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Investigation of Hybrid Pseudo Bipolar HVDC Performances Supply Power to Passive AC Network

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Abstract: The traditional HVDC plays an important role in the development of power grid. But the traditional HVDC cannot supply power either to entirely passive AC network or to weak AC system. In fact, an entirely passive AC network can be effectively powered through VSC-HVDC. However, the cost of investment in VSC-HVDC is amazingly high due to the limitation of power electronics technology. Based on CSC and VSC, this paper proposes a method to build Hybrid HVDC, which makes the power supply to the passive AC network come true and, at the same time, lowers the investment cost. The effect of topology, steady mathematical model, startup characteristic, steady and transient characteristics in Hybrid HVDC system are systematically studied in this paper. The simulation result shows that Hybrid HVDC can supply power to the passive AC network with high stability. This study provides a theoretical basis for the further development of HVDC. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Hybrid high voltage direct current, Current source converter, Voltage source converter, Passive network.

1. Introduction

The HVDC system, which can be divided into flexible DC system based on Voltage Source Converter (VSC) and traditional DC system based on Current Source Converter (CSC) due to the difference of the DC-side power, has been widely used and matured in the accelerating process of large power grid interconnection.

Though CSC-HVDC is a proven technique, it is only applied when supplying power to high short circuit ratio system, and cannot realize the power supply to passive AC system [1]. A lot of work had been done on VSC-HVDC and business operation had been realized in the development of power electronics [2-3]. Compared with the CSC-HVDC, the VSC-HVDC not only works well in the passive network but it also can realize reactive power and active power decoupling control. Modular Multilevel Converter (MMC) based on VSC-HVDC, which was proposed by Siemens Company, can reduce the operating loss and improve the transmission efficiency [4].

Extensive and in-depth research had been done on VSC-HVDC used in connecting wind power to grid, supplying power to offshore drilling platform, supplying power to passive big cities because of the advantages of supplying power to passive network, high power factor, small harmonic influence and high stability, etc. [5-9]. The research about VSC-HVDC mainly focuses on control mode and controller parameters optimization [10-12].

Many scholars carried out related research on multi-terminal hybrid HVDC. Reference [13] proposed a new hybrid bipolar HVDC based on CSC-HVDC and VSC-HVDC. Though the topological structure has the ability of supplying power to passive network, it cost highly on investment and get low economic benefit. Reference [14] proposed multi-terminal HVDC (MTDC) based on VSC and CSC. MTDC possesses both the advantages of CSC-HVDC and VSC-HVDC and effectively extends the use of traditional DC. However, MTDC has disadvantages of coordinated control complex among multiple converter stations. The coordination control strategy should be further studied especially among the converter stations when MTDC system is divided into two-terminal HVDC system in the case of failure. Reference [15] proposed two-terminal hybrid HVDC based on VSC and CSC. But the system is limited to the case of both ends are AC networks, and further study should be done on supplying power to passive network.

VSC-HVDC has a high investment because of the limit of power electronic technology, so VSC-HVDC can only be applied in the small capacity of DC transmission system. CSC-HVDC has a low investment compared with VSC-HVDC, but CSC-HVDC can't supply power to passive network. Especially in the 21st century, people are increasingly demanding on the environment. There will be more and more passive cities and big load cases because of power stations being away from electricity market. In view of the above situations, this paper proposed a hybrid topology that could supply power to passive network base on VSC and CSC.

This paper describes the principles of the proposed hybrid system, main control strategies, topological structure when supply power to passive network. And the characteristics of hybrid HVDC startup, steady state, transient properties are studied further. PSCAD/EMTDC is used to validate the system performance under various operating conditions. The simulation result shows that proposed topology and control strategy can effectively realize passive network power supply, and this hybrid HVDC is stable.

2. Hybrid HVDC System

2.1. Topological Structure

The topology structure of hybrid HVDC system is shown in Fig. 1.

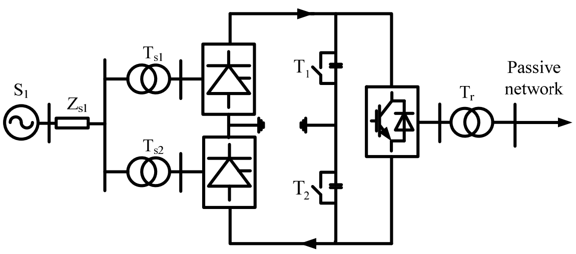

Fig. 1. Topology diagram of Hybrid-HVDC.

In Fig. 1, the rectifier is connected with AC network and the inverter is connected with passive network. In this paper, S1 is the equivalent sending AC system and Zs1 stands for impedance of equivalent system. T1 and T2 stand for the bypass switch with capacitor in parallel. Rectifier includes two six-pulse converters based on CSC and inverter includes a six-pulse converter based on VSC. This DC topology is asymmetric between rectifier and inverter, so this topology is named the pseudo bipolar system.

The CSC-HVDC engineering mostly adopts two six-pulse converter stations because of the CSC can be blocked easier, and study of this converter station filter is more mature. In order to ensure the transmission capacity as large as possible, while guarantee the reliability of the transmission as much as possible to reduce construction investment. Pseudo bipolar structure is elected as transmission model that supply power to passive network.

The switch T1 is closed when the positive pole rectifier blocked. The pseudo bipolar HVDC system negative pole and the earth could come into being a circle and converted into monopole operation mode. The pseudo bipolar HVDC system could realize monopole operation in some cases, and this topology further increase the stability of the system.

Three-phase two-level model is used as inverter. The topology is shown in Fig. 2.

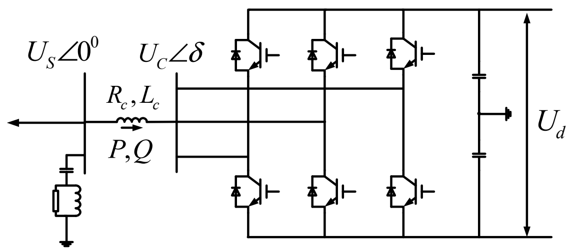

Fig. 2. Topology diagram of two-level VSC.

2.2. Steady State Mathematical Model

Mathematical model of rectifier can be expressed as

$$I_{dr}=\frac{U(\cos\gamma-\cos(\gamma+\mu))}{\sqrt{2}n_{r1}X_{r1}}, \quad (1)$$

$$U_{dr}=\frac{3\sqrt{2}U}{\pi n_{r1}}\cos\gamma-\frac{3}{\pi}X_{r1}I_{dr}, \quad (2)$$

$$\cos\phi=-[\cos\gamma+\cos(\gamma+\mu)]/2, \quad (3)$$

$$P_{dr}=U_{dr}I_{dr}, \quad (4)$$

$$Q_{dr}=P_{dr}\tan\phi, \quad (5)$$

where U is the converter bus voltage of rectifier, I_{dr} and U_{dr} are the DC current and DC voltage of rectifier, μ and γ are the overlap angle and turn-off angle, X_{r1} is the transformer leakage reactance of rectifier, P_{dr} and Q_{dr} are the active and reactive power from rectifier.

Inverter VSC using the pulse width modulation (PWM) technology, and the mathematical model can be written as

$$P_{di} = \frac{U_s U_c}{X_i}\sin\delta, \quad (6)$$

$$Q_{di} = \frac{U_s(U_s - U_c\cos\delta)}{X_i}, \quad (7)$$

$$U_c = \frac{\mu m}{\sqrt{2}} U_{di}\angle\delta, \quad (8)$$

where U_s and U_c are the fundamental frequency voltage component of grid side and converter valve side, U_{di} is the DC voltage of inverter, δ is the phase angle difference between U_s and U_c, P_{di} and Q_{di} are the active and reactive power to inverter, X_i is the commutation reactance of inverter, μ is the DC voltage utilization, and m is the modulation degree.

3. Control Strategy

3.1. Rectifier Control Strategy

Rectifier control strategy is shown in Fig. 3.

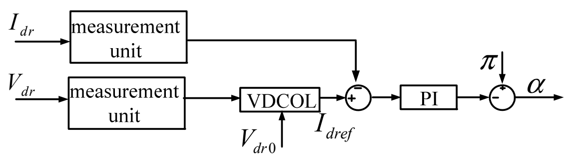

Fig. 3. Rectifier controller.

In this figure I_{dref} is the DC current reference value, I_{dr} and V_{dr} are the DC current and DC voltage measured value at rectifier. The V_{dr} under the action of Voltage Dependent Current Order Limit (VDCOL) get the I_{dref}. Then the deviation between I_{dref} and I_{dr} passed the PI and get the firing angle α.

3.2. Inverter Control Strategy

Inverter using D-Q decoupling control strategy, which stands for DC current double closed loop decoupling control strategy, is used widely in the PWM modulation.

According to the general control law of VSC-HVDC system, the VSC-HVDC needs to provide stable AC voltage when supply power to passive network. Therefore, the reactive power control class should adopt constant AC voltage control strategy. In order to realize the hybrid HVDC transmission power level constant, the active power control class of inverter should adopt constant DC voltage control strategy. In conclusion, inverter uses constant AC-DC voltage control strategy.

Control logic diagram of inverter side is shown in Fig. 4.

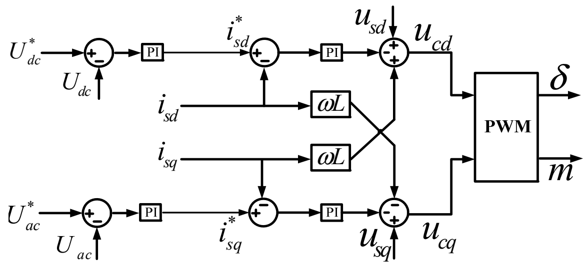

Fig. 4. Inverter controller.

Where u_{sd} and u_{sq} are D and Q axis component of the grid voltage, u_{cd} and u_{cq} are D and Q axis of the AC voltage fundamental component, i_d and i_q are D and Q axis of the grid current, R and L are the equivalent resistance and inductance of transformer add phase reactor.

Therefore, the m and δ of VSC control variable can be expressed as

$$m = \frac{2\sqrt{u_{cd}^2 + u_{cq}^2}}{U_{dc}}, \quad (9)$$

$$\delta = \arctan\frac{u_{cd}}{u_{cq}} \quad (10)$$

3.3. Coordinated Control Strategy

The rectifier consists of constant DC current control, VDCOL and minimum firing angle control. Rectifier is working in the constant DC current control at steady state. The inverter uses double closed loop decoupling control strategy which is constant AC-DC voltage control. The coordinated control strategy is shown in Fig. 5.

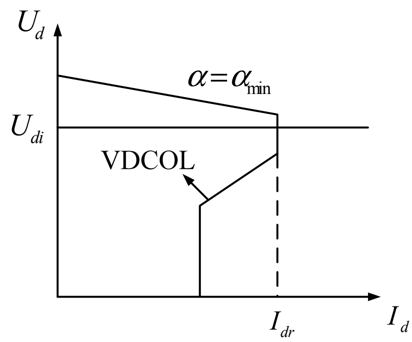

Fig. 5. Coordinated control strategy of Hybrid HVDC.

4. Operating Characteristic

4.1. The System Parameters

The hybrid HVDC system was studied using PSCAD/EMTDC. In order to realize supply power to the passive cities, the rated power and rated voltage are 400 MW and ±200 kV. The rectifier side AC voltage is 220 kV and the inverter side passive network voltage is 10.5 kV. The inverter side DC capacitance is 600 µF and the phase reactor is 0.0543H. The optimal allocation of reactive power and the harmonic characteristic are not the focus of this paper, therefore not described in detail.

4.2. Steady State Operation

1) Startup Characteristic

Because of the VSC converter station there is no support power at inverter, the start strategy is that the rectifier and inverter turn start successively. Firing the rectifier at 0.04 s firstly, and then unlock the inverter at 0.2 s when DC capacitance charging is complete. The converter bus voltage of rectifier and inverter are shown in Fig. 6.

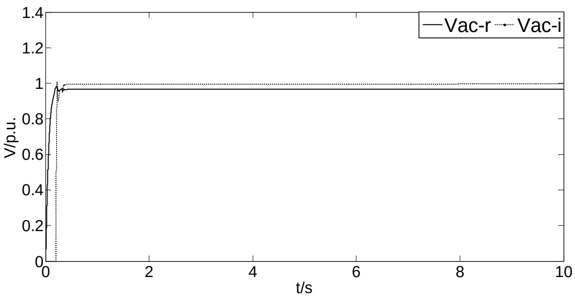

Fig. 6. Converter bus voltage of rectifier and inverter.

In Fig. 6, the converter bus voltage of rectifier and inverter achieve 220 kV and 10.5 kV rapidly. It can also be seen from Fig. 6 that the hybrid HVDC have advantage of good start strategy and fast startup, and the system can achieve stable operation state at 0.4 s.

2) Steady Characteristic

Transmission power of rectifier and inverter are shown in Fig. 7.

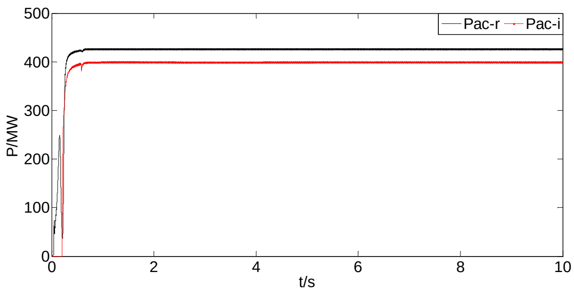

Fig. 7. Transmission power of rectifier and inverter.

It can be seen from Fig. 7 that the transmission power of rectifier and inverter are 420 MW and 400 MW. The DC power loss is 20 MW and the loss rate is 5 %. The DC voltage of rectifier and DC current are shown in Fig. 8 and Fig. 9.

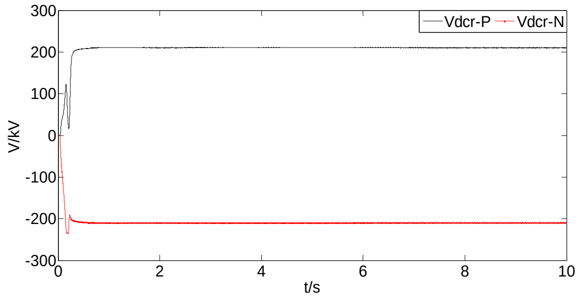

Fig. 8. DC voltage of rectifier.

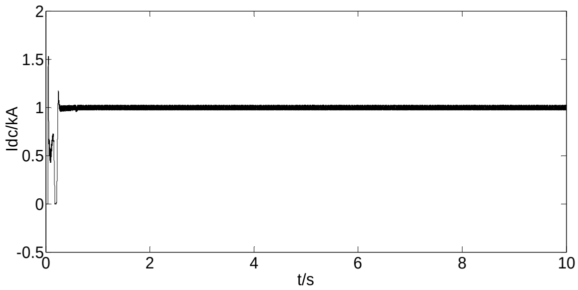

Fig. 9. DC current.

It can be seen from Fig. 7-Fig. 9 that hybrid HVDC have a good steady characteristics, and the system can quickly start and achieve the rated running state. The system can meet the demand of practical engineering.

4.3. Transient State Operation

1) Three-phase Ground Fault at Rectifier

Applying a three phase to ground fault of 0.02 s on the rectifier converter bus at t=2 s. DC voltage and current of rectifier after disturbance are shown in Fig. 10 and Fig. 11.

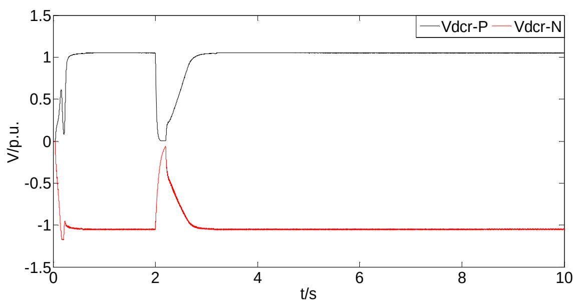

Fig. 10. DC voltage of rectifier after rectifier fault.

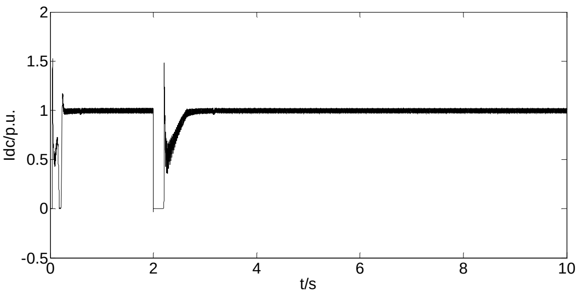

Fig. 11. DC current after rectifier fault.

It can be seen from Fig. 10 and Fig. 11 that the DC voltage drops to 0 when fault occurs, and the system can quickly restore stability when the fault clearing. The DC current drops to 0 when fault occurs at rectifier side. The frequency of inverter converter bus is shown in Fig. 12.

In Fig. 12, the frequency of inverter converter bus drops to 46 Hz, and keep in 46 Hz during the fault. The frequency restores 50 Hz quickly when fault clearing.

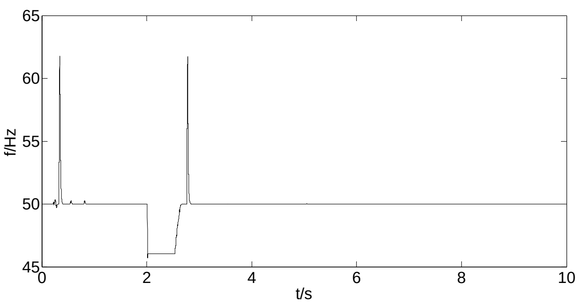

Fig. 12. The frequency of inverter converter bus after rectifier fault.

2) Three-phase Ground Fault at Inverter

The same fault occurred in the inverter converter bus. DC voltage and current of rectifier are shown in Fig. 13 and Fig. 14.

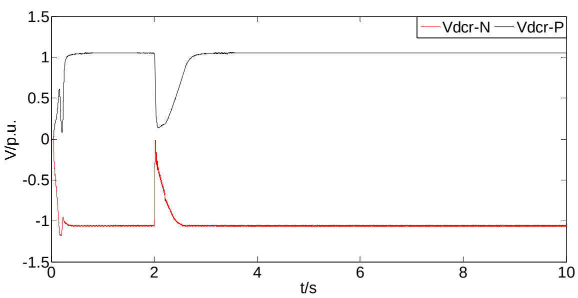

Fig. 13. DC voltage of rectifier after inverter fault.

It can be seen from Fig. 13 and Fig. 14 that the DC voltage drops to 0 when fault occurs, and the system can quickly restore stability when fault clearing. The DC current drops to 0.5 p.u. when fault occurs on inverter.

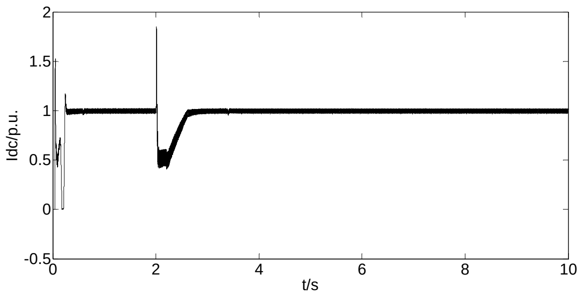

Fig. 14. DC current after inverter fault.

The frequency of inverter converter bus is shown in Fig. 15.

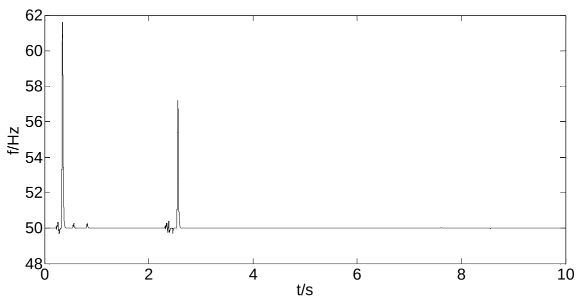

Fig. 15. The frequency of inverter converter bus after inverter fault.

In Fig. 15, the frequency of inverter converter bus has a larger fluctuation when unlock the inverter and clear the fault, and frequency has no fluctuation during the fault.

In Fig. 12 and Fig. 15, the frequency has a bigger fluctuation when fault occurs at rectifier, which because of the reference frequency of PLL (Phase Locking Loop) derived from the AC voltage of rectifier converter bus.

It can be seen from Fig. 10-Fig. 15 that the system fluctuates when fault occurs at rectifier or inverter converter bus, and the system can quickly restore stability when fault clearing. The simulation result shows that the hybrid HVDC system has high stability and strong anti-interference. Especially, the AC voltage and frequency of passive network could be maintained stability at the steady state, and the voltage and frequency could quickly restore stability when fault clearing.

3)Single-phase Ground Fault

Applying a single phase to ground fault of 0.02 s on the rectifier and inverter converter bus at t=2 s. The DC current and the frequency of inverter converter bus are shown in Fig. 16 and Fig. 17 when fault at rectifier side and inverter side.

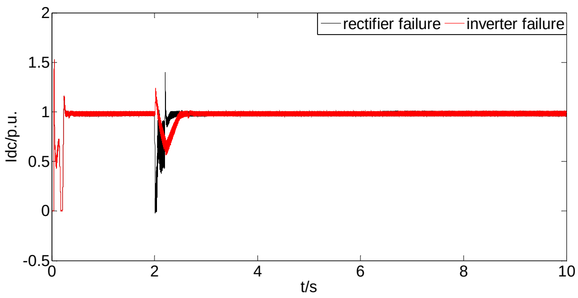

Fig. 16. The DC current after rectifier and inverter fault.

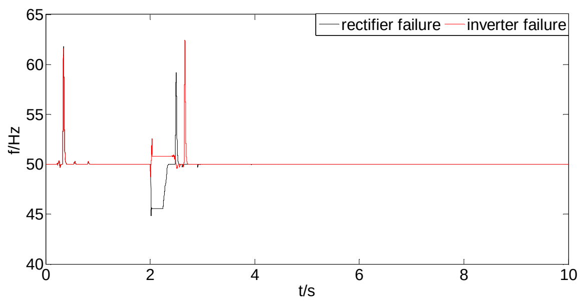

Fig. 17. The frequency of inverter converter bus after rectifier and inverter fault.

In Fig. 16, the DC current fluctuates when applying a single phase to ground fault at rectifier or inverter converter bus, and the system can quickly restore stability when fault clearing. It can be seen from Fig. 17 that the frequency has a significant reduction when imposed disturbance at rectifier. On the whole, the hybrid HVDC system can quickly restore stability when the fault clearing. Hybrid HVDC system has high stability during either small disturbance or large disturbance.

4) Monopole Block

The hybrid pseudo bipolar HVDC system's negative occur monopole block fault at t=2 s. And close the T_2 at t=2.01 s. The transmission power of rectifier and inverter, the DC voltage of rectifier and DC current are shown in Fig. 18.

In Fig. 18, the transmission power drop from 400 MW to 200 MW and the negative DC voltage drop to zero when the monopole block occurred. The DC current have a small fluctuation when fault occurs and current can quickly restore stability.

5. Conclusions

This paper provides a hybrid pseudo bipolar HVDC supplying to passive AC network based on VSC and CSC. The mathematical model of steady state is derived, and the coordination control strategy between rectifier and inverter is studied when supplying power to passive network. PSCAD/EMTDC is used to validate the system performance under startup, steady state and transient state. The following conclusions could be drawn from the results in this study.

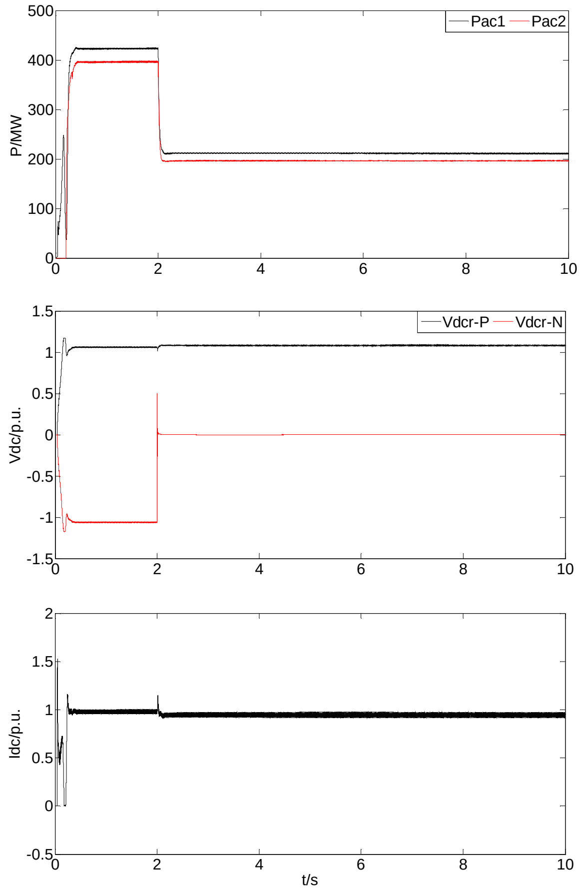

Fig. 18. Simulation results of monopole block.

1) Hybrid HVDC supplying power to passive network can be realized when the system adopts VSC at inverter. The cost of investment could be reduced when the system adopt CSC at rectifier.

2) The system need to stabilize AC voltage and frequency of inverter when supplying to passive network. Inverter uses constant AC-DC voltage control strategy. The system steady state and transient simulation show that the control mode is determined.

3) Applying single phase to ground fault and three phase to ground fault at rectifier and inverter converter bus which are used to verify the transient stability of the system. The simulation result shows that hybrid HVDC system has strong anti-jamming ability and the system can quickly restore to be stable when fault is cleared, and the control strategy could maintain the AC voltage and frequency of passive network.

4) Hybrid HVDC transmission by cable transmission can't realize the trend reversal. The DC fault protection strategy when the DC line fault should be further study.

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