Modeling of a Multi-level Converter Based MTDC System for the Study of Power System Steady-State and Transient Characteristics

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Abstract : *Multi-terminal High Voltage Direct Current HVDC (MTDC) systems are supposed to be one of the cost-effective ways to aggregate a huge amount of renewable energies on one side, and on the other side connect it to the main AC system through a common DC network. This paper investigates the dynamic performance of Voltage Source Converter (VSC) based Multi-terminal HVDC System in power transmission system, based on the analysis of the VSC model, the coordinated control strategy for the proposed MTDC system is discussed. Finally, a three terminal MTDC system is simulated for demonstrating the controller performance in the operation range against some steps change in power flow direction. Following that, typical operating contingency scenarios are simulated in order to evaluate transient performance. Simulation was carried out using PSCAD/EMTDC package.*

Key words: *HVDC, MTDC, VSC, Multilevel converter..*

1. INTRODUCTION

The world is facing today a global energy transition challenge since developed and emerging countries need more and more energy for their economy growth in a framework of limited and poorly distributed energy resources . In the meantime, the climate change owing to greenhouse gas emission leads to change the energy pattern with more climate-friendly energy resources such as hydro, wind or solar[1] [3].

The multi-terminal HVDC (MTDC) system was first developed in the 1980s in the Italy–Corsica–Sardinia HVDC project [2] [4]. Another MTDC system is the Quebec–New England project [5], transferring hydropower from Canada to USA. Both of these MTDC systems are current source converters CSC-HVDCs. However, the application of MTDC system using CSCs is, technically and operationally, limited because the direct current is always flowing in one direction between two converter terminals. Reversing the direction of the dc power flow between any two terminals can only be achieved by reversing the polarity of the dc voltage. This implies sophistication in the coordination of control and operation among terminals[7]. When VSCs are used in the MTDC system, the coordination of control and operation among terminals will be much easier compared to CSCs because the dc power flow is changed by changing the direct current direction and no need to change the polarities of direct voltage. Connecting a new VSC station to an existing VSC-HVDC system is like connecting an AC substation to an AC grid [8].

The paper proposes the use of voltage source converter based MTDC system for outward transmission of the large-scale power. An MTDC system for aggregating and dispatching power is proposed firstly and then the coordinated control strategy for the proposed MTDC system is discussed. Finally, a three-terminal MTDC system connecting three AC sources is simulated for demonstrating the performance of the MTDC system under steady state and transient. Finally, simulations and results are presented in PSCAD/EMTDC [6].

2. MULTITERMINAL HVDC TRANSMISSION MODEL

A. TOPOLOGY ANALYSIS

In general, the typical layouts of the multiterminal DC grids can be divided into three types of structures shown in the fig.1. The radial stricture is shown in fig.1 (a), the operation and control are not as complex as those for the interconnected triangle and meshed structures in fig .1. (b)&(c).

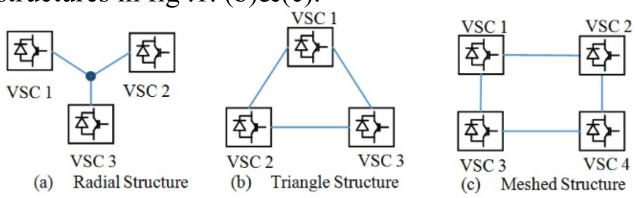


Fig. 1. Topologies for Typical MTDC Structures

However, in terms of the operation reliability, the interconnected structures can be extended with the combination among those three basic structures [9-10]. For the current condition, the initial three-terminal VSC-based MTDC grid with the radial topology is proposed in many HVDC system projects in the world for delivering the offshore wind energy.

Three series connected DC capacitors of same size are employed across the DC transmission line with grounded midpoint for VSC operation, to reduce the ripples in DC voltage. A smoothing reactor is also connected in series with transmission line for reducing the ripple in DC current. During failure or scheduled maintenance of one pole of transmission line, a reduced amount of power can still be transmitted by other pole [8-11].

B. FUNDAMENTAL OF VSC-HVDC TRANSMISSION

The fundamentals of VSC transmission operation may be explained by considering each terminal as a voltage source connected to the AC transmission network via a three-phase reactor. Changing the fundamental frequency, voltage phase angle across the series reactor controls the power; whereas, changing the fundamental frequency voltage magnitude across the series reactor controls the reactive power. If three voltage source converters (VSC) are connected together, an asynchronous transmission link is formed. The converters can be connected in back-to-back configuration or at either end of a transmission line or cable, as schematically shown in Fig. 1[12].

Fig. 2 shows a phasor diagram for the VSC converter connected to an AC network via a transformer inductance. The fundamental voltage on the valve side of the converter transformer, i.e. $U_{V(1)}$, is proportional to the DC voltage has been expressed in equation (1) [13].

$$U_{v(1)}=k_u.U_d \quad (1)$$

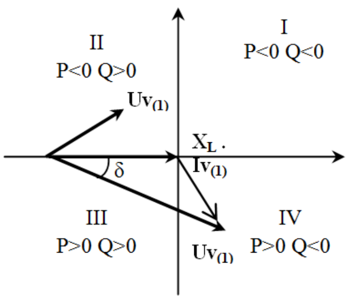


Fig.2. Phasor diagram of VSC and direction of power flows

The quantity can be controlled by applying additional number of commutation per cycle, i.e. applying pulse with modulation (PWM). Using the definition of the apparent power and neglecting the resistance of the transformer results in the following equations for the active and reactive power:

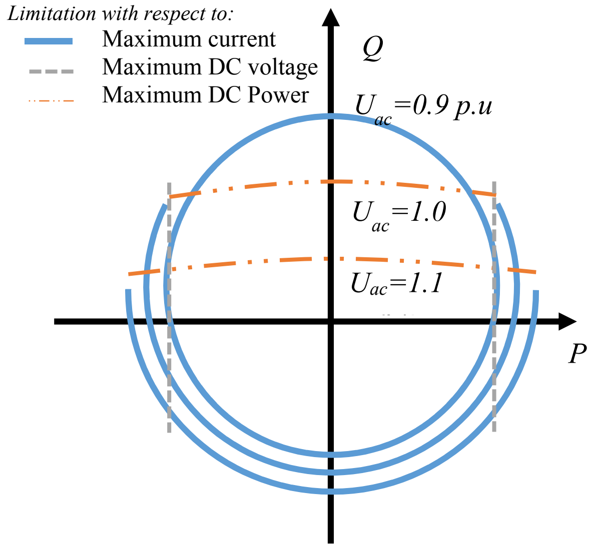
$$P = U_d.I_d = \frac{U_L.U_{v(1)}}{X}\sin\delta \quad (2)$$

$$Q = \frac{U_L\left(U_L - U_{v(1)}.\cos\delta\right)}{X_L} \quad (3)$$

The active power and reactive power exchanged by VSC-HVDC and AC system can be adjusted promptly by change the magnitude and angle of the output AC voltage of the VSC-HVDC. This characteristic of VSC-HVDC makes itself more flexible than other FACTS technology, such as SVC, STATCOM, also than traditional HVDC. By means of Pulse Width Modulation (PWM) technology, especially Sinusoidal PWM (SPWM), two degrees of freedom, i.e. phase and amplitude can be acquired. Phase and Amplitude Control (PAC) technology is developed for VSC-HVDC applications [6,7]. The VSC can easily interchange active and reactive power with an AC network as well as a synchronous machine [13].

However, the extent of the active power and reactive power, which can be adjusted in VSC-HVDC, is subject to the rate power limit and the operation condition of the time. The adjusting ability of the active power and that of the reactive power influence each other dynamically. Therefore, it is necessarily to analyse the ability in real time.

As explained before, active and reactive power can be controlled independently as long as they are not exceeding the operating limits fixed by the converter and the DC line rating. All these limits are reported in Figure.3 [1] [10]. The three main quantities, which limit the VSC range of operation, are:



(1) The maximal admissible AC current feeding in the converter.
(2) The maximal converter voltage on the AC side.
(3) The maximal DC current.

Fig.3. P-Q characteristics of a VSC-HVDC system [14]

$$P^2 + \left(Q - \frac{U_L^2}{X_L}\right)^2 = \left(\frac{U_L . U_{v(1)}}{X_L}\right) \qquad (4)$$

If the output voltage of the converter U_V (1) is reduced, e.i by using PWM, supply of any active and reactive power within the circle is possible [10].

3. CONTROL STRATEGY

Generally, the control strategy of a multi terminal VSC-HVDC transmission line is to keep one terminal DC voltage constant as operation point, and adjust the other terminals DC current or active power order. The AC voltage or the reactive power of all terminals can be controlled [13-17].

Fig. 4 shows an overview diagram of the VSC control system and its interface with the main circuit [10] [19]. The converter 1 and converter 2 & 3 controller designs are identical. The three controllers are independent with no communication between them. Each converter has two degrees of freedom. In our case, these are used to control:

1.DC voltage and AC voltage in station 1.

2.Active power and AC voltage in station 2 & station3

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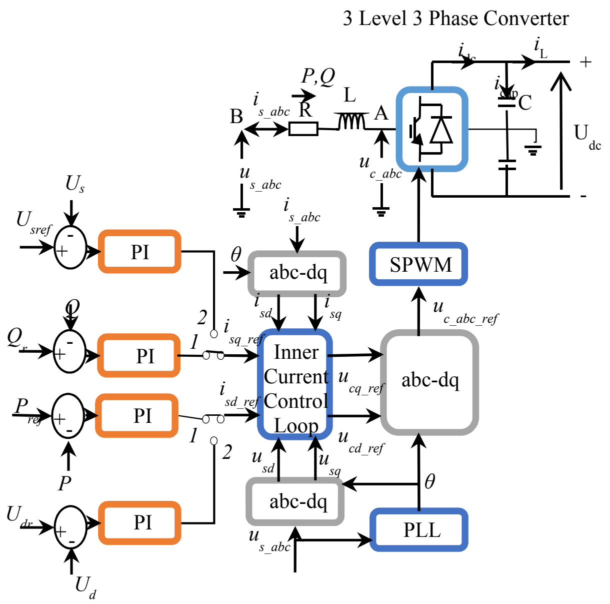

Fig.4. Overview diagram of the VSC control system

3.1 Phase locked loop

The phase locked loop (PLL) shown in fig.5 is used to synchronize the converter control with the line voltage and also to compute the transformation angle used in the d-q transformation. The PLL block measures the system frequency and provides the phase synchronous angle Θ for the d-q transformations block. In steady state, sin (Θ) is in phase with the fundamental (positive sequence) of the α component and phase A of the point of common coupling voltage (U_{abc}).

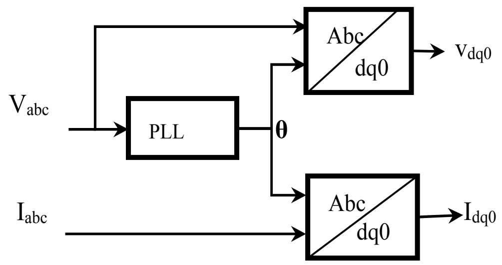

Fig.5. Phase locked loop block

3.2 Outer active and reactive power and voltage loop

The active power or the DC voltage is controlled by the control of δ and the reactive power is controlled by the control of the modulation index (*m*). The instantaneous real and imaginary power of the inverter on the valve side can be expressed in terms of the *dq* component of the current and the voltage on the valve side as follows:

$$p = \frac{3}{2} \cdot \mathrm{Re}(\bar{u}_f^{dq} \cdot \bar{i}_v^{*dq}) = \frac{3}{2} \cdot (u_{fd} \cdot i_{vd} + u_{fq} \cdot i_{vq}) \qquad (5)$$

$$q = \frac{3}{2} \cdot \mathrm{Im}(\bar{u}_f^{dq} \cdot \bar{i}_v^{*dq}) = \frac{3}{2} \cdot (-u_{fd} \cdot i_{vq} + u_{fq} \cdot i_{vd}) \qquad (6)$$

If the reference of the *dq*-frame is selected such that the quadrature component of the voltage is being very small and negligible ($u_{Lq} \approx 0$) then the equations (5) and (6) indicate that the active and the reactive power are proportional to the d and q component of the current respectively. Accordingly, it is possible to control the active power (or the DC voltage or the DC current) and the reactive power (or the AC bus voltage) by control of the current components i_{vd} and i_{vq} respectively. The active and reactive power and voltage loop contains the outer loop regulators that calculate the reference value of the converter current vector (I^*_{dq}) which is the input to the inner current loop [17].

3.3 Inner current loop

The AC Current Control block tracks the current reference vector (“d” and “q” components) with a feed forward scheme to achieve a fast control of the current at load changes and disturbances (e.g., so short-circuit faults do not exceed the references) [5] [6] [7]. In essence, it consist of knowing the U_dq vector voltages and computing what the converter voltages have to be, by adding the voltage drops due to the currents across the impedance between the U and the PWM-VSC voltages. The state equations representing the dynamics of the VSC currents are used (an approximation is made by neglecting the AC filters). The “d” and “q” components are decoupled to obtain two independent first-order plant models. A proportional integral (PI) feedback of the converter current is used to reduce the error to zero in steady state. The output of the AC Current Control block is the unlimited reference voltage vector Vref_dq_tmp.

3.4 DC voltage balance control

The difference between the DC side voltages (positive and negative) are controlled to keep the DC side of the three level bridge balanced (i.e., equal pole voltages) in steady-state. Small deviations between the pole voltages may occur at changes of active/reactive converter current or due to nonlinearity on lack of precision in the execution of the pulse width modulated bridge voltage. Furthermore, deviations between the pole voltages may be due to inherent unbalance in the circuit components impedance [22].

4. SYSTEM INVESTIGATED

A 3-terminal VSC-MTDC connected three active AC networks, simulation model is established in PSCAD/EMTDC simulation tool and the system structure is shown in fig.6. The base voltage of system and the transformer ratio are the same in system 1 and 2: 420 kV and 420/230 kV, the ones of system 3 are 500 kV and 500/230kV, the frequency is the same for system 2 and 3: 50Hz and 60 Hz for the system1. The VSC 1 operates in the constant DC voltage and constant AC voltage mode, and the DC voltage is set to 400 kV. The VSC 2 and VSC 3 operate in the constant active power and constant AC voltage mode, the active power setting is 100 MW in VSC2 (rectifier) and -200MW in VSC3 (inverter).

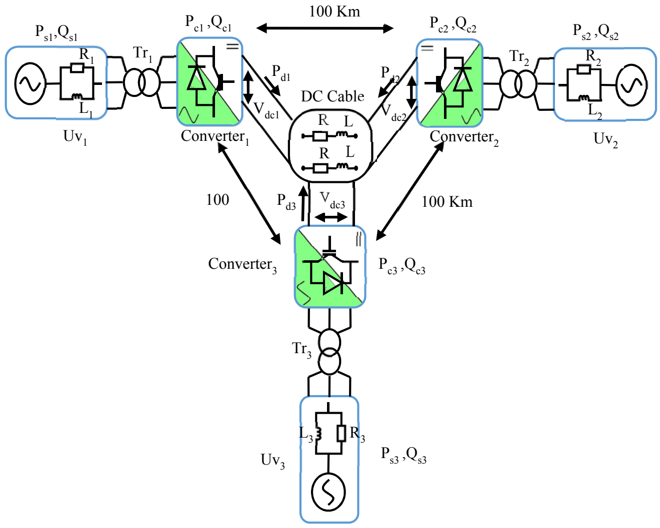

Fig.6. Three-terminal VSC-HVDC

5. MODEL PERFORMANCE ANALYSIS

The dynamic performance of the transmission system is verified by simulating the:

-Active power flow reversal.

-VSC_HVDC response to external AC single phase to ground fault.

-VSC_HVDC response to external AC three phase to ground fault.

Case1:

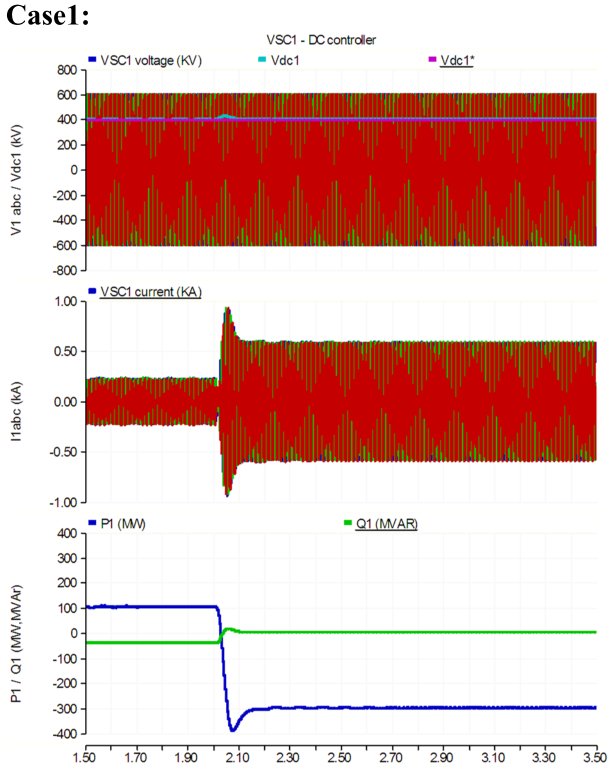

Fig. 7. Steps on the regulators references (VSC1).

In Fig.7,8,9 the initial reference value of the power flow is 100 MW at VSC1 and VSC2, and -200MW at VSC3. At t=2s, the reference value in VSC3 is reversed from -200 MW to +200 MW. It can be seen that the active power follows the reference rapidly with a slight oscillation and reaches the new reference of -300 MW within 0.05 s. correspondingly, the active power at VSC 1 changes around from 100 MW to -300 MW while the active power at VSC2 remains at the same value of 100 MW.

At the same time, the reactive power flow changes with the active power reversal at VSC1 and VSC3 and remains the same at VSC2

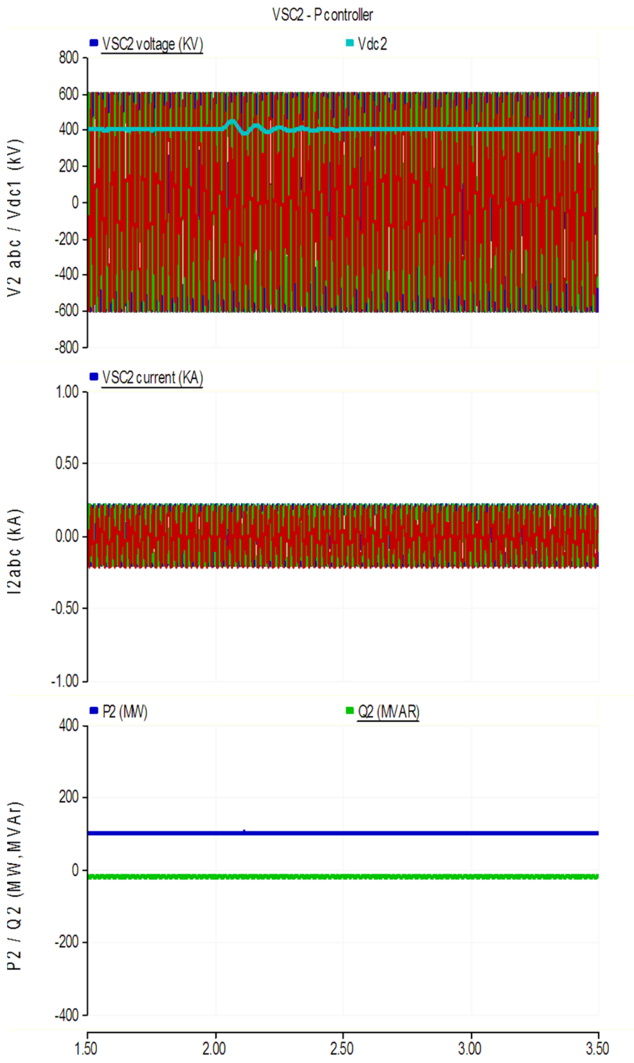

Fig. 8. Steps on the regulators references (VSC2).

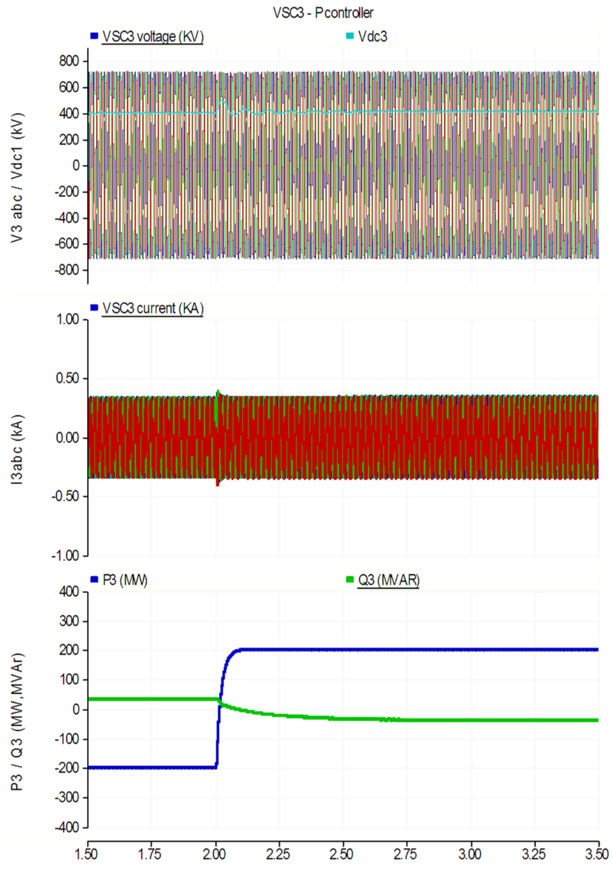

Fig. 9. Steps on the regulators references (VSC3).

As can be seen, the active power can track the reference of the active power. The transferred active powers at VSC1 and VSC3 change the direction, which causes slight transients on the DC voltage of the three converters then returns to the reference value due to the DC voltage controller. The AC current at VSC1 change from 0.25 kA to 0.75 kA caused by the active power reversal with an oscillation and stabilized after 0.05s while the AC currents at VSC2 and VSC3 remains the same. The AC voltages at the three converters can be kept constant without noticeable transients when the step changes are applied.

Case 2:

A single phase to ground fault was applied at t = 2s during 0.1s (6 cycles) at AC side of VSC3 in order to investigate the behavior of VSC-MTDC during unbalanced faults, Fig.10,11,12 presents the simulations results.

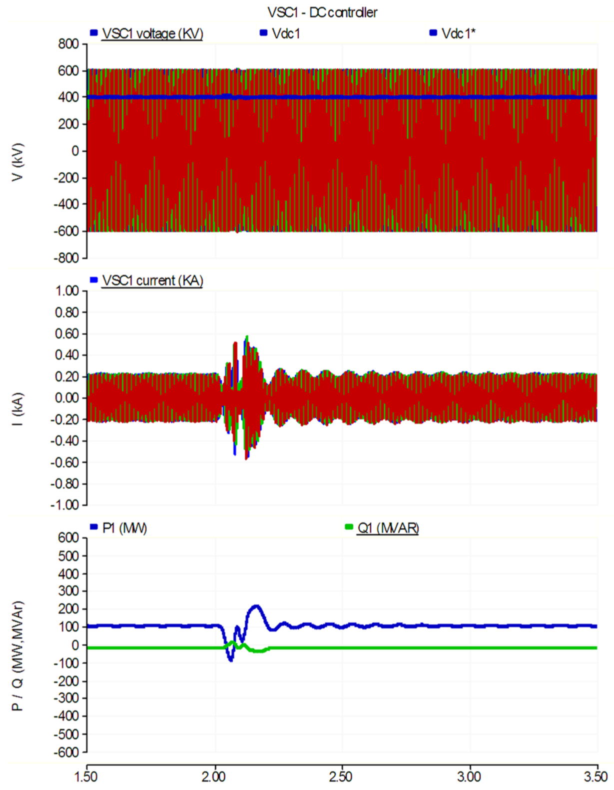

Fig. 10. Steps on the regulators references (VSC1).

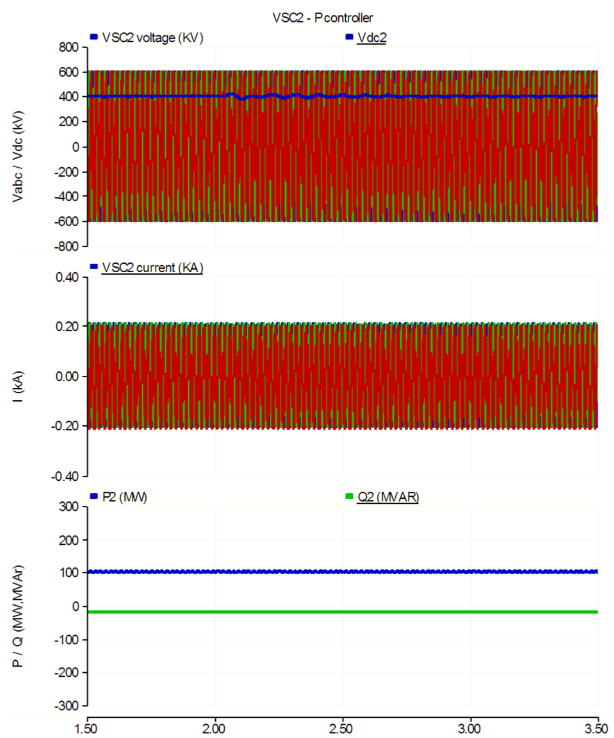

Fig. 11. Steps on the regulators references (VSC2).

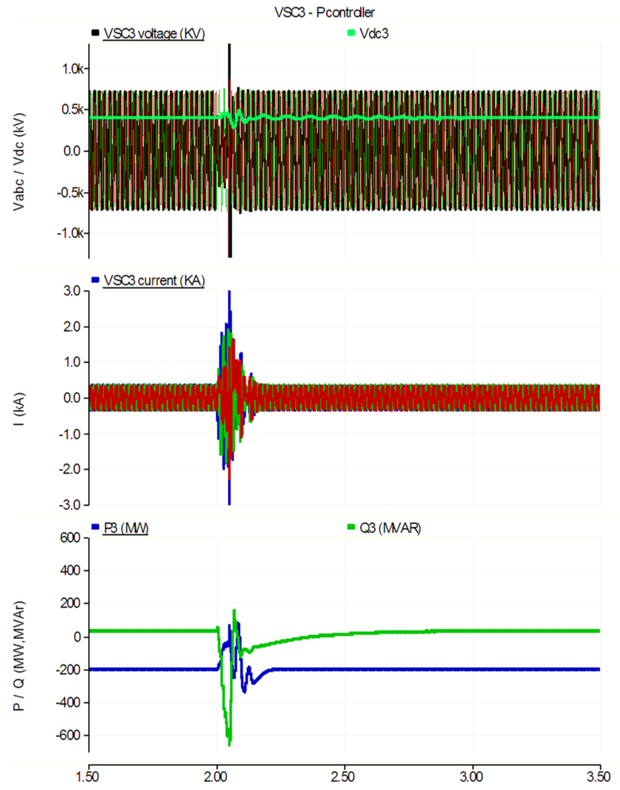

Fig. 12. Steps on the regulators references (VSC3).

From the simulation, fig.10 shows that before a single phase to ground fault at VSC1, the active power flow is 100 MW, and shock seriously during the fault and restore stability after 0.2s running when the fault is removed, while a slight oscillation is noticed on the reactive power flow.

The fault causes also the AC current oscillation at VSC1, and stabilized after 0.2s when the fault is removed.

It can be seen from fig.11 the VSC2 remains intact during the fault, and from fig.12 the active and reactive power flow in VSC3 shock seriously during the fault and restore stability after 0.1s running when the fault is removed, the fault also causes transient on the AC current and voltage.

The DC voltage of the three converters contains a slight oscillation during the fault. In addition, the AC voltage of VSC1 and VSC2 can be kept constant.

Case 3:

A three-phase to ground fault is applied at AC side of VSC3 at t = 2 s, in order to investigate the behaviour of VSC-MTDC during symmetrical faults, and is cleared at 6 cycles after the fault, i.e., at t = 2.1s. Fig.13,14,15 presents the simulations results.

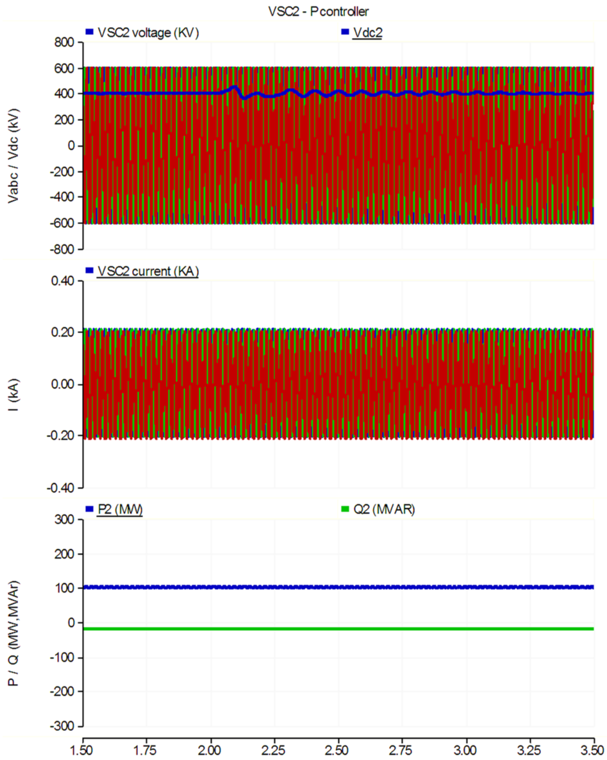

Fig. 13. Steps on the regulators references (VSC2).

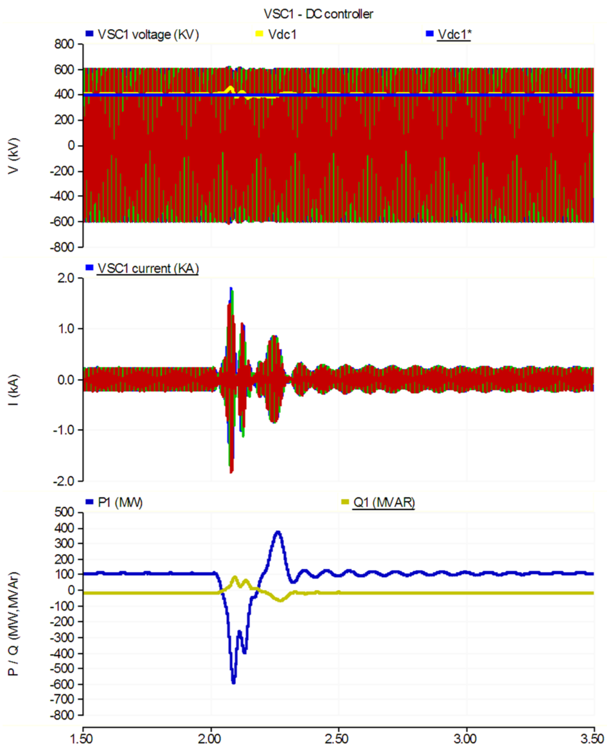

Fig. 14. Steps on the regulators references (VSC1).

The DC voltage of the three converters contains a slight oscillation and the VSC2 remains intact during the fault.

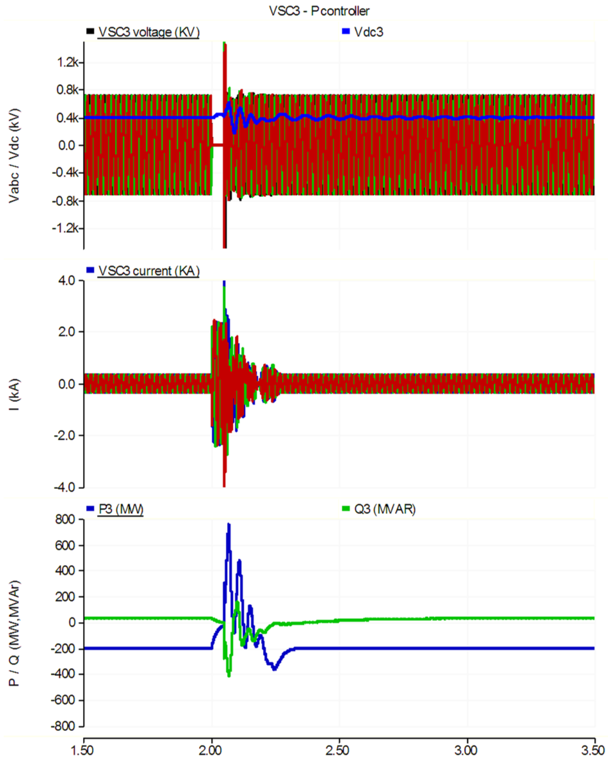

Fig. 15. Steps on the regulators references (VSC3).

During the three-phase fault, the active and reactive power of the VSC1 and VSC3 still tracing the reference value with a noticeable oscillation, and reach stability after 0.8s when the fault is cleared, the AC current of the VSC1 and VSC3 also present a transient and restore stability after 0.3s. The AC voltage of the VSC1 remains intact while the AC voltage of the VSC3 drops to zero and recovers after 0.2s running when the fault is removed.

6. CONCLUSION

In this paper, we have presented the steady state and dynamic performances of Multiterminal HVDC Transmission system during step changes of the active power, balanced and unbalanced faults. In all cases, the proposed control strategy (coordinated control) has been shown to provide fast and satisfactory dynamic responses of the proposed system. From the simulation, it can be obtained that the VSC-HVDC can fulfil fast and bi-directional power transfers. It can be obtained also that during a single-phase fault the transmitted power can be kept constant except a small oscillation during the fault. However, during a three-phase fault; the decreased voltage at the converter terminals strongly reduces the power flow by the DC link. When the fault is cleared, normal operation is recovered fast.

The system advantages of deploying a VSC based Multiterminal HVDC network with standby dynamic voltage control during network contingencies. The controlled power transfer capability allows an easy connection of a new offshore load/generation terminal and the exchange of power between the several networks with different frequencies (50/60 Hz).

APPENDIX

Table 1. The parameters of MTDC

	Station1	Station2	Station3
Uv(kV)	420	420	500
S(MVA)	1500	1500	1500
SCR	2.5	2.5	2.5
Z(Ω)∠ (degree)	26.45 ∠80°	26.45 ∠80°	26.45 ∠80°
f(Hz)	60	50	50
Transformer	Yg/Δ,420kV/ 230kV	Yg/Δ,420kV/ 230kV	Yg/Δ,500 kV/230k V
Main DC capacitor	2x300 μF		
DC Cable	100 Km×2 (R_d=0.0139 Ω /km, L_d = 0.159 mH/km)		
Switching frequency	1980 Hz		

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