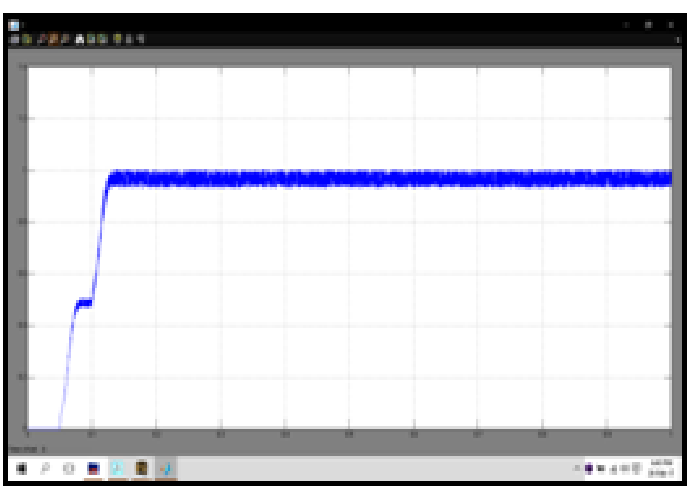


(e)

Fig.3. MTDC without a starting resistor and without reduced DC voltage control (Case A): (a) MMC-2 DC side voltage, (b) SM capacitor voltages; (c) MTDC currents, (d) active power, and (e) reactive power.

In this case, the MTDC is started without starting resistor and without reduced dc voltage control. Simulation results are shown in Fig.3.



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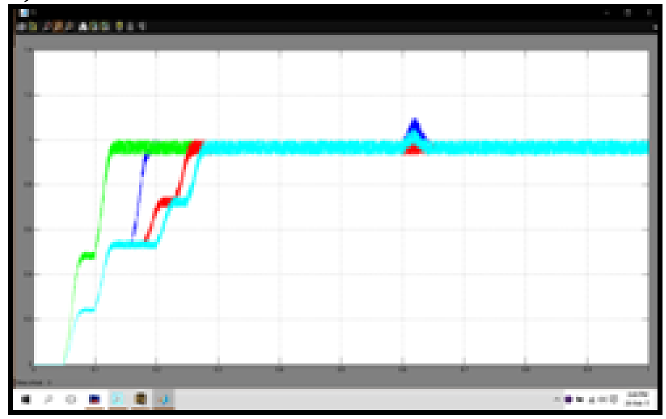

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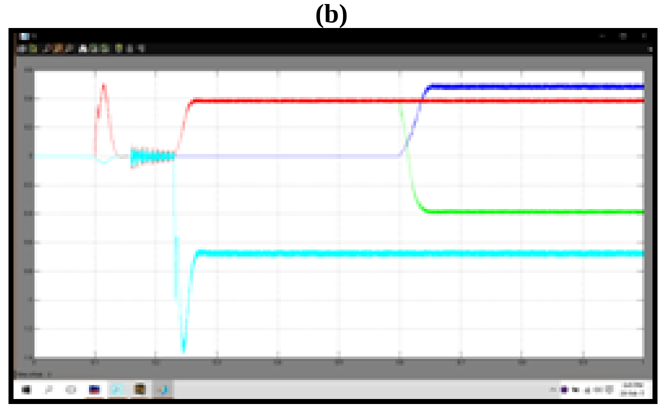

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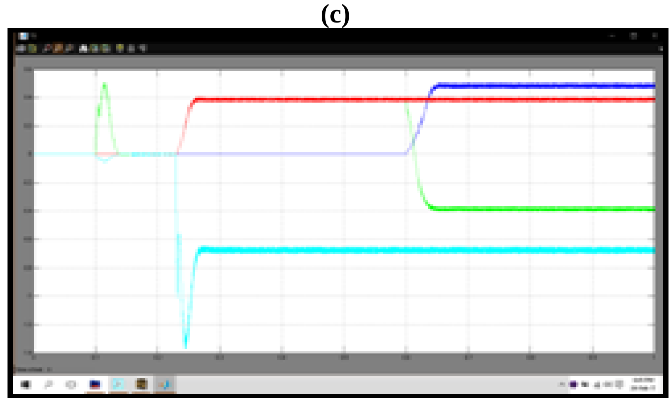

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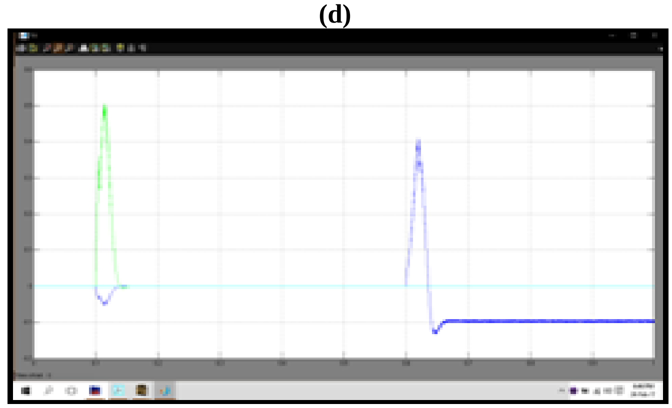

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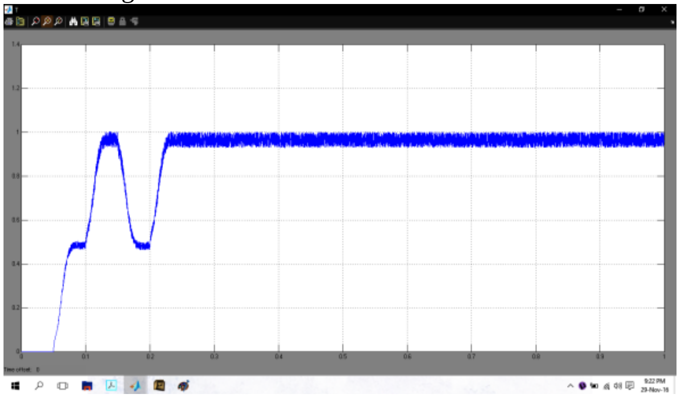
Fig.4. MTDC with a starting resistor and without reduced DC voltage control (Case B). (a) MMC-2 dc side voltage. (b) SM capacitor voltages. (c) MTDC currents. (d) Active power. (e) Reactive power.

In this case, the start-up sequence is similar to that of Case A, except that the starting resistor is used. Simulation results are shown in Fig.4.



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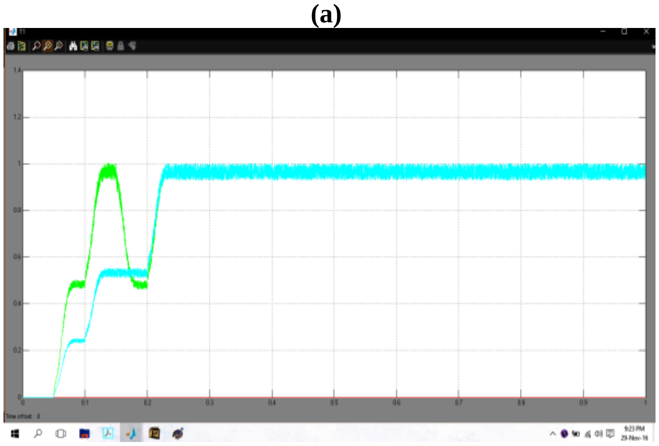

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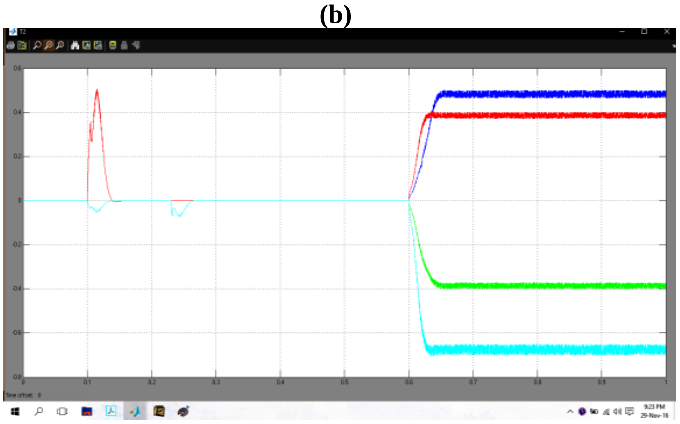

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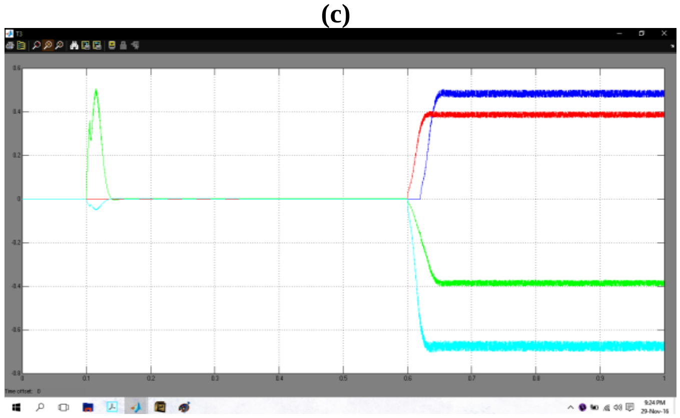

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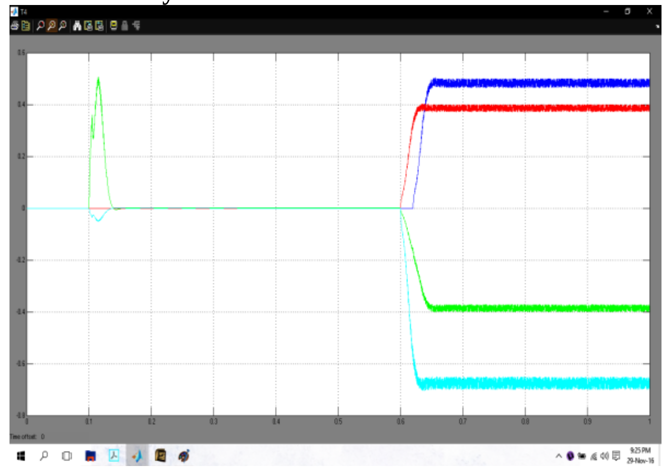

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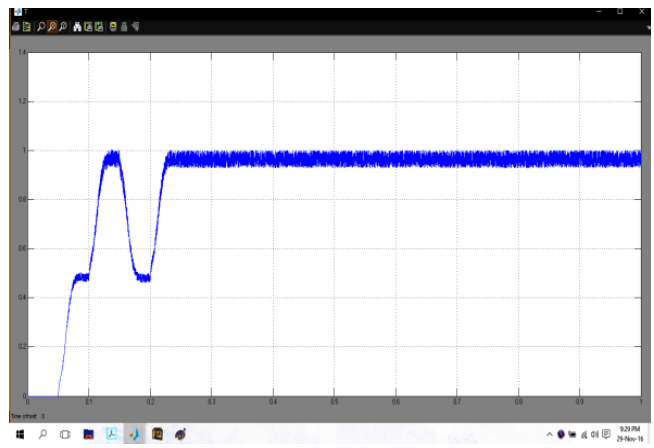
Fig.5.MTDC with master-slave control using the proposed sequential start-up control (Case C). (a) MMC-2 dc side voltage. (b) SM capacitor voltages. (c) MTDC currents. (d) Active power. (e) Reactive power.

In this case, the start-up sequence is similar to that of Case B, except that the reduced dc voltage control is applied, that is to say, the proposed sequential start-up control is applied. Simulation results using the proposed sequential start-up scheme are shown in Fig.5.



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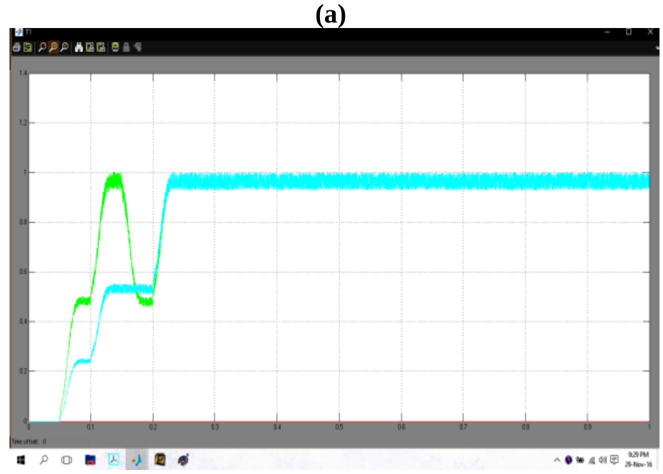

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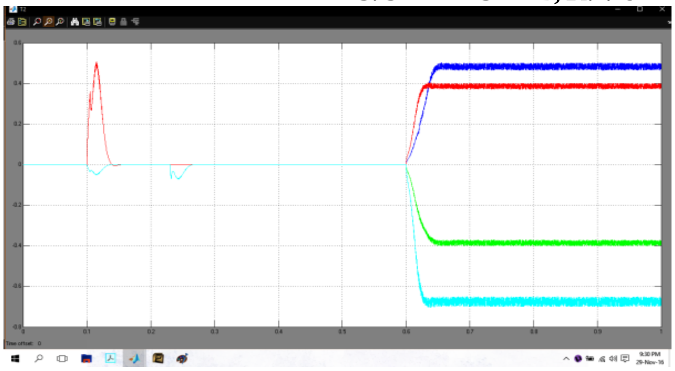

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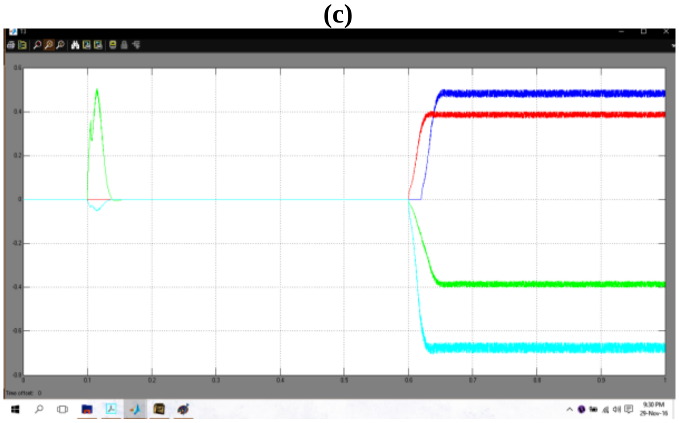

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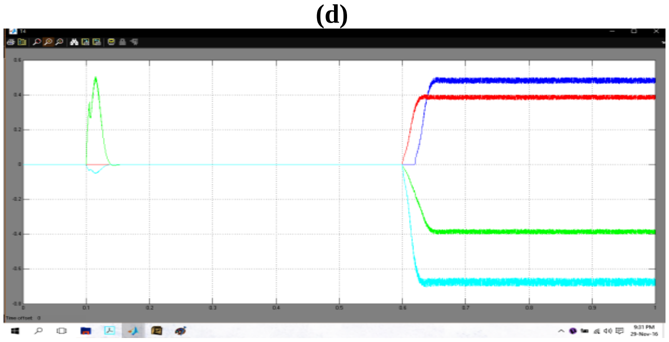

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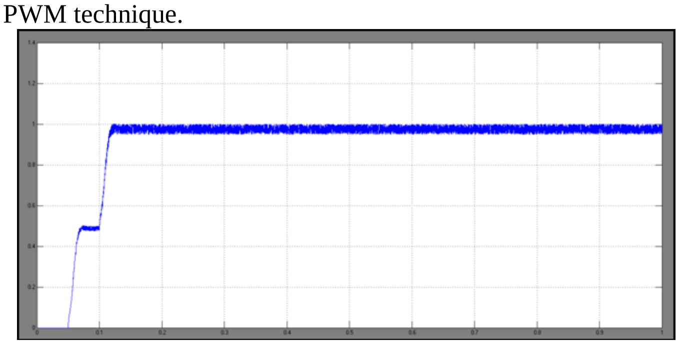
Fig.6. MTDC with droop control using the proposed sequential start-up control (Case D). (a) MMC-2 dc side voltage. (b) SM capacitor voltages. (c) MTDC currents. (d) Active power. (e) Reactive power.

For the future scope of this project, in this system the Phase shifting carrier based PWM is used for reducing the power oscillations. So that the system stability will be improved. The below figs.6 to 9 shows that the Phase shifting carrier based PWM technique.



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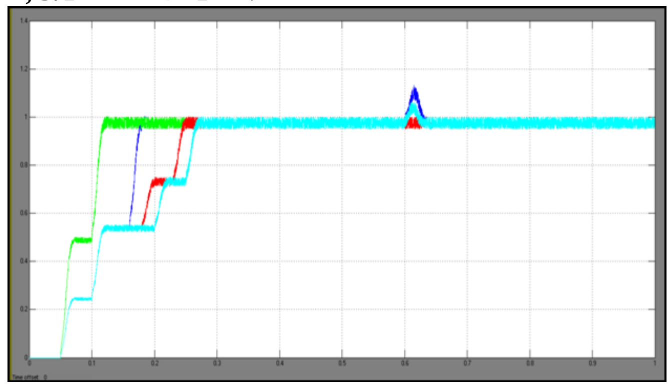

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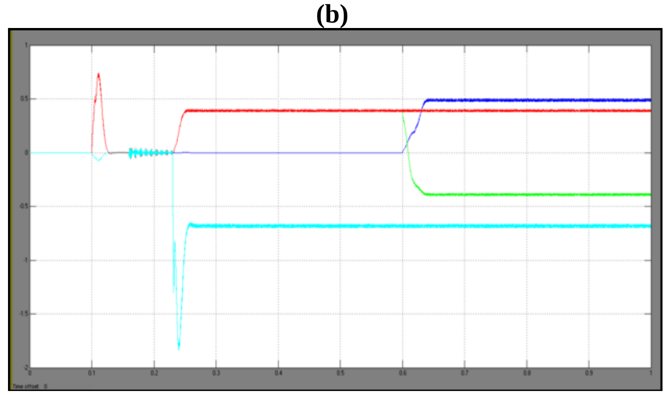

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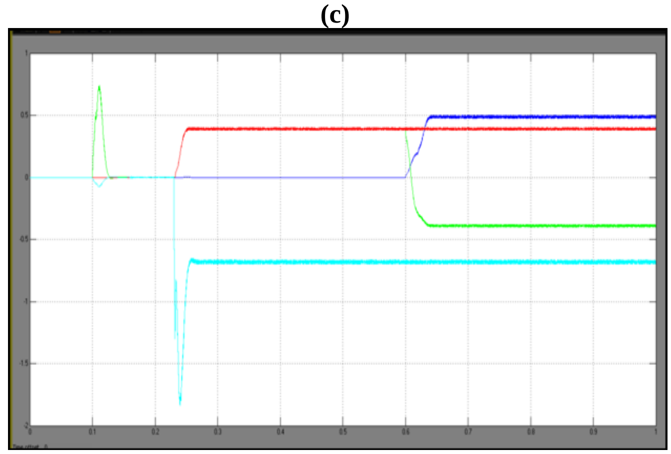

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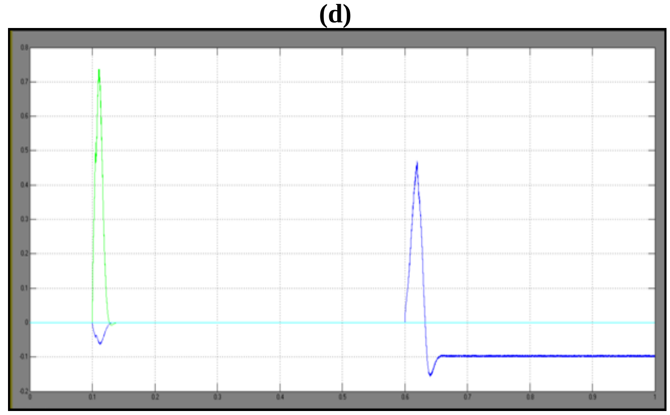

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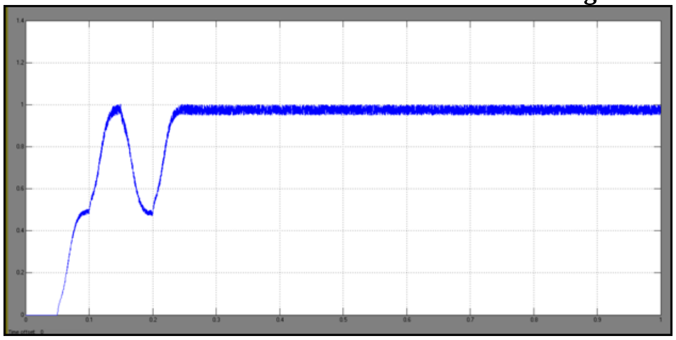
Fig.7. MTDC without a starting resistor and without reduced DC voltage control (Case A): (a) MMC-2 DC side voltage, (b) SM capacitor voltages; (c) MTDC currents, (d) active power, and (e) reactive power.



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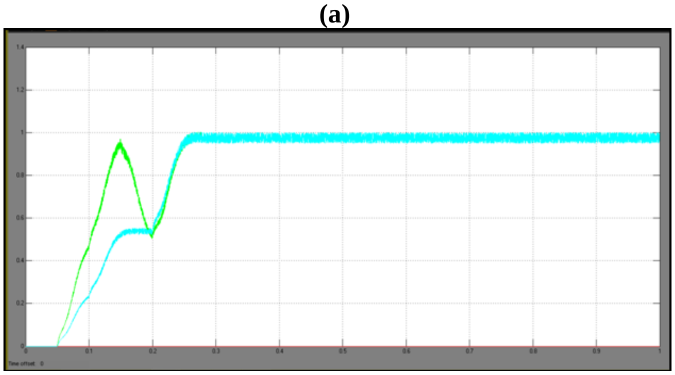

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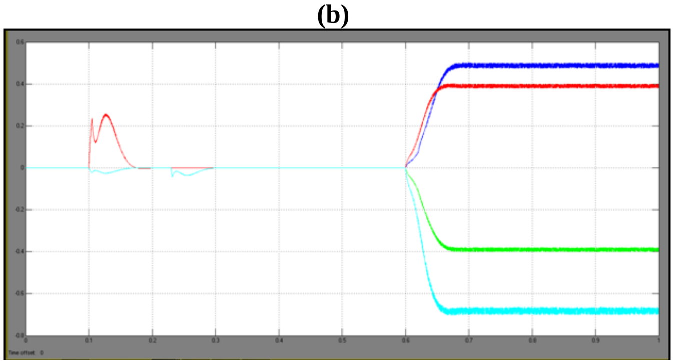

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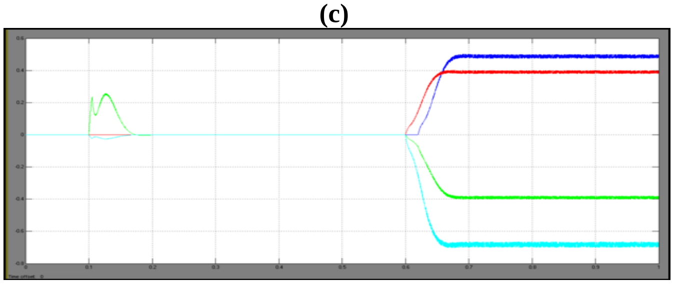

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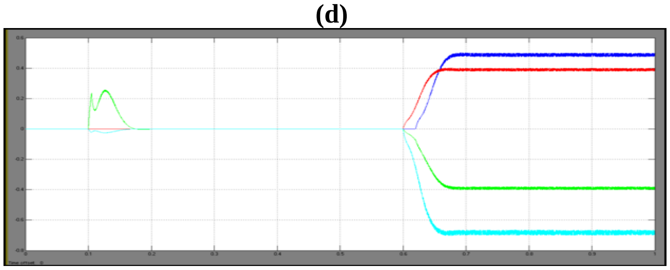

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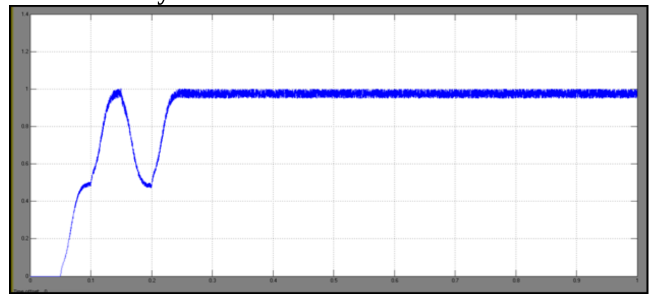
Fig.8. MTDC with a starting resistor and without reduced DC voltage control (Case B). (a) MMC-2 dc side voltage. (b) SM capacitor voltages. (c) MTDC currents. (d) Active power. (e) Reactive power.



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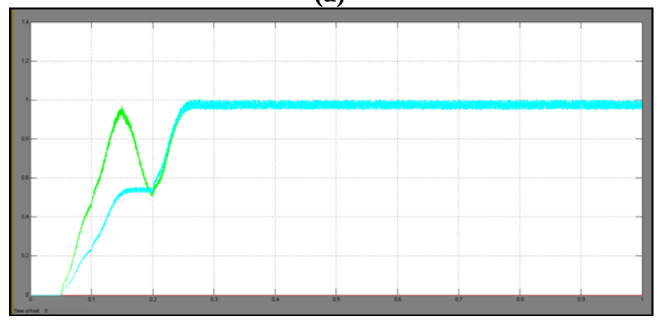

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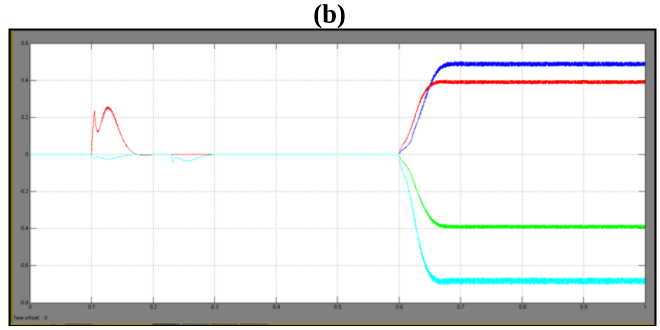

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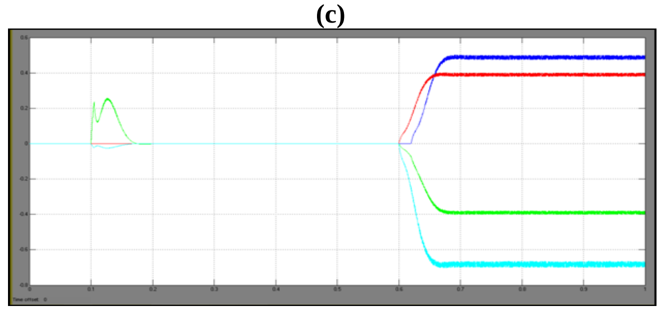

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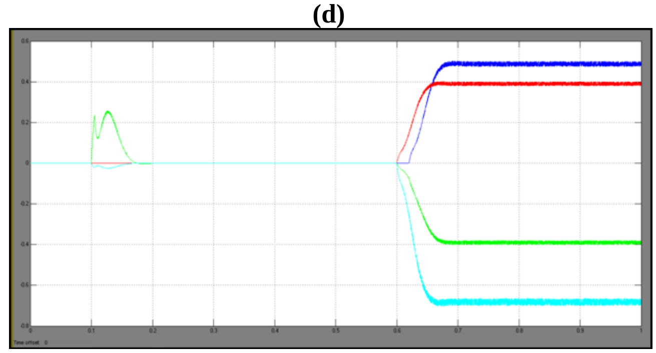

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Fig.9. MTDC with droop control using the proposed sequential start-up control (Case D). (a) MMC-2 dc side voltage. (b) SM capacitor voltages. (c) MTDC currents. (d) Active power. (e) Reactive power.

IV. CONCLUSION

This project has investigated the start-up control of an OWF integrated MMC MTDC system. After the derivation and analysis of the mathematical models on both the active and passive networks connected MMCs, a hierarchical control scheme for the active network connected MMCs and a reduced dc voltage control scheme for the OWF connected MMC have been proposed. The combination of both schemes forms an overall sequential start-up control scheme. A four-terminal MMC HVDC system with one terminal connected with an OWF has been established on the RTDS. The system with either master-slave control or droop control can be well started using the proposed control scheme with small voltage spikes and current surges. In comparison with the start-up control schemes with/without starting resistor and half dc voltage control, the superiority of the proposed scheme has been observed. This project has also discussed the potential development on the proposed scheme and the importance of the sequential start-up for the MTDC. The proposed sequential start-up control scheme has less complexity and is easy to realize. Although half dc voltage control scheme may not be applicable for every MMC MTDC projects, the reduced dc voltage control scheme can be applied for all of them. For the future scope of this project, in this system the Phase shifting carrier based PWM is used for reducing the power oscillations.

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