PR based power management and control of MT-HVDC based power system

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Abstract

In this work, clearing of DC faults in a hybrid multi-terminal HVDC transmission system consisting of line commutated converters (LCCs) and voltage source converters (VSCs) implemented using half-bridge modular multilevel converter (MMC) technology is examined by proportional resonant (PR) controller. While the hybrid HVDC system has several possible configurations, this paper focuses on two of them: 1) a half-bridge MMC-HVDC link piggybacking on the transmission line of a LCC-HVDC link and 2) LCC-HVDC link tapped by half-bridge MMC inverters. The proposed DC fault recovery strategy employs a high rating series diode valve placed at each VSC inverter pole to block fault currents; AC circuit breakers to isolate the faulty VSC rectifier pole; and force retardation applied at LCC rectifier to extinguish the arc. Detailed simulations demonstrate fast fault recovery performance with the proposed fault recovery procedure. In the case where a single transmission line is shared by the LCC and VSC links, the VSC rectifier is subjected to considerably high current for a period of few hundreds of milliseconds, and the AC side voltage dips momentarily. During a single pole fault, interrupting power flow on the healthy pole of VSC rectifier may be necessary to maintain smooth operation.

KeywordsHVDC transmission system, PR controller, VSCs, LCC, MMC

1.0 Introduction

Thomas Alva Edison invented the first direct-current (DC) generator. But, not so long after that, Nikola Tesla and George Westinghouse came up with the alternating current (AC) concept. AC had two undeniable advantages: its voltage could be changed using AC transformers. Therefore, the power loss was decreased and it was possible to transmit power over long distances. Moreover, it is easier in AC system to build the breakers, due to the zero crossing in AC systems. After world war II, the need for electric power increased. In some countries like Sweden, the hydro power is located far from the population centers. Therefore, the Swedish engineers at Swedish state power board (now Vattenfall) and ASEA (now ABB) tried to use DC to transmit power over long distance, but the power electronic technology could not offer this capability. As a result they utilized 380 kV series-compensated AC lines instead. By advances in mercury switch technology, the high-voltage direct-current (HVDC) system became a reality. The first order for an HVDC system was given to ASEA in 1950 to connect the system of the Swedish island of Gotland to the mainland system.

Multi-Terminal High Voltage Direct Current (MTHVDC) transmission systems are being seriously considered as an alternative solution to overcome some of the limitations of HVAC power transmission systems [1]. Two main converter technologies, namely, line commutated converters (LCCs) and voltage source converters (VSCs) implemented using multi-level modular converter (MMC) technology, are utilized for HVDC transmission. In certain applications, it is possible to exploit individual advantages of each converter technology using a hybrid grid configuration [2]. When the capability of changing the direction of power is not useful or necessary at all converter stations in an MTHVDC system, there are many possible hybrid MT-HVDC configurations. Large capacity LCC based rectifier stations can be built at less cost near energy rich areas where commutation failure is less likely [3], for example, to deliver power from a remotely located system of large hydropower plants. Then, VSC inverter stations can be used to supply distributed urban load centres [4], exploiting their advantages such as smaller footprint and the ability of connecting to weak AC systems[5].

The black-start capability and independent controllability of real and reactive power can be exploited in isolated locations [3], [6]. All over the world, there are many long, high capacity, point-to-point LCC-HVDC links connecting large generating stations and load centers. Often, they are built with some spare capacity in the transmission line for future expansion or to meet other design requirements. The spare capacity of these transmission lines can be utilized to supply energy for the small cities or load centers located along these HVDC lines in an economical manner, if an appropriate technology such as VSC based inverters is used to tap into the HVDC line [7]. Because the VSC technology is relatively mature and commercially available, currently it is more practical and economical to use VSCs to tap into an HVDC line, compared to the other options such as using DC-DC converters [8] or using series tapping with current source converters [9]. Furthermore, energy collected from renewable energy resources (weak sources) at intermediate locations can be fed into a point-to-point HVDC link using VSC based rectifier stations. Another interesting possibility is to utilize the spare capacity of a point-to-point LCC-HVDC transmission line to transfer power from an intermediately located VSC based rectifier to an intermediately located VSC based inverter [10]. In this configuration, VSC link essentially piggy-backs on part of the DC line, and thus it is shared by the two independent HVDC links; the main LCC link and the VSC link. One major design challenge encountered when tapping into LCC-HVDC links using the more economical half-bridge MMC technology using any of the configurations mentioned above is the response of VSCs to DC side faults. A DC side fault appears as a three-phase short circuit to the AC systems connected through VSCs [11]. The energy stored in the capacitors of the VSC is rapidly discharged into the fault giving rise to very high fault currents. This is in contrast to the LCCs, which can control the fault currents through force retardation.

A simple but elegant solution to block the fault currents when a VSC is operating only as an inverter is proposed in [6]. The fault current from a VSC inverter can be blocked by placing a series high rating diode valve at each pole of the station [6], [2]. When VSC stations are used with series diode values in hybrid systems having a LCC rectifier, fault is cleared by force retardation at LCC rectifier and VSC inverters are operated in STATCOM mode during the faultclearing process [2]. The other options for DC fault current control include use of full-bridge MMCs as in [12] or fault tolerant VSCs as in [13]. As fault current is suppressed by changing VDC with the help of fast low level controllers in full-bridge sub-module based fault tolerant converters, fault current can be quickly suppressed [12].

2.0 Multi-Terminal HVDC System

Multi-terminal HVDC (MTDC) systems are HVDC systems consisting of more than two terminals. The first MTDC system was built based on CSC technology by adding a third 50 MW converter station at Corsica island to the HVDC link between Sardinia and mainland Italy. This system was commissioned in 1986 [1]. However, in CSC-MTDC systems, in order to change direction of the flow of power, DC voltage polarity must be changed.while maintaining it in the others requires a switching arrangement. Multi-terminal CSC-HVDC may be applied in situations where there is a pre-dominant power flow direction. In contrast, in a VSC-HVDC system it is possible to change the flow of power without changing the polarity. Therefore, it is easier to extend the number of terminals in a VSC-MTDC system, which makes the VSC technology a more attractive solution for MTDC systems [12, 13]. We consider offshore wind farms. The MTDC system is represented in Figure 1.

Offshore wind farms may be one of the main sources of renewable energy in the future. Major offshore wind sources can be far away from the coast. The energy extracted from the wind farms must be transmitted to the shore by means of submarine cables. As stated earlier, the VSC-HVDC system can be an attractive solution. Moreover, wind has an intermittent nature, and by interconnecting wind farms to other grids, the effect of intermittency and variability decreases [14]. VSC-MTDC systems make it possible to connect many of these wind farms together and to multiple AC grids and form a DC system. Furthermore, there are a lot of oil and gas platforms in the sea. These platforms usually use gas turbines. It would be more efficient if these platforms are supplied from the offshore grid or wind farms [4]. VSC-MTDC systems make it possible to build a grid under the sea, which can supply offshore platforms. Moreover, for HVDC grids to become more economically efficient, each individual link should have a capacity around 2 GW and 500 kV voltage rating [5,7]. Considering that currently the VSC-HVDC technology built by ABB can transfer 1800 MW at 500 kV, developing an HVDC grid seems completely feasible.

The challenges of operating MTDC systems, like controlling the DC voltage, power flow in DC lines, interaction between converters, have been discussed in [7]. One of the most important issues is that the DC voltage across the MTDC system must be kept in an acceptable range. DC over-voltage could damage the converters, whereas DC under-voltage may result in reducing the converter controllability [18]. If the power balance in the MTDC system is not maintained, the DC voltage will change. VSC operating in rectifying mode injects active power to the MTDC system, while the VSC operating in inverting mode extract active power from it. If more active power is injected into the DC grid than is extracted, the DC voltage will increase.

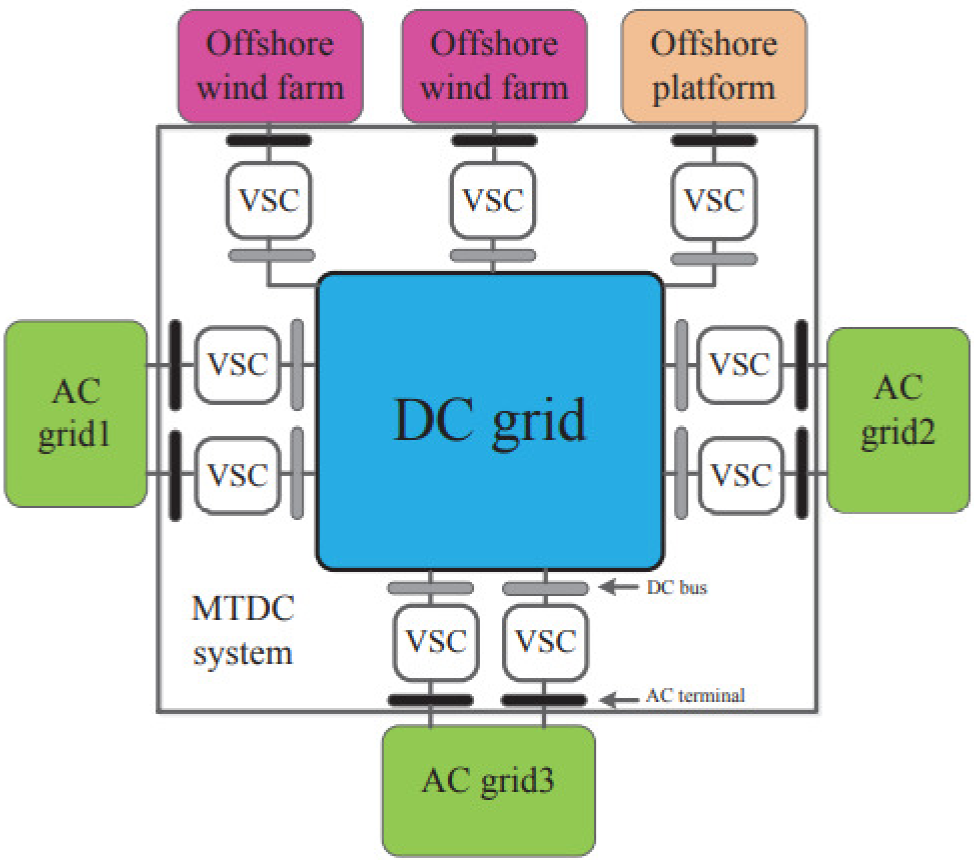

Figure 1 A VSC-based MTDC System.

3.0PR Controller

The ideal resonant controller, which is given by, can be mathematically derived by transforming an ideal synchronous frame PI controller to the stationary frame and achieves infinite gain at the AC frequency of ω0 as to force the steady-state voltage error to zero, and no phase shift and gain at other frequencies. For Kp, it is tuned in the same way as for a PI controller. Unfortunately, the ideal PR controller acts like a network with an infinite quality factor, which is hard to implement the PR controller in reality. Firstly, the infinite gain introduced by PR controller leads to an infinite quality factor which cannot be achieved in either analogy or digital system. Secondly, the gain of PR controller is much reduced at other frequencies and it is no adequate to eliminate harmonic influence caused by grid voltage. Therefore, an approximating ideal (non-ideal) PR controller.

$$G_S(s) = K_p + \frac{2K_i s}{s^2 + \omega_0^2}$$

$$G_S(s) = K_p + \frac{2K_i \omega_{cut} s}{s^2 + 2\omega_{cut} s + \omega_0^2}$$

where Kp, Ki are gain constants; ω_0 (= 2π×60rad/s) is grid frequency and ω_{cut} is cut off frequency.

In addition, a wider bandwidth is observed around the resonant frequency, which minimizes the sensitivity of the controller to slight grid frequency variations. At other harmonic frequencies, the response of the non-ideal PR controller is comparable to that of the ideal PR controller. From equation, it can be seen that there are three parameters in the PR controller including Kp, Ki and ωcut. For simplicity of analysis, we assume two of these parameters to be constant, and then the effect of changes in the third parameter can be easily observed.

4.0 Simulation Results

Case-1:- Cable to Ground Fault in the Middle of a DC Cable

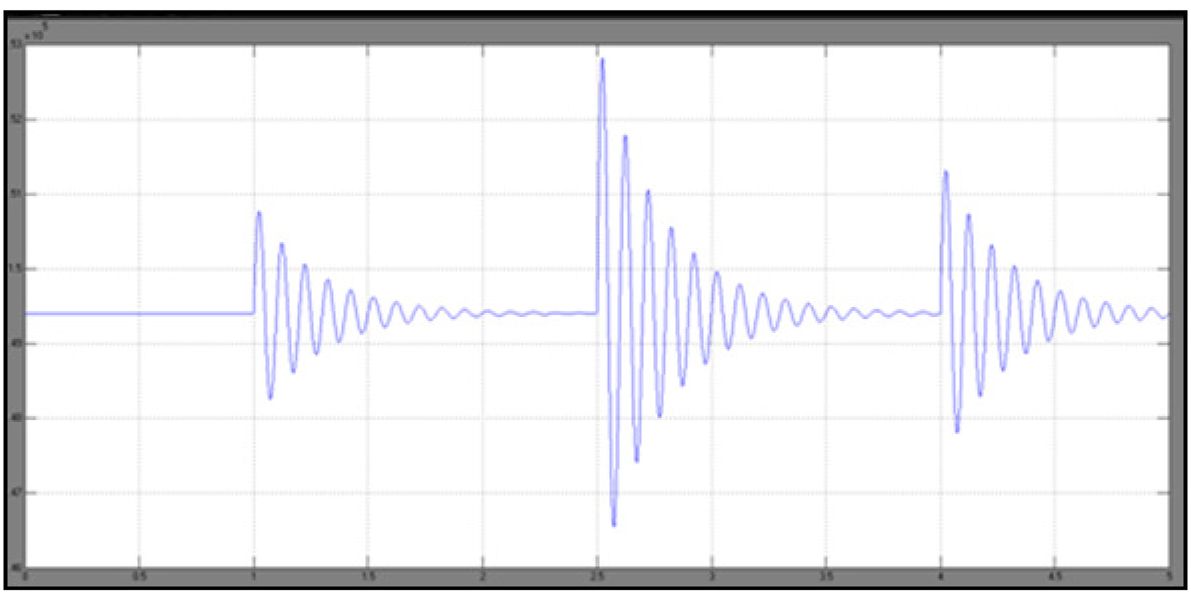

Fig.2. Simulation for case-1 The MTDC modelled with only VMM Controller

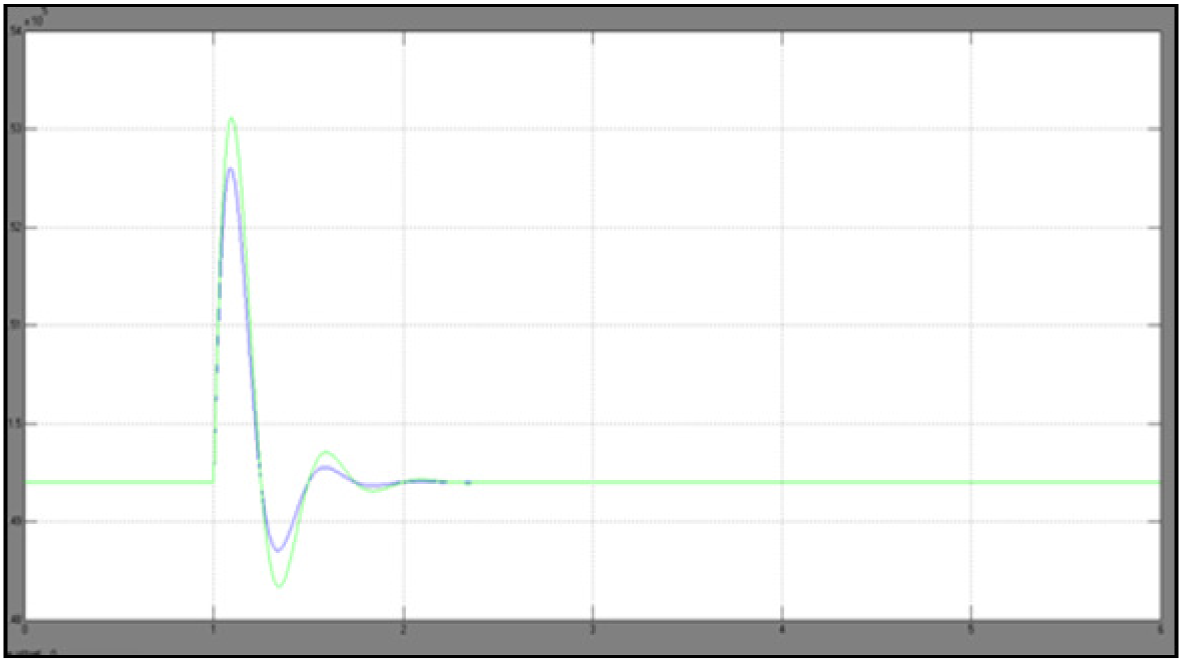

Fig.3. Comparison between VMM and SCM-VMM

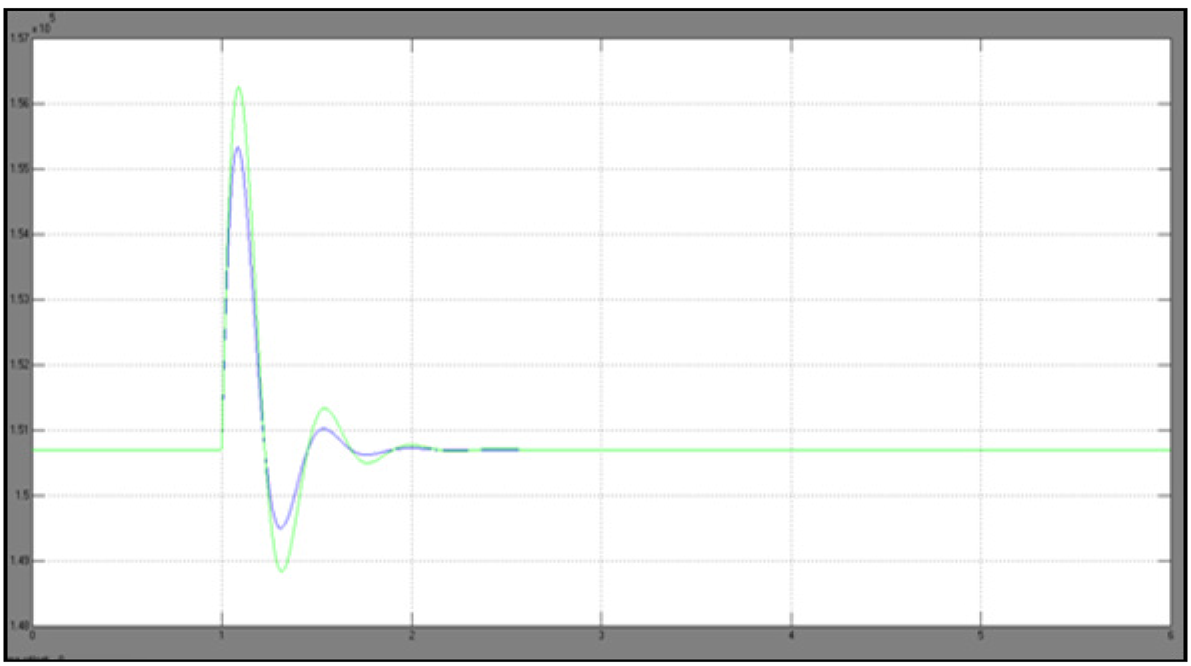

Fig.4. Comparison between VDM and SMC-VDM

Case.2: A Five Terminal Cable to Ground Fault Very Close to a Converter

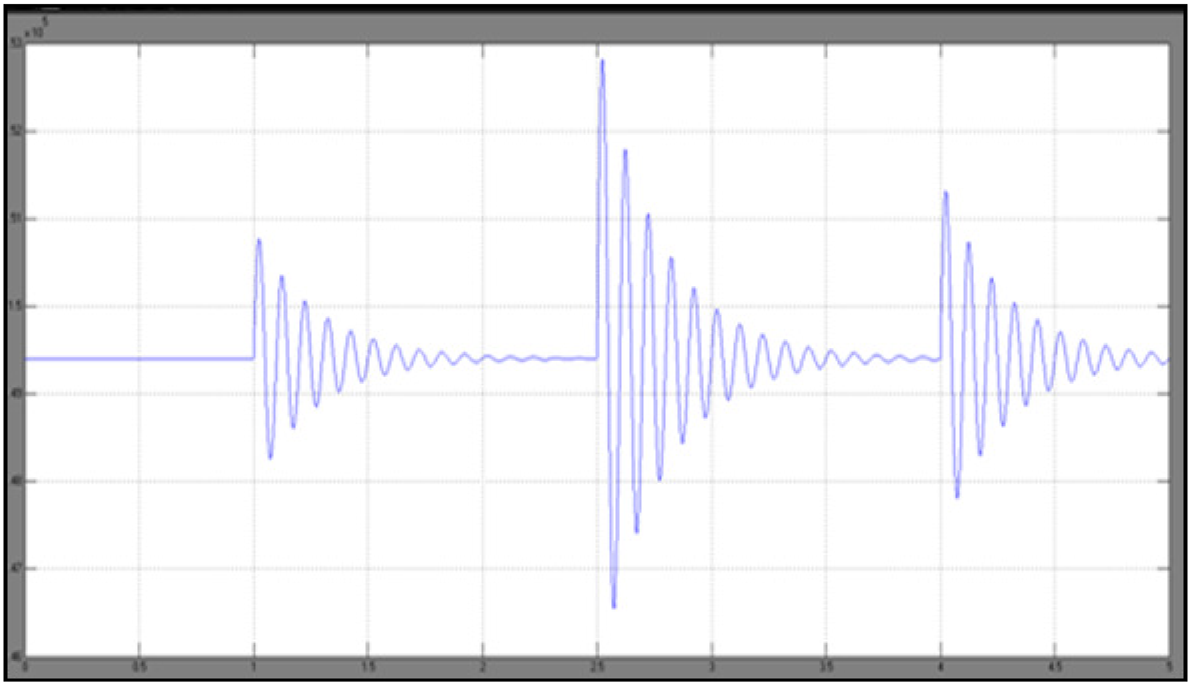

Fig.5. Five terminal system reaction for the fault if system imposed with only VMM controller

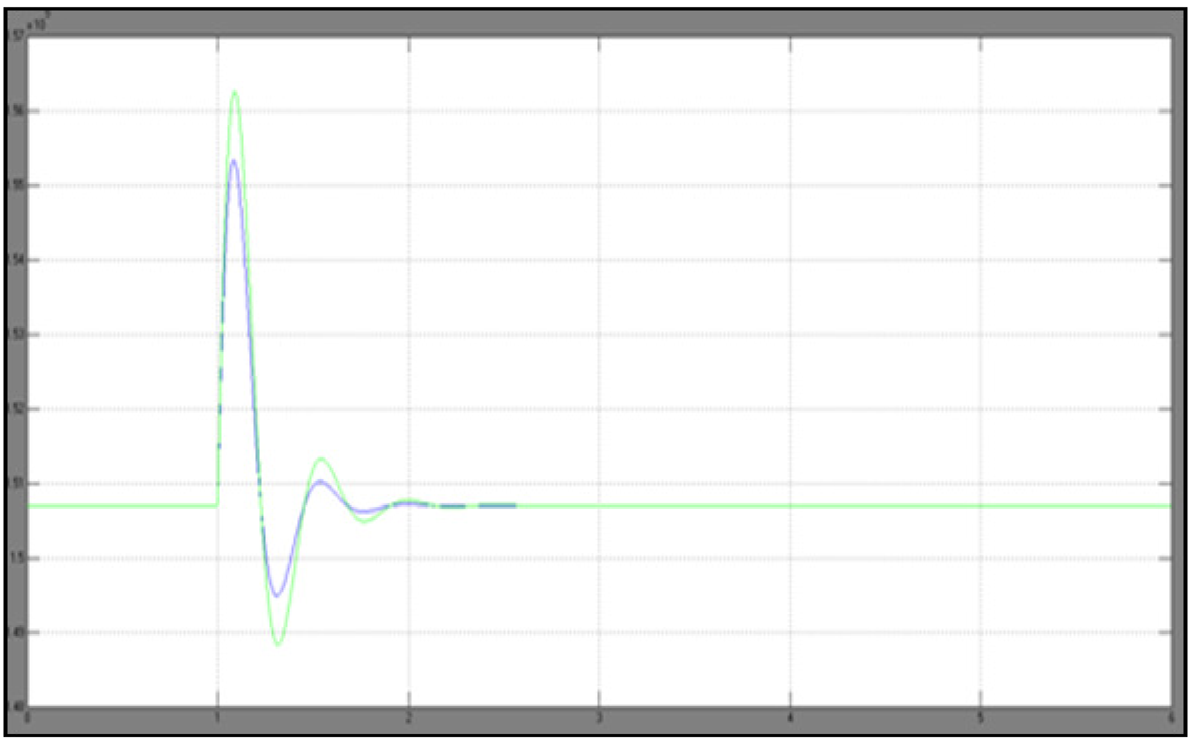

Fig.6. Comparison between VMM and SCM-VMM

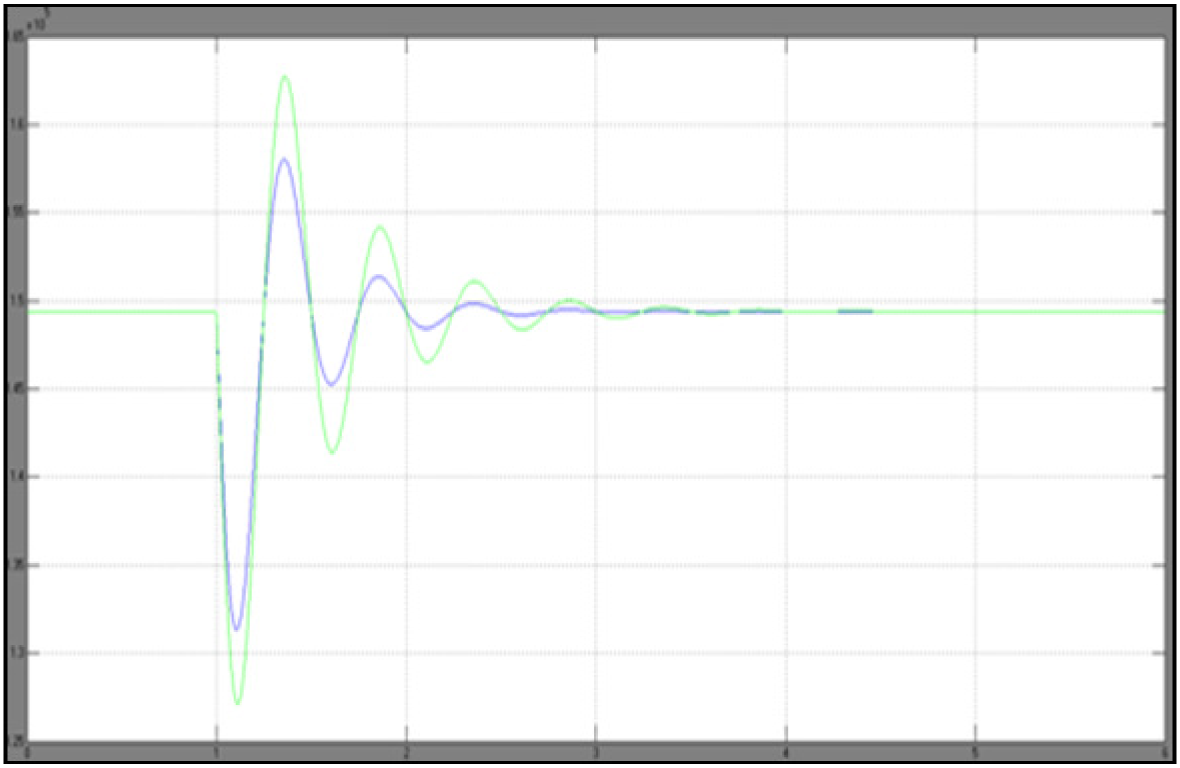

Fig.7. Comparison between VDM and SCM-VDM

5.0 Conclusion

A novel LCC-VSC hybrid multi-terminal HVDC transmission structure and it has been investigated by the PR controller for reliable operation. A strategy to clear DC faults was proposed. It uses a combination of actions including force retardation of LCCs, opening of AC side breakers of VSCs and blocking fault currents using series diode valves. Expected DC fault recovery behavior of the hybrid multi-terminal HVDC system was investigated using a mixed converter type HVDC grid simulated in PSCAD/EMTDC. The simulation results demonstrate: (i) the ability of the proposed power master controller to operate converter station both under normal operation and during faults; (ii) the effectiveness of the proposed procedure for recovering from both pole to pole faults and pole to ground faults with reasonable delay; (iii) the ability of the series diode valves to block DC fault currents from VSC inverters without having to open AC breakers. In the piggy-backing configuration (Configuration-1) where a common transmission segment is shared by both LCC and VSC HVDC links, the VSC rectifier injects a large initial fault current due to discharge of MMC cell capacitors. This current decays over several hundreds of milliseconds, even after the opening of AC circuit breakers, delaying the fault recovery compared to the case of the stand-alone LCC link. A supplementary controls (such as power oscillation damping (POD)) can be developed for the converters to improve the dynamic performance of the AC-DC system. The impact of the proposed control strategies in this work and the aforementioned supplementary controls on the hybrid AC-DC system can be studied.

6.0 References

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