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Comparison between Two VSC-HVDC Transmission Systems Technologies: Modular and Neutral Point Clamped Multilevel Converter

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***Abstract*— The paper presents a detail comparison between two voltage source converter high voltage dc transmission systems, the first is based on neutral point-clamped (also known as HVDC-Light) and the second is based on innovative modular multilevel converter (known as HVDC-Plus). The comparison focuses on the reliability issues of both technologies such as fault ride-through capability and control flexibility. To address these issues, neutral point-clamped and three-level modular converters are considered in both stations of the dc transmission system, and several operating conditions are considered, including, symmetrical and asymmetrical faults. Computer simulation in Matlab-Simulink environment has been used to confirm the validity of the results.**

***Key words*—Modular multilevel converter (MMC), neutral point-clamped converter (NPC), pulse width modulation, and voltage source converter high voltage DC transmission system (VSC-HVDC)**

I. INTRODUCTION

Currently, there are two distinct approaches for construction of dc transmission systems based on voltage source converters; both of them are using high frequency pulse width modulation (PWM) with switching frequency in order of 3 kHz or less and forced commutated switching devices such as IGBT.

The first approach using neutral point clamped converter with special stack of IGBT as the main switching devices, typically, 50 kV-300 kV DC to generate high voltage. The second approach using modular multilevel converter with increased number of levels to enable use of commercial IGB, typically, 2.5 kV-6.5 kV as the main switching devices to generate high voltage, 300 kV DC and 132 kV ac. Both technologies are designed to handle power level up to 1000 MW.

The second approach has better performance compare to the first approach in terms of low voltage stress on switching device *dv/dt* and low voltage total harmonic distortion (THD), because it uses full potential of true multilevel converter. Also, it provides additional features which will improve system reliability such as, ability to operate successfully with unbalanced load without increasing the risk of system collapse; better fault ride through capability; it has fault management capability, in other words, failure in one or few switching devices may not lead to system collapse, instead it allows safe shutdown of the system.

In this paper a detail comparison of neutral point clamped and modular multilevel converter is presented. The comparison was focused on reliability issues such as performance under symmetrical and asymmetrical faults, and control flexibility of each technology to identify their operation limitations. Intensive computer simulation has been conducted in Matlab environment to confirm the validity of the results.

II. CONVERTER TOPOLOGIES

A. Neutral Point-Clamped (NPC) Converter

Fig. 1 shows one phase of neutral point clamped converter (also, known as three-level diode clamped converter), each phase produces three-level waveform voltage between, a and 0 [1]-[5]. The voltage across each dc link capacitor must be maintained at ½Vdc, the maximum voltage stress across each switching device in the structure, including clamping diodes and freewheeling diodes is limited to one capacitor voltage[4],[5]. The high frequency pulse width modulation PWM used to control the switches of NPC converter suppresses the voltage harmonics around and beyond the switching frequency components that allows the use of small filter at converter output to attenuate these high frequency harmonics.

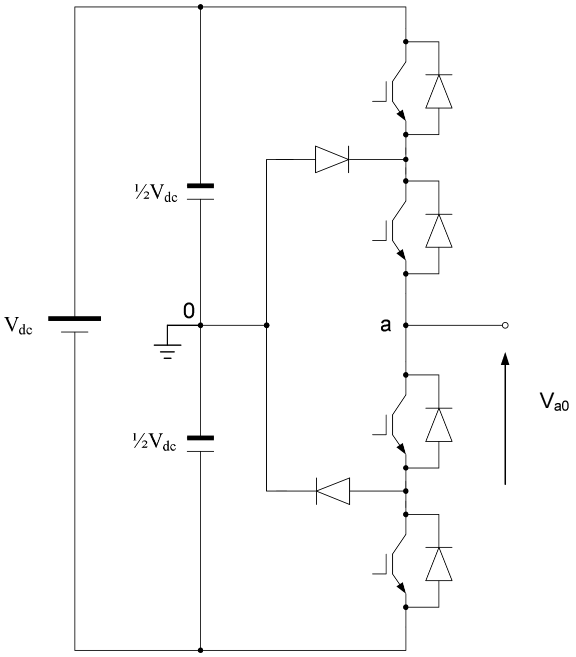


Fig. 1: One-phase of neutral point-clamped converter

There are three methods commonly used to maintain dc link capacitors voltage balance of NPC converter [1],[3][5]. The first method is based on carrier based PWM which injects small dc offset to the reference signals to redistribute the currents through the capacitors in order to maintain the voltage balance of the dc link capacitors [5]. This method is not accepted in power system industries, because the added dc offset may saturate the power transformers in the system. The second method is based on space vector modulation that uses redundant switching states that produce the same line-to-line voltage to maintain the dc link voltage balance [1]. This method is preferred in many applications such as medium voltage high power drive systems. However, it may jeopardize the stability of power system in cases such as unbalance operating conditions and asymmetrical faults. The third method uses auxiliary balancing circuit to maintain the dc link voltage balance [3],[5],[6]. This method is not preferred in many applications because it adds cost and complexity to control system. However, it might be accepted in power system since it can guarantee the system stability regardless of operating condition or type of fault.

B. Modular Multilevel Converter (MMC)

Fig. 2 shows one phase of three-level modular converter, the voltage across each capacitor must be maintained at ½Vdc and voltage stress on each switching device is limited to one capacitor voltage [8]-[10]. With modular multilevel converter, the high frequency pulse width modulation using carrier based is favoured over space vector modulation, because it simplifies the complexity of capacitor voltage balancing method, improves the robustness of the capacitor voltage balancing method to deal with different operating conditions, including unbalance operating conditions and asymmetrical faults. With increased number of levels modular multilevel converters can provide real advantages compare to diode clamped converters such as:

- Since voltage balance of the dc link is achievable with any number of levels, it generates high voltage with increase number of levels that allows elimination of interface transformer and ac filter and replaces them by cheap reactor to attenuate high frequency harmonics and allows active and reactive power control [11].
- It generates high voltage high quality waveforms with extremely low THD and dv/dt due to small voltage step.
- As modular multilevel converters are capable of surviving symmetrical and asymmetrical faults and continuous operation with unbalance load without increasing the risk system collapse, it improves system reliability.
- Allows the use of small dc link capacitors and commercial switching devices (reduced construction cost).

III. SYSTEM OUTLINE

Fig. 3 shows 275kV dc point-to-point VSC-HVDC transmission systems, the converters VSC_1 and VSC_2 are connected to the AC systems 1 and 2 through 200MVA, 230kV/132kV transformers; the low voltage sides are connected to the converters while the high voltage side to the AC systems 1 and 2. The converter station VSC_1 regulates active power and ac voltage magnitude at bus B_1, while the converter station VSC_2 regulates dc link voltage and ac voltage magnitude at bus B_2 [12]-[16]. Sinusoidal pulse width modulation with switching frequency of 2.1 kHz is used to control both converter stations of the dc transmission system.

IV. PERFORMANCE EVALUATION

For comparison purposes comparison the converter stations of VSC-HVDC transmission systems are simulated as neutral point-clamped and three-level modular converter. The comparison focuses on reliability issues such as ability of the system to operate successfully under several operating conditions and ride through different types of faults, and flexibility of the control their control.

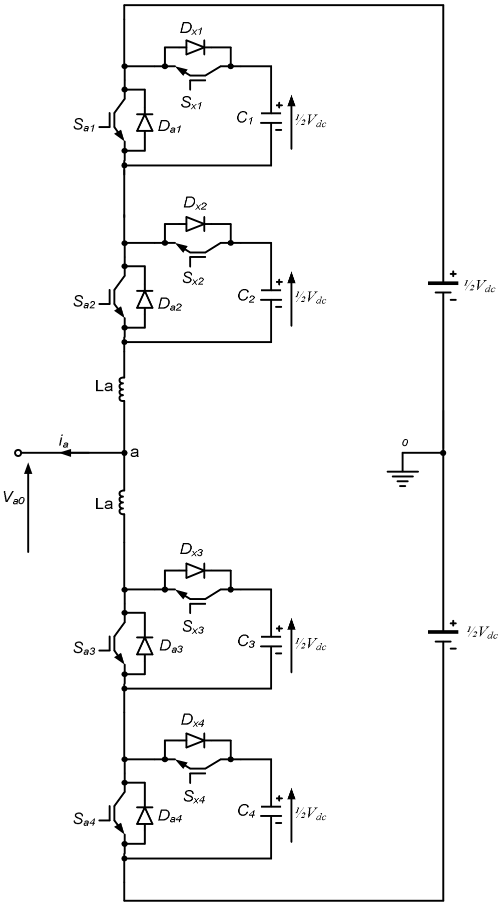


Fig. 2: One-phase of three-level modular converter

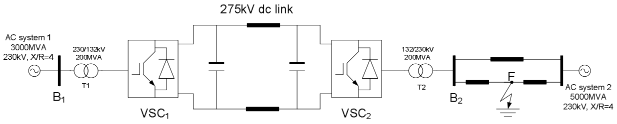


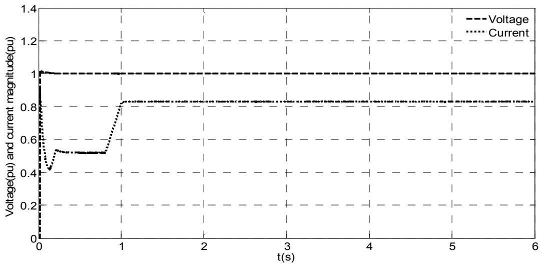
Fig. 3: Test system

A. Neutral point-clamped inverter

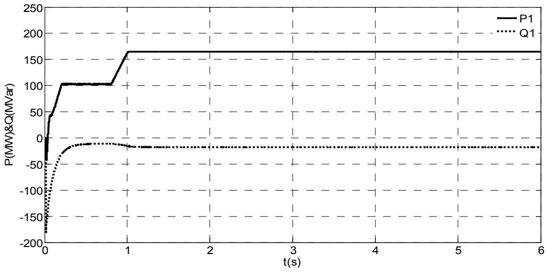
Case 1A

In this case, the converters VSC_1 and VSC_2 in Fig. 3 are simulated as neutral point-clamped converter, the voltage balance of the dc link capacitors are maintained using dc offset method proposed in [5]. The power command is given to VSC_1 to ramp up active power from 0 to 100MW during

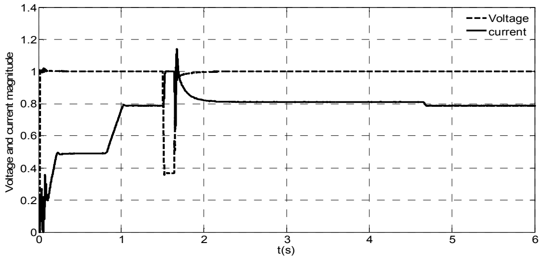
200ms and the power command is maintained at 100MW until 800ms. At time t=800ms, another power command is given to increase the active power from 100MW to 160MW within 200ms and then the power command is maintained at 160MW until the end of the simulation. At time t=1.5s the system is subjected to a solid three-phase short circuit at the point F with duration of 140ms.



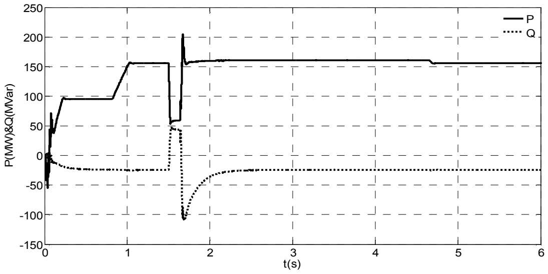
(a) Voltage and current magnitude at bus B1



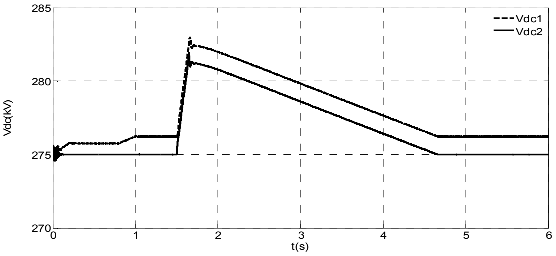
(b) Active and reactive power at bus B1



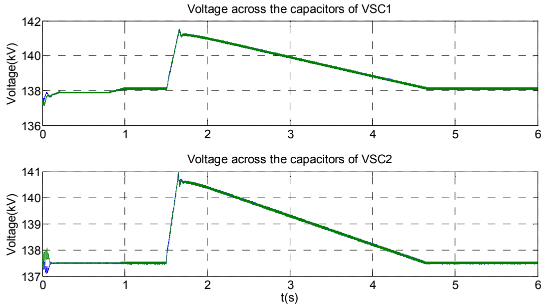
(c) Voltage and current magnitude at bus B2



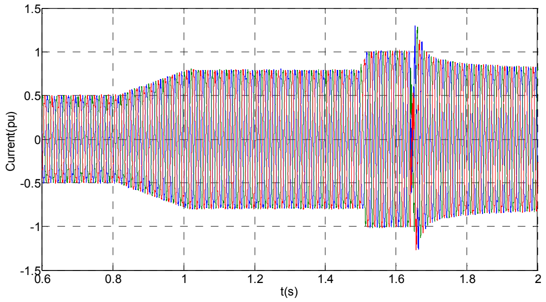
(d) Active and reactive power at bus B2



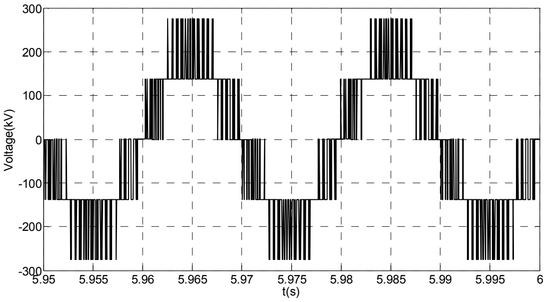
(e) DC link voltage at both ends of the link



(f) Voltage across the dc link capacitors of the converters VSC1 and VSC2 respectively



(g)Current waveform at bus B1



(h)Voltage at terminal converter VSC$_2$

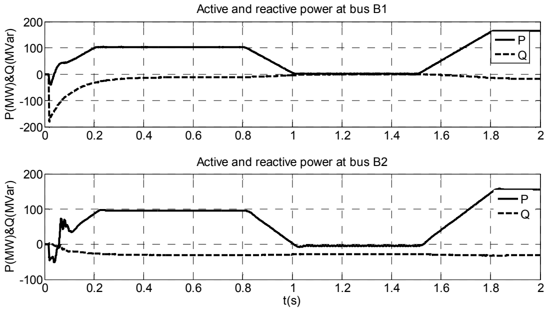
Fig. 4: Key waveforms obtained to demonstrate the reliability of VSC-HVDC transmission system based on NPC

The results in Fig. 4 show the VSC-HVDC transmission systems is capable of surviving three-phase fault without increasing the risk of system collapse as a result of devices failure due to increased voltage stress from dc link capacitor voltage imbalance. Fig. 4a through 4d show that the AC voltage at busses B$_1$ and B$_2$ are regulated at their nominal values over entire operating conditions imposed. During solid three-phase at point F the current controller of VSC$_2$ limits its current contribution to 1.0 pu (full load current) as shown in Fig. 4c and 4g. Fig. 4e and 4f show the dc link voltages at both ends of the dc link during three-phase short circuit and voltage sharing by the dc link capacitors of converters VSC$_1$ and VSC2. It can be noticed that the dc link voltage requires longer period to recover to its previous value. It has been found that when the carrier based dc link capacitors voltage balancing technique using dc offset are employed to maintain the dc link voltage balance NPC converters of VSC-HVDC transmission system, the dc transmission systems are capable of ride through three-phase , line-line and single-phase to ground fault. But they can not survive single-phase open circuit.

As capacitors voltage balancing method based on dc offset limits the maximum modulation index can be attained, the successful active power reversal is not always guaranteed because it requires relatively large dc offset to be added to modulation signals in order to maintain voltage balance of the dc link capacitors.

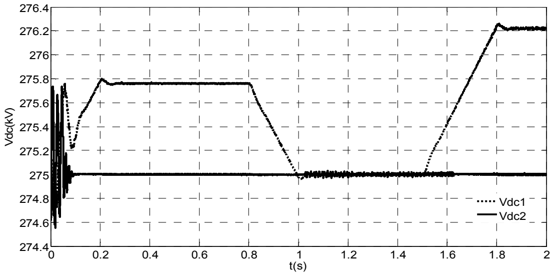
Case 2A

To demonstrate the control flexibility of VSC-HVDC transmission system based NPC, the system was started with operating conditions similar to that previous case and at time t=0.8 the power command is given to ramp down the active power from 100MW to 1MW within 200ms and maintain at 1MW until time t=1.5s. At time t=1.5s another active power command is given to ramp up again the power from 1MW to 160MW. From Fig. 5, it can be noticed that during the period from 0.8s to 1.5s both converters of the dc transmission systems are operating in sleep mode as STATCOM. Both converters VSC_1 and VSC_2 are absorbing small active power to maintain their dc link voltage at 275kV. This case demonstrate the typical scenario where there is no need to transfer the active power from AC system1 to 2 or vice versa. Therefore, instead of shutting down the dc link, the converters VSC_1 and VSC_2 of the VSC-HVDC transmission system must be switched to STATCOM mode to provide reactive power support to both ac systems 1 and 2.

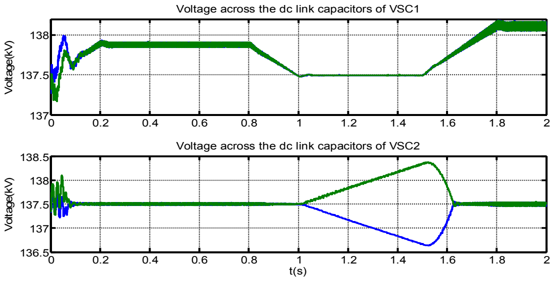

Active and reactive power at bus B1

Active and reactive power at bus B2

(a) Active and reactive power at buses B1 and B2



(b) Voltages across the dc link of converters VSC1 and VSC2


Voltage across the dc link capacitors of VSC1

Voltage across the dc link capacitors of VSC2

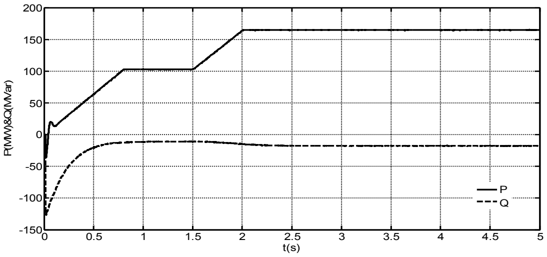
(c) Voltage across the dc link capacitors of converter VSC1 and VSC2

Fig. 5: Key waveforms to demonstrate the control flexibility of voltage source converter based on NPC

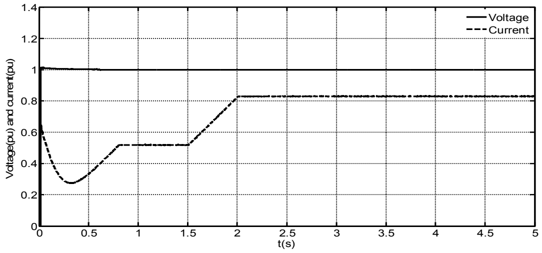
B. *Three-level modular converter*

Case 1B

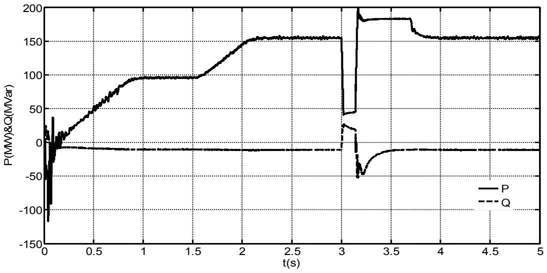
In this case, the converter VSC_1 and VSC_2 in Fig. 3 are replaced by three-phase modular converter. The results in Fig. 6 are obtained when the system is subjected the same operating condition as in case I with neutral point-clamped converters. It can be seen that the VSC-HVDC system using modular multilevel is able to recover without any problem and recovery of the dc capacitors voltages are faster than that in the system using neutral point-clamped converter. The results in Fig. 7 are obtained with similar operating condition as in previous case except the three-phase fault at point F is replaced by single-phase open circuit in phase A near to the AC system 2. From the results in Fig. 7, it can be noticed that the system with modular converter is able to recover and maintain the voltage balance of its dc link capacitors.



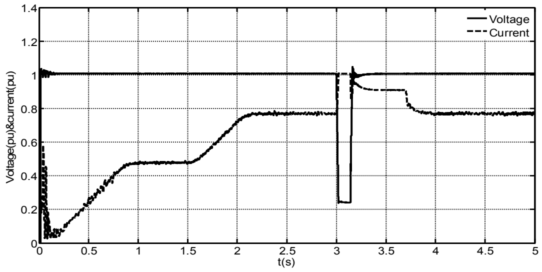
(a) Active and reactive power at bus B1



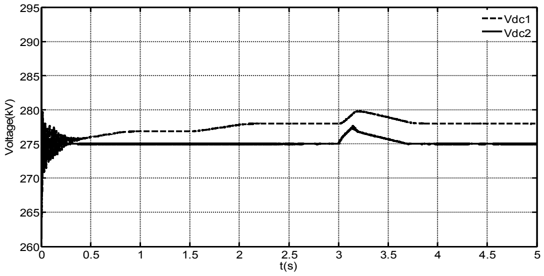
(b) Voltage and current magnitude at bus B1



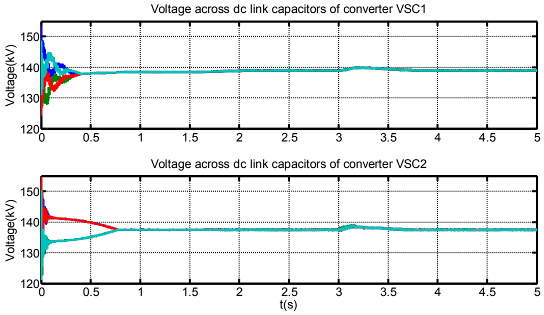
(c) Active and reactive power at bus B2



(d) Voltage and current magnitude at bus B2

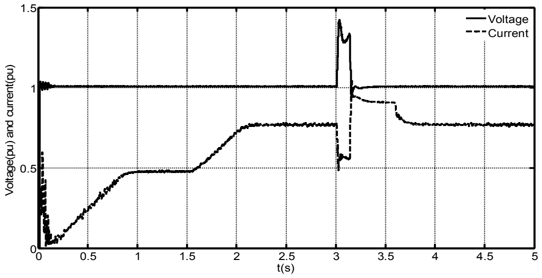


(e) DC link voltages of the converters VSC1 and VSC2

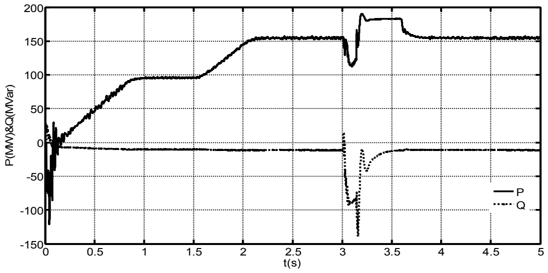


(f) Voltage across dc link capacitors of modular converters

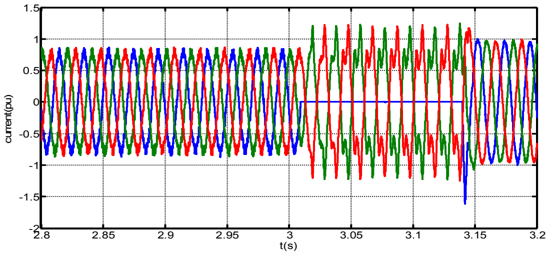
Fig. 6: they waveforms to demonstrate the reliability of VSC-HVDC transmission system based on modular converter, including three-phase short circuit at point F.



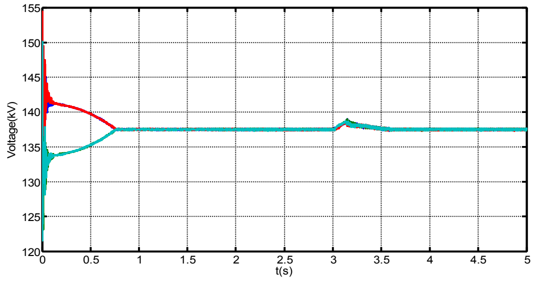
(a) Voltage and current magnitude at bus B_2



(b) Active and reactive power at bus B_2



(c) Three-phase current at but B_2

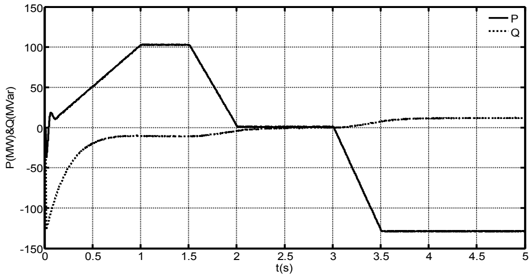


(d) Voltage across capacitors of converter VSC2

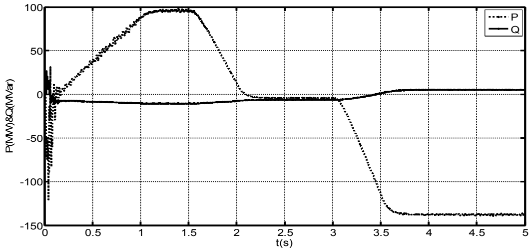
Fig. 7: Key waveforms during single-phase open circuit at B2

Case 2B

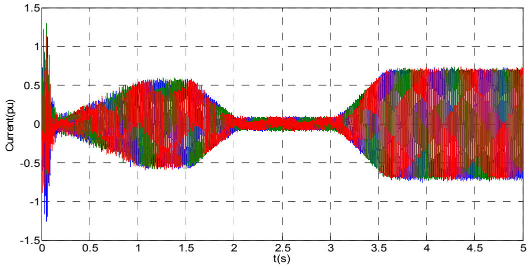
To demonstrate the control flexibility and robustness of VSC-HVDC transmission system based on modular converter. The system in Fig. 3 was started by ramping up the active power from 0 to 100MW within 1s and maintain at 100MW until 1.5s. At time t=1.5s the active power command is given to ramp down the power from 100MW to 500kW with 0.5s and maintain the same power level until t=2s, then another power command is given to reverse the power to -130MW within 0.5s. The results in Fig.8 show the ability of VSC-HVDC transmission system based on modular to operate successfully in sleep mode and during active power reversal without creating voltage imbalance between the dc link capacitors of modular converter.



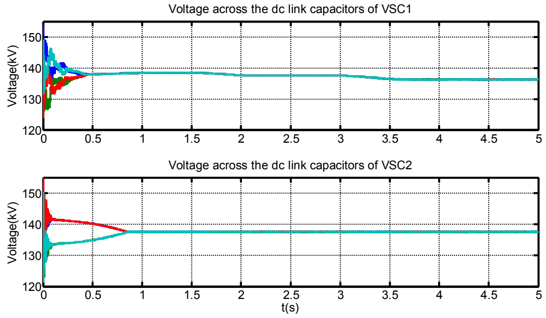
(a) Active and reactive power at bus B_1



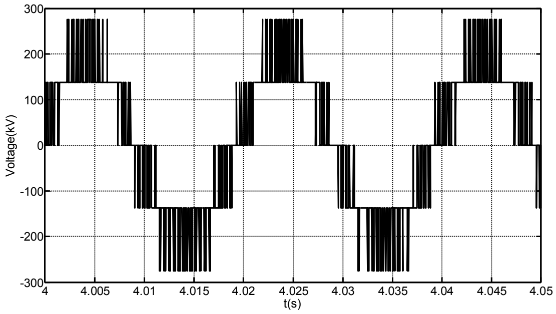
(b) Active and reactive power at bus B_2



(c) Three-phase current waveforms at bus B_2



(d) Voltage across dc link capacitors of modular converter in station VSC_1 and VSC_2



(e) Voltage at the terminal of converter VSC_2

Fig. 8: Key waveforms during sleep mode and active power reversal

V. CONCLUSIONS

The paper presents a detail comparison between two voltage source converter DC transmission technologies, mainly, neutral point clamped and three-level modular converter. The comparison focuses on reliability issues such as their ability to ride through the faults that include three-phase fault, line-to-line fault, single-phase to ground fault and single-phase open circuit fault; In addition to the flexibility of the control in both technologies. The results of this study are summarized as follow:

- Neutral point-clamped VSC-HVDC transmission systems when controlled with carrier based PWM perform better than that controlled using space vector modulation, and they are capable of riding through different types of faults such as symmetrical and asymmetrical faults excluding single-phase open circuit fault. However, the successful active power reversal cannot be guaranteed over full operating range of the system without using auxiliary voltage balancing circuit for dc link capacitors.
- VSC-HVDC transmission systems based on Modular multilevel converters are capable of riding through different types of ac faults and they are able to operate in sleep mode and reverse the power flow without creating voltage imbalance problem at the dc link capacitors.
- Since modular multilevel converter uses each cell in the structure for only *T/(n-1)*,where T is fundamental period and n is number of levels, and each switching device in the structure for only ½T/(n-1), the voltage source converter dc transmission system based on modular multilevel converter is excepted to have lower switching and conduction losses compare to that with NPC. In addition to better device utilization than NPC and smaller heat sink.
- Since the dc link capacitors of the diode clamped converters with more than three levels are difficult to balance, while the voltage balance of the dc link capacitors of modular converters are achievable regardless of number of levels, therefore, the use modular converters in application such as VSC-HVDC transmission systems are preferred, because with increased number of levels they generate low output voltage with low THD and dv/dt, have potential to eliminate interface transformer and output filter, improved system reliability and fault ride-through capability, and allow the use of commercial IGBT that may reduce the construction cost significantly.

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