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Research on coordinated reactive power control strategy of hybrid-HVDC

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Abstract: Based on the hybrid HVDC transmission system, which is composed by line-commutated converter (LCC) in parallel with voltage source converter (VSC), a coordinated reactive power control strategy of hybrid-HVDC in both steady and transient states is proposed. The operation characteristics in situations like low load operation, filter switching, and de-locking process are analysed. Influence of the method to AC bus voltage and system power factor is taken into account. Three kinds of reactive control methods of VSC and LCC are studied, and the logical relationship between the filter and VSC reactive power controller is also given. Considering both the system voltage drop and the risk of commutation failure caused by AC faults, the VSC in voltage control mode is utilised to maintain AC bus voltage stability by providing emergency power support. Simulation results show the feasibility and effectiveness of presented control strategy, then the proposed strategy is applied in practical DC project, whose results achieve the desired effect by engineering field test.

1 Introduction

Line-commutated converter-based high voltage direct current (LCC-HVDC) has been widely used in the world [1], however it needs a large number of reactive power compensators to guarantee a reliable system. On the other hand, LCC-HVDC cannot independently control active/reactive power, so the variable active power can easily lead to the fluctuations in reactive power [2], which consequently bring the bus voltage variations, affect the power quality. Much attention has been focused on the reactive power support and voltage stability problem in power system, and there are two main reactive control strategies: Converter Reactive Power Control (QPC) and Gamma_Kick control. Although the two kinds of angle control strategies can be carried out quickly to make reactive power balance, at the same time the transmission efficiency of the system is sacrificed, and the firing angle and extinction angle have a certain range of adjustment, power balance effect is limited. Nowadays, with the maturity on power electronic devices, the Voltage Source Converter-based HVDC (VSC-HVDC) [3, 4] system becomes a competitive choice for power transmission. Based on flexible power regulation performance of VSC-HVDC, many authors have considered that VSC-HVDC technology can provide a new measure to both reactive power and voltage control in power system of LCC-HVDC.

In this paper, based on the hybrid HVDC transmission system [5], which is composed by LCC in parallel with VSC, a coordinated reactive power control strategy of hybrid-HVDC in both steady and transient states is proposed. First, coordinated reactive power control of hybrid-HVDC was proposed in steady states, three kinds of reactive control methods of VSC and LCC are studied, and the logical relationship between the filter and VSC reactive power controller is also given in the situations like low load operation, filter switching, and de-locking process. Considering both the system voltage drop and the risk of commutation failure caused by AC faults, transient reactive power coordination control was also presented in the paper. Influence of the method to main electrical variables was taken into account.

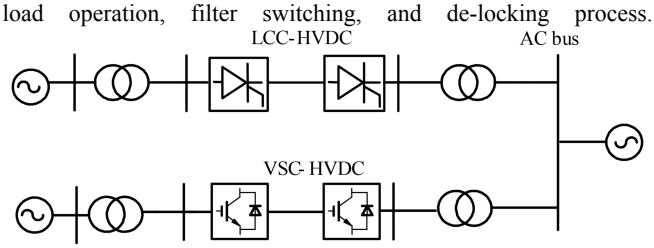

Fig. 1 *Topology structure of Hybrid dual-infeed HVDC system*

Then, based on the Luxi back-to-back asynchronous interconnection HVDC project in China, the verification of the studied system and proposed control method are carried out using the dynamic simulations in PSCAD/EMTDC, compared to the previous reactive power control methods, the proposed control scheme effectively reduces the reactive power and voltage fluctuation in the studied system.

2 Reactive power fluctuation of HVDC system under several typical working conditions

Fig. 1 is the topology structure of Hybrid dual-infeed HVDC system.

For LCC-HVDC, under steady state, the relationship of reactive power balance among converter stations, AC systems, VSC-HVDC, and filtering devices is as follows [1]:

$$Q_{\mathrm{dc}} = Q_{\mathrm{filter}} + Q_{\mathrm{ac}} + Q_{\mathrm{vsc}} \tag{1}$$

where Q_{dc} is the reactive power absorbed by the converter station, Q_{ac} is the reactive power transmitted by AC system to LCC-HVDC, Q_{vsc} is reactive power transmitted by VSC to LCC and Q_{filter} is the reactive power provided by filter.

The mathematical relationship among Q_{dc}, DC power and firing angle is as follows:

$$\begin{aligned} Q_{\mathrm{dc}} &= P_{\mathrm{dc}} \tan\varphi \\ \tan\varphi &= \frac{(\pi/180)\mu - \sin\mu \times \cos(2\alpha + \mu)}{\sin\mu \times \sin(2\alpha + \mu)} \end{aligned} \tag{2}$$

where P_{dc} is DC power, α is firing angle, μ is commutation angle.

In the normal operation of the system, Q_{ac} should be maintained in a certain range, to ensure that the AC bus voltage is in the allowable range.

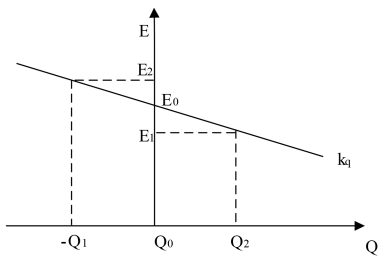

Fig. 2 *Droop control principle*

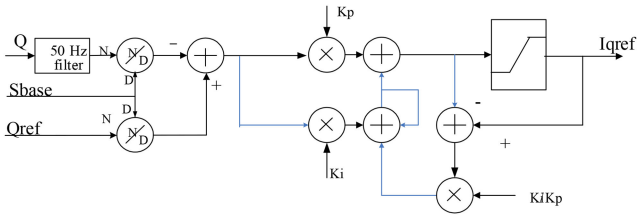

Fig. 3 *Control strategy diagram of reactive power*

2.1 Under normal operation state

(i) bipolar locking: When system receives blocking command, the DC power drops to 0, with reactive power requirement is decreasing. In this case, the filter bank is too late to cut-off. The reactive power consumed by the converter is less than that compensated by the AC filter, so that the remaining reactive power is instantaneously injected into the AC system, which is prone to result in over-voltage, affecting the service life of equipment.

(ii) operation in low load: In the starting process of the inverter, the DC requires a certain number of AC filters at low power levels to filter out harmonic. However, the reactive power consumed by the converter is less than that compensated by the AC filters, which is prone to result in overvoltage.

2.2 Under transition operation state

In each transition process such as DC faults and AC faults, the variation of the reactive power cannot be compensated in time by the reactive compensation equipment with relatively slow action, which will lead to AC voltage fluctuations.

Therefore, in order to meet the demands of the reactive power (voltage) balance, the coordinated reactive power control strategy of hybrid-HVDC in both steady and transient states should be studied.

3 Reactive power control strategy of HVDC

There are mainly three types of reactive power control in hybrid HVDC system: whole station slow reactive control, fast reactive power control of LCC, and fast reactive power control of VSC, and detailed theoretical analysis of the three reactive power control schemes is shown as follows.

3.1 Whole station slow reactive control

The essence of whole station slow reactive control is filter-switching control of LCC. For LCC, the reactive power is demanded at both rectifier and inverter side, whose value is not only related to DC power but also to the mode of operation and control methods.

DC station control by switching the filter bank could meet the demands of conventional DC reactive power and harmonic filtering. Reactive power control functions of LCC consist of several sub-functions, which include: Abs_Min_Filer, Umax, Qmax, Min_Filer, Voltage Control (U_control) and reactive control (Q_control).

3.2 Fast reactive power control of LCC

There are two main reactive control strategies: Converter Reactive Power Control (QPC) and Gamma_Kick control, which through adjusting the firing angle of the converter or extinction angle to assist the reactive power adjustment, although the angle control can be carried out quickly to make reactive power balance, at the same time the transmission efficiency of the system is sacrificed, and the firing angle and extinction angle have a certain range of adjustment, power balance effect is limited.

3.3 Fast reactive power control of VSC

For VSC, it uses full control of power electronics, so that independent regulation of the active and reactive power could be achieved through controlling the phase angle δ and the magnitude of fundamental output voltage of AC system U_{C1} (modulation ratio M), whose formulation can be deduced:

$$\begin{cases} P_{\text{VSC}} = \dfrac{U_1 U_{C1}}{X}\sin\delta \\ Q_{\text{VSC}} = \dfrac{U_1(U_{C1}\cos\delta - U_1)}{X} \end{cases} \tag{3}$$

where X is the equivalent reactance of both converter transformer and converter reactor. U_1 is the AC source voltage.

The flexible power regulation performance of VSC can make reactive power balance quick and control voltage fluctuation. The reactive power control includes constant AC voltage control and constant reactive power control, which are realised in outer-loop controller of VSC.

The constant AC voltage control is open-loop control. Based on the mature droop control principle, it provides reactive power support to the system

$$E - E_0 = -k_q \times (Q - Q_0) \tag{4}$$

where k_q is voltage amplitude droop coefficient, which is a constant between 0 and 1, E is AC voltage value, and Q is reactive power that VSC can be output. E_0 is initial value of AC voltage, Q_0 is reactive power reference value corresponding to it. The dynamic characteristics of the control are shown as:

Seen from Fig. 2, as E fluctuates from E_1 to E_2, Q will be regulated from $-Q_1$ to Q_2, the voltage stability can be maintained by adjusting the system reactive power value under constant AC voltage control.

The reactive power control is mainly used to control the inverter output reactive power. Within the inverter capacity, the output of reactive power is controlled in the value of expectation. This control also belong to outer-loop controller, same to the constant AC voltage control, so the system setting only can choose one of them, to ensure that there is only one reactive control target. Control strategy diagram is shown as (see Fig. 3).

Where, the 50 Hz is the rated frequency of AC system. S_{base} is reference value of system capacity, Q_{ref} is expected value of reactive power, I_{qref} is q-axis current reference value, and kp, ki are PI regulator parameters, Q is reactive power of transformer in grid side, which can be calculated by:

$$\begin{aligned} Q = {} & [(E_{b0} - E_{c0}) \times I_{a0} + (E_{c0} - E_{a0}) \times I_{b0} \\ & + (E_{a0} - E_{b0}) \times I_{c0}]/\sqrt{3} \end{aligned} \tag{5}$$

where E_{a0}, E_{b0}, E_{c0} are the three-phase voltage sampling value at grid-side, respectively, I_{a0}, I_{b0}, I_{co} are the three-phase current sampling value at grid-side, respectively

VSC can flexibly modulate the system reactive power and voltage amplitude through AC voltage control and reactive power control, without additional reactive power compensation device such as filters, and it can act quickly when the system is blocked, under low load and fault conditions. Therefore, in this paper, based on the hybrid HVDC transmission system, which is composed by LCC in parallel with VSC, a coordinated reactive power control strategy of hybrid-HVDC in both steady and transient states is studied.

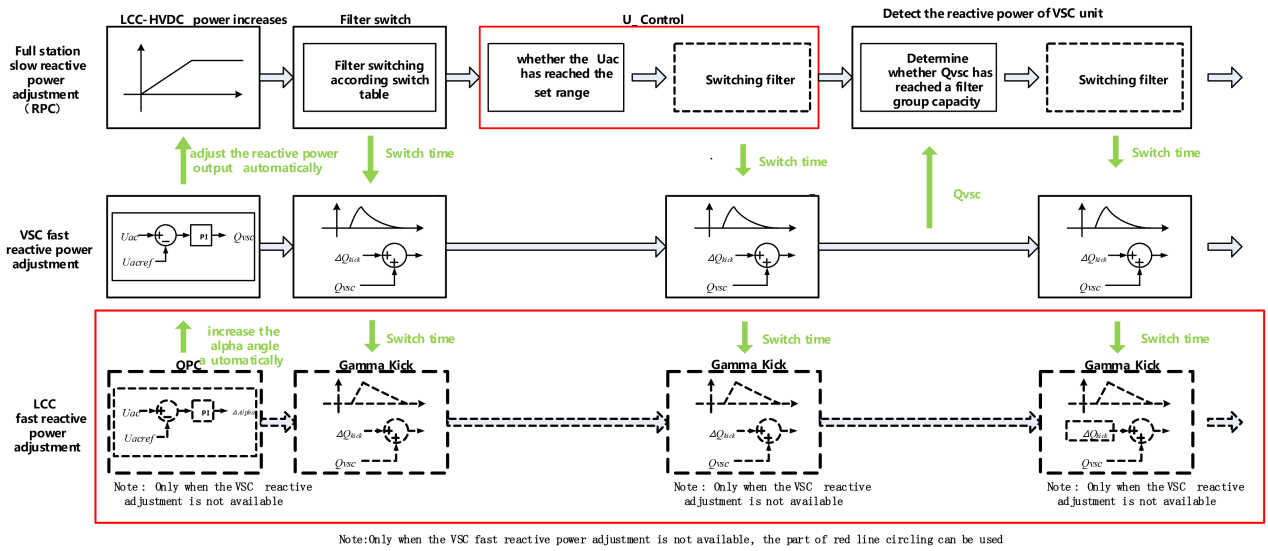

Fig. 4 *Coordinated reactive power strategy of U_Control*

4 Coordinated reactive power control strategy of hybrid-HVDC

4.1 Coordinated reactive power control strategy in steady state

Coordinated reactive power control strategy of hybrid-HVDC also includes two modes mainly: voltage control (*U*_Control) and reactive power control (*Q*_Control). Ideally, both LCC and VSC choose the same control mode of reactive power, Q_{ac} can be kept at zero through fast reactive power control of VSC. What is more, when VSC is not available or the coupling between VSC and LCC is not tight, two system can control their reactive power independently, and VSC supports reactive power only at the moment of LCC switching filters.

4.1.1 Coordinated reactive power strategy of U_Control: In the *U*_Control mode, the whole station slow reactive control regulates the AC voltage value by switching filters or capacitor group, note that it can only control the AC bus voltage to its set reference range.

In order to prevent frequent switching of filter banks, the hysteresis characteristics are used to set the upper and lower limit amplitude of the hysteresis window to be greater than half of the voltage variation.

In the *U*_Control mode, aimed at AC voltage, VSC inputs the deviation between the AC bus voltage and its set value to the PI regulator to obtain the reference value of reactive power or current, which can control the AC bus voltage to its set reference value accurately and fast.

The coordinated control strategy diagram under *U*_Control mode is shown as Fig. 4 (Take the power rising process as an example.). In order to ensure that VSC has a high capacity utilisation, it is preferable to use the filter bank to provide static reactive power. When the static capacitive reactive power provided by VSC is greater than the reactive power of an available filter bank, the filter bank is input and the VSC adds a set target value (the target value decays to zero according to the set curve) to offset the reactive impact when the filter bank is put into operation, same as the Gamma_Kick function of LCC; When the static inductive reactive power provided by VSC is greater than the reactive power of an available filter bank, the filter bank is cut and the VSC adds a set target value (the target value decays to zero according to the set curve) to offset the reactive impact when the filter bank is put into operation, same as the Gamma_Kick function of LCC;

4.1.2 Coordinated reactive power strategy of Q_Control: In the *Q*_Control mode, the whole station slow reactive control regulates Q_{ac} by switching filters or capacitor group, note that it can only control Q_{ac} to the set reference range. In order to prevent frequent switching of filter banks, the hysteresis characteristics are used to set the upper and lower limit amplitudes of the hysteresis window to be greater than half of the capacity of maximum reactive power equipment group.

In the *Q*_Control mode, aimed at Q_{ac}, VSC inputs the deviation of between Q_{ac} and its set value to the PI regulator to obtain the reference value of reactive power or current, which can control Q_{ac} to its set reference value accurately and fast.

The coordinated control strategy diagram under *Q*_Control mode is shown as Fig. 5 (Take the power rising process as an example.). In order to ensure that VSC has a high capacity utilisation, it is preferable to use the filter bank to provide static reactive power. When the static capacitive reactive power provided by VSC is greater than the reactive power of an available filter bank, the filter bank is input and the VSC adds a set target value (the target value decays to zero according to the set curve) to offset the reactive impact when the filter bank is put into operation, same as the Gamma_Kick function of LCC; When the static inductive reactive power provided by VSC is greater than the reactive power of an available filter bank, the filter bank is cut and the VSC adds a set target value (the target value decays to zero according to the set curve) to offset the reactive impact when the filter bank is put into operation, same as the Gamma_Kick function of LCC;

Note that, in the *Q*_Control mode, there are two main reactive control strategies for LCC: Converter Reactive Power Control (QPC) and Gamma_Kick control, and the function of QPC is aimed at controlling Q_{ac}. In order to prevent the conflict with fast reactive power control of VSC and to avoid the influence of α and γ on the DC system performance of LCC, the functions of QPC and Gamma_Kick will be exit when the *Q*_Control function of VSC is enabled.

4.1.3 Coordinated control strategy in the mode of LCC and VSC decoupling: It should be noted that, the VSC and LCC also do not need to be coupled too close at sometimes, so the two system can choose their own reactive control mode independently. Thus, coordinated control strategy can be simplified, whose function is same as the Gamma_Kick function.

The voltage fluctuation caused by the filter switching may exceed the allowable value of the system, even causing inverter commutation failure. It can be suppressed through increasing gamma of the inverter. However, the DC voltage of inverter will decrease due to the increase of gamma, then the DC power gets lower as well, which reduces the rate of equipment utilisation.

As VSC can realise fast reactive power output to inhibit the fluctuation of voltage caused by the filter switching, improving system stability and availability. In the mode of coordinated control, the Q_{vsc} is zero under normal operation state; once the filters get switched, the Q_{vsc} gets changed accordingly to stabilise

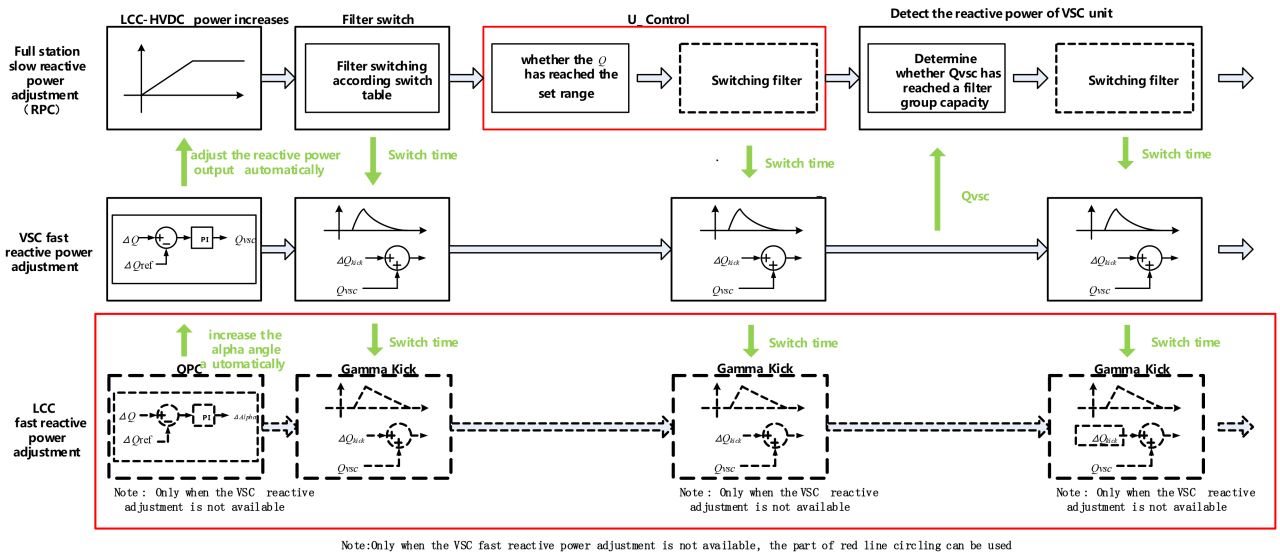

Fig. 5 *Coordinated reactive power strategy of Q_Control*

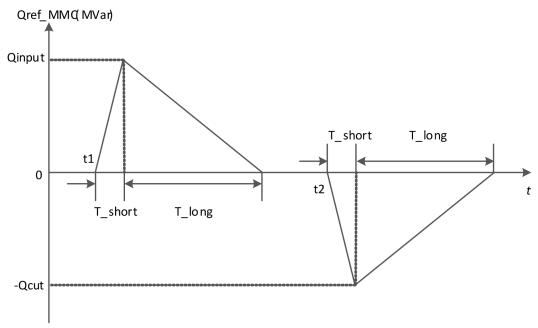

Fig. 6 *Filter switching with fast reactive power control of VSC*

the voltage value, after the filters switching is finished, the Q_{vsc} returns to zero.

As shown in Fig. 6, the moment the filter group gets input at t_1, the reference value of reactive power Q_{ref_MMC} increases from 0 to Q_{input} during the time $T_{\_short}$; when the Q_{vsc} increases to Q_{input}, its value will decrease from Q_{input} to 0 during the time $T_{\_long}$, which will take a longer time than $T_{\_short}$.

The moment filter group gets cut at t_2, the reference value of reactive power Q_{ref_MMC} changes from 0 to $-Q_{cut}$ during the time $T_{\_short}$; when the Q_{vsc} reaches $-Q_{cut}$, its value will change from $-Q_{cut}$ to 0 during the time $T_{\_long}$, which will take a longer time than $T_{\_short}$.

Where Q_{input} is reactive capacity of the filter group input, and Q_{cut} is reactive capacity of the filter group cut.

4.2 Coordinated reactive power control strategy in transient state

Transient coordination control mainly means the emergency reactive control strategy of the converter in the case of a fault happening in the AC or DC system, and its response speed is extremely demanded.

For LCC, it usually does not have the ability to provide emergency reactive power support to maintain the AC voltage when AC faults happen, thus the LCC control strategy in transient state means commutation failure prediction control function (CFPRED)

For VSC, it can provide emergency reactive support to maintain the exchange voltage stability in transient state. When AC faults happen, VSC quickly detects a transient fault and enters transient control mode. In the transient control mode, the VSC adopts the AC voltage control mode and the control of reactive power has the priority: First, according to the drop of AC voltage, the PI regulator with larger open-loop gain gives the command of reactive current, providing three-phase symmetrical reactive current to the power grid quickly, and utilising the remaining capacity to keep delivering part of the active current at the same time. As fault recovers, VSC reduces the reactive output with the given slope and increases the active current until it reaches the command value given by system and the power gets back to its pre-fault level quickly.

4.3 Influence of coordinated reactive power control on system parameters

4.3.1 AC bus voltage of inverter: For LCC, the active power of converter changes, along with the demand reactive power changes at the same time, and when the filter is too late to switch or the step change of reactive power command is caused by switching of the filter, there must be a reactive power exchange between AC and DC systems to balance the reactive power demand, which will lead to fluctuation of AC voltage, shown as,

$$\Delta U = \frac{\Delta Q}{S_{SC\min} - \Delta Q} \times 100\% \tag{6}$$

where ΔU is the value of AC voltage fluctuation, ΔQ is the reactive power that AC and DC system exchange, $S_{SC\min}$ is AC system minimum short circuit capacity.

Seen from formulation (6), using reactive coordination control strategy, and maintaining ΔQ (or ΔU) constant, can ensure that the other parameter ΔU (or ΔQ) is constant, which could realise the purpose of compensating LCC reactive power with VSC dynamically.

4.3.2 Power factor cosφ: Power factor of converter can be deduced:

$$\begin{aligned} \cos\varphi_{rec} &= \frac{1}{2}[\cos\alpha + \cos(\alpha+\mu)] \\ \cos\varphi_{inv} &= \frac{1}{2}[\cos\gamma + \cos(\gamma+\mu)] \end{aligned} \tag{7}$$

Seen from (7), α, γ and μ all affect the system power factor, for LCC, in order to balance the fluctuation of both AC voltage and reactive power caused by filter switching and faults happening, the QPC and Gamma_Kick control will regulate α, μ and γ, especially when the filter provides surplus reactive power, the system will increase α to balance some of it. However, the coordinated reactive power control strategy replaces the QPC and Gamma_Kick control, making the DC system still has a higher transmission efficiency even at non-rated operating conditions.

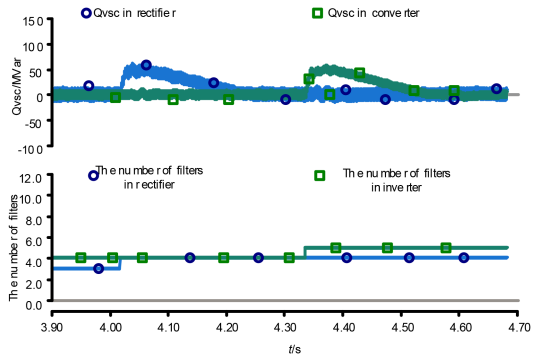

Fig. 7 *Dynamic reactive power performances of VSC when filter is input*

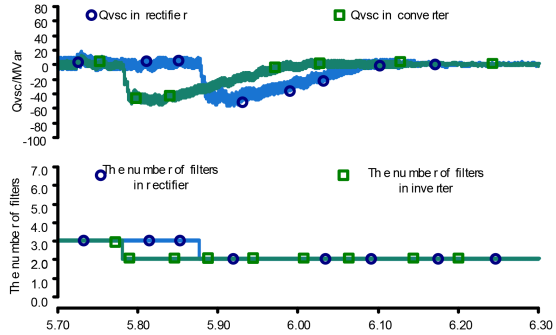

Fig. 8 *Dynamic reactive power performances of VSC when filter is cut*

5 Simulation study

Taking the actual project in the field as an example, a hybrid system model is set up in the PSCAD / EMTDC. The topology of it is shown in Fig. 1, whose system parameters and control mode are consistent with the practical engineering, and coordinated reactive power control is developed in the model. The dynamic response characteristics of VSC during the switching of filter banks during the DC power rises and falls are simulated and analysed, whose simulation results are shown in Fig. 7.

Seen from Fig. 7, the initial value of Q_{vsc} is 0, and the reactive capacity value of one filter group is 60 Mvar, when the filter group is input at 4.01 s, the reference value of Q_{vsc} increases from 0 to 60 Mvar quickly. When the actual value of Q_{vsc} reaches 60 MVar, the reference value of Q_{vsc} will decrease from 60 Mvar to 0 and the actual value of it gets to 0 slowly.

Seen from Fig. 8, the initial value of Q_{vsc} is 0, also the reactive capacity value of one filter group is 60 Mvar, when the filter group is cut at 5.78 s, the reference value of Q_{vsc} decreases from 0 to −60 Mvar quickly through the coordinated reactive power control system. When the actual value of Q_{vsc} reaches −60 MVar, the reference value of Q_{vsc} will increase from −60 Mvar to 0 and the actual value of it gets to 0 slowly.

The results show that, at the moment of filter switching, the coordinated reactive power control system can provide reference value of Q_{vsc} for VSC to mitigate the fluctuation of AC voltage quickly and accurately. The hybrid reactive power control strategy of HVDC proposed in this paper has been verified at the actual project site.

6 Conclusion

In this paper, based on the hybrid HVDC transmission system, which is composed by LCC in parallel with VSC, a coordinated reactive power control strategy of hybrid-HVDC in both steady and transient states is proposed. The verification of the studied system and proposed control method are carried out using the dynamic simulations in PSCAD/EMTDC, the proposed control scheme effectively reduces the reactive power and voltage fluctuation in the studied system, which exhibits favourable steady state and dynamic performances.

7 References

[1] Zhao, W.: '*High voltage direct current project technology*' (China Electric Power Press, Beijing, 2011, 2nd edn.)

[2] Kundur, P.: '*Power system stability and control*' (McGraw-Hill, New York, 1994), pp. 463–464

[3] Wang, X., Ooi, B.T.: 'High voltage direct current transmission system based on voltage source converters'. 21st Annual IEEE Power Electronics Specialists Conf., PESC '90 Record, San Antonio, USA, 1990, pp. 325–332

[4] Yin, M., Li, G., Li, G., *et al.*: 'Modeling of VSC-HVDC and its active power control scheme'. Proc.-IEEE PES/CSEE, POWERCON'04, Singapore, 21–24 November 2004, vol. 2, pp. 1351–1355

[5] Guo, C., Zhao, C., Wang, J.: 'Operation characteristic research on novel double-infeed HVDC system supplying passive network', *Trans. China Electrotech. Soc.*, 2012, **27**, (11), pp. 211–218