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Coordinated control strategy of reactive power for large-scale wind power transmission by LCC-HVDC links

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Abstract: The intermittence and fluctuation of outputs of large-scale wind farms lead to significant problems in power transmission system by line-commuted converter high-voltage direct current (LCC-HVDC) links. Traditional reactive power compensation devices such as AC filters are not capable of adjusting reactive power balance continuously. This paper presents a coordinated reactive power control strategy to realise continuous adjustment. A synchronous condenser (SC) is applied in the DC converter station to cooperate with AC filters. The capacity of the SC is determined by the minimum capacity and dead zone of the AC filter unit, and cost saving is also taken into account. While power outputs of wind farms fluctuate, the setting value of DC power gets changed. The SC responses rapidly to reduce the reactive power exchange. When the reactive power demand is beyond the capacity of the SC, one AC filter unit operates and the SC readjusts to maintain the reactive power balance. The proposed control strategy is validated by simulation in PSCAD/EMTDC.

1 Introduction

The environment problems caused by fossil fuel consumption impel the development of renewable energy. In the last 30 years, wind power has developed rapidly and has become technically mature. Currently, there are mainly two types of wind power generators, which are doubly-fed induction generator and permanent magnetic synchronous generator (PMSG) [1]. The installed capacity of wind farms in China is currently the largest all around the world. According to the national energy administration, several tens of MW level wind farms will be built in northwest provinces. The wind energy source is highly concentrated in these areas and long transmission is inevitable. HVDC links are more suitable than high-voltage alternating current systems due to the long distance transmission [2].

Line-commuted converter high-voltage direct current (LCC-HVDC) system is ideal for the power transmission in the northwest area, whose power network is of weak strength, poor frequency modulation and peak shaving capability. In general, it is agreed that LCCs are superior to other HVDCs in terms of reliability, cost and efficiency. LCC-HVDC can adjust active power rapidly to adapt to the fluctuation of the output of wind farms and transfer the power variance to the load centre in central and eastern areas. Nevertheless, LCC-HVDC has some limits. Reactive power compensation devices (RPCDs) are obligatory in LCC-HVDC systems, and with the increasing capacity of the system, the reactive power balance at the converter stations will become more and more complicated [3]. Meanwhile, the intermittence and fast variance of wind outputs increases the difficulty of reactive power control (RPC) in the LCCHVDC system. Thus, it is very urgent to solve the RPC problem for large-scale wind farms by LCC-HVDC links.

The literature proposes several RPC strategies in LCC-HVDC systems which can be classified in three major aspects, optimising the consumption of reactive power of LCC-HVDC converter [4, 5], improving the typology of RPCDs [6] and enhancing the stability of HVDC converters in weak AC systems or more specifically in wind farm systems [7–10].

Dai *et al.* [4] proposed a RPC function of LCC implemented in an energy management system, to minimise the reactive power net consumption of HVDC system by collaboratively controlling diverse reactive power devices, including AC filters, shunt capacitors, shunt reactors, SCs, and static var compensato (SVC)s. Xue and Zhang [5] presented a RPC at the inverter side of the LCC-HVDC system with controllable capacitors. The ability of operating under negative extinction angle is utilised to achieve a wide range of RPC and the ability of exporting reactive power.

Besides, an operation scheme of LCC-HVDC to maximise the shunt capacitor size in AC system is proposed in [6] so that the number of shunt capacitor is minimised.

A reactive power balance strategy is proposed in paper [7] to enhance the stability of the HVDC inverter connected to weak grids. A new converter transformer and related fully tuned branches are included in the converter subsystem for implementing an inductive filtering method. With the fast development of power electronic devices, power electronic RPCDs are integrated to realise fast RPC. Elmehdi *et al.* [8] discussed the determination of dynamic reactive compensation of a LCC-HVDC system connected to a weak AC system at the rectifier bus. Results show that the synchronous condenser (SC) offers better dynamic performance than the fixed capacitor. Specifically, the literature also makes research on coordinated control strategy between wind farms and HVDC converters. A coordinated RPC strategy between wind farms and HVDC converters to solve AC voltage oscillation is proposed in [9, 10] which presents a coordinated control strategy and configuration scheme of the RPCD of DC system for wind-thermal-bundled power transmission, replacing conventional RPCD with SVC to decrease action times of conventional RPCD.

However, few studies work on the coordinated RPC strategy in HVDC converters considering the power outputs of wind farms fluctuate frequently. Power electronic RPCDs such as SVC and

SVG could realise fast coordinated power control, but difficult to meet the requirement of transient reactive power supply.

In this paper, a coordinated RPC strategy is proposed. First, a configuration scheme of dynamic RPCDs in DC converters is proposed. A SC is applied to cooperate with AC filters. The capacity and grouping of AC filters are determined by engineering discipline. The determination of dead zone of switching AC filters takes account of avoiding frequent device switching, and the capacity of the SC is calculated from this dead zone and cost saving is optimised. Second, a coordinated control method is proposed based on AC filters and the SC. While power outputs of the wind farm fluctuate, the setting value of DC active power varies, and the reactive power demand changes as well. The SC responses rapidly to balance the reactive power. When the reactive power demand is beyond the capacity of the SC, one AC filter unit operates and the SC readjusts to maintain the reactive power balance. The simulation results show that proposed coordinated control strategy can achieve effective reactive power compensation, realising fast and continuous adjustment.

2 Model of the system

The studied system is shown in Fig. 1. The system applies PMSG wind farm as the energy source, while LCC-HVDC is used for long distance power transmission from the source to the load centre. AC filters are installed in both DC converters for harmonics filtration and for the reactive power compensation. A SC is applied at each converter station to cooperate with AC filters. In this study, the impact of the load centre at the inverter side of HVDC is neglected, and it is considered as a strong AC system. A constant voltage source consisting of a source impedance is applied as the load centre for simplification of analysis [11].

2.1 PMSG system

The detailed model of PMSG has been discussed in [12]. The PMSG model applied is briefly presented here. The topology of the PMSG system is shown in Fig. 2. The wind turbine is directly connected to the PMSG, which is further fed to a fully controlled converter. It consists of a pulse width modulation (PWM) rectifier, an intermediate boost circuit and a PWM inverter, to improve the power output performance. The PWM controlling technique employed is for providing constant voltage output. Besides, the maximum power tracking is applied in the control system.

While the wind speed varies, the mechanical power generated by a wind turbine is expressed as follows:

$$P_{\text{mec}} = \frac{1}{2}\rho A c_p v_{\text{w}}^3 \tag{1}$$

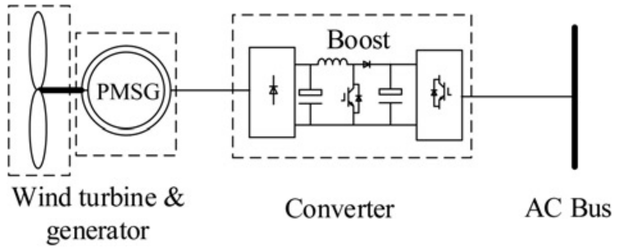

Fig. 2 *Configuration of the PMSG system*

where ρ is the density of the air, A is the area swept, c_p is the ratio of wind power by turbine power and v_{w} is the wind velocity.

The tip speed ratio λ is expressed as follows:

$$\lambda = \frac{\Omega R_b}{v_{\text{w}}} \tag{2}$$

where R_b is the turbine radius and Ω is the rotation speed of the turbine.

Thus, the maximum turbine power is expressed by a function of optimum turbine rotation speed

$$P_{\max} = \frac{(1/2)\rho\pi R_b^5 c_p \max}{\lambda_{op}^3}\Omega_{op}^3 \tag{3}$$

Employing optimum values of λ and Ω and adjusting c_p to the maximum value, while regulating the system to satisfy the power limit specification, the maximum power tracking is realised.

2.2 HVDC system

The HVDC model applied is based on CIGRE HVDC Benchmark Model, in which the pole control is integrated in the HVDC control system [13].

The 12-pulse converter is employed in both rectifier and inverter. The rectifier applies constant DC current control and constant-firing-angle control, while the controller of inverter consists of constant DC voltage control, voltage-dependent current order limiter control and constant-extinction-angle control. The commutation overlap as well as the influence of tap change are ignored in the analysis.

3 Coordinated reactive power control

In the LCC-HVDC system for wind power transmission, the setting value of DC active power can be adjusted quickly in order to

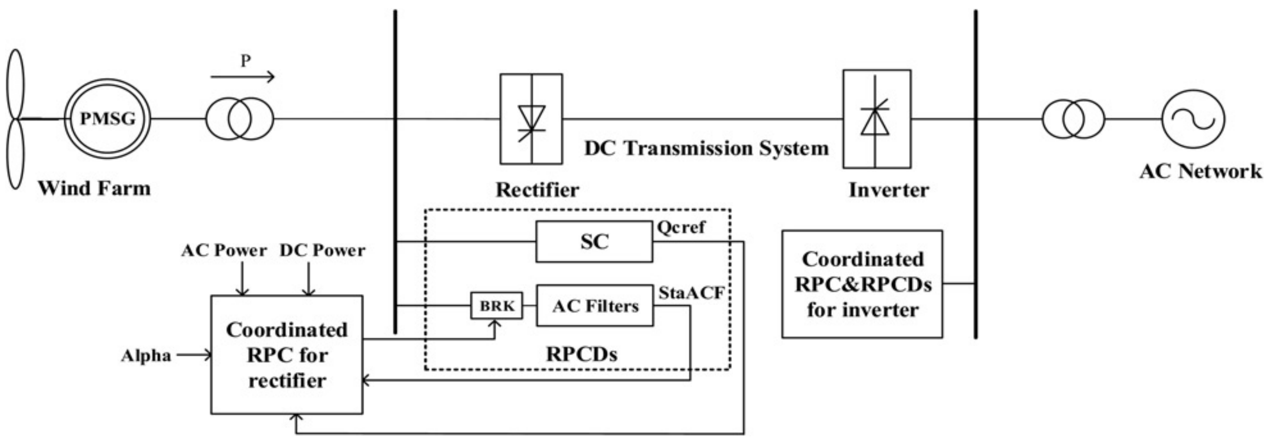

Fig. 1 *Configuration scheme of the studied system*

coordinate with the fluctuating power output of wind farms. Traditionally, AC filters should act as well to maintain the reactive power balance. However, if the wind power fluctuate frequently, the action times of AC filters will be increased. Meanwhile, the adjustment is discontinuous because of the AC filter switching. Applying the SC as RPCD to cooperate with AC filters will be able to realise continuous RPC and reducing the action times of AC filters.

3.1 RPCD capacity determination

The reactive power compensation requirement of the DC system depends on the reactive power consumed by the converter, from which the capacity and grouping of RPCDS can be determined.

The consumed reactive power by the converter can be calculated as follows:

$$Q_{\text{dc}} = P \tan \varphi \tag{4}$$

$$\tan \varphi = \frac{(\pi/180)\mu - \sin \mu \cos(2\alpha + \mu)}{\sin \mu \sin(2\alpha + \mu)} \tag{5}$$

$$\mu = \cos^{-1}\left(\cos \alpha - \frac{\sqrt{2}X_c Id}{E_{11}}\right) - \alpha \tag{6}$$

where P is the DC active power, φ is the power angle of the converter, α is the firing angle of the rectifier, μ is the commutation angle, I_d is the DC current of the converter, X_c is the commutated reactance of the converter transformer and E_{11} is the line voltage of the valve side in the converter transformer. α should be replaced by γ while the converter works as the inverter.

For AC filters, as the main RPCD at the converter stations, the reactive power generated is

$$Q_{\text{filt}} = \left(\frac{U_{\text{ac}}}{U_{\text{ac}N}}\right)^2 \sum Q_{\text{filt}N} \tag{7}$$

where $Q_{\text{filt}N}$ is the smallest group capacity of AC filters, U_{ac} is the real line voltage rms of the AC bus at the converter and $U_{\text{ac}N}$ is its rating.

The capacity and grouping of AC filters is determined by engineering discipline. The switching control of AC filters takes account of avoiding frequent device switching, thus the dead zone of switching one AC filter unit should be defined. Normally, the value is established as $(1/2)Q_{\text{filt}N}$.

The SC is integrated as the dynamic RPCD in the system. Its capacity Q_{csc} should meet the requirement of continuous adjustment, with adequate margin, and should also take economics into consideration. The value of Q_{csc} is between $(1/2)Q_{\text{filt}N}$ (the dead zone of switching AC filter unit) and $Q_{\text{filt}N}$, and is established to $(2/3)Q_{\text{filt}N}$.

Thus, the reactive power exchange at the AC bus of converter can be expressed as follows:

$$Q_{\text{exc}} = Q_{\text{filt}} + Q_{\text{refc}} - Q_{\text{dc}} \tag{8}$$

Q_{refc} is the reactive power provided by the SC. The objective is to keep Q_{exc} to the minimum value and to realise continuous adjustment.

3.2 Coordinated RPC strategy

The proposed RPC strategy flow in one period is shown in Fig. 3. The calculation cycle is set to 0.5 s. First, current reactive power exchange Q_{exc} is calculated by the measured signals in AC/DC system. While Q_{exc} is equal to 0, no RPCD acts. Otherwise, determine the difference between Q_{csc} and reactive power demand $Q_{\text{cref}} - Q_{\text{exc}}$. Then, if the difference is under the limit $\pm Q_{\text{csc}}$, adjust the reactive power provided or absorbed by the SC from Q_{cref} to $Q_{\text{cref}} - Q_{\text{exc}}$. However, if the difference is beyond the limit, the AC filter should be switched.

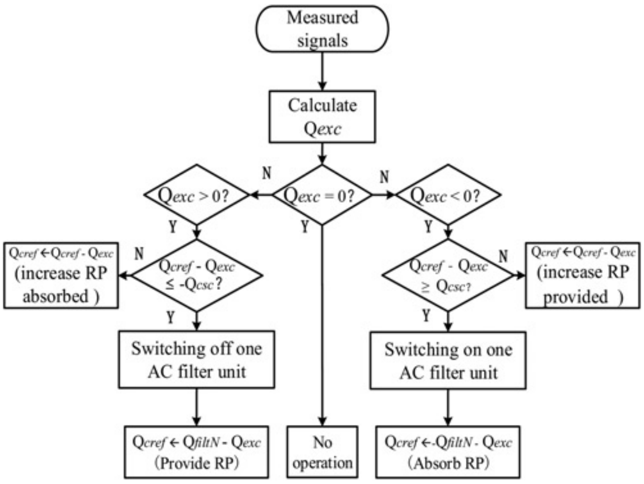

Fig. 3 *Flow diagram of coordinated RPC*

The control logic of switching order of AC filters is as follows:

(i) (i) If the following conditions are met, one AC filter will be switched on:

$$\begin{cases} Q_{\text{exc}} = Q_{\text{filt}} - Q_{\text{dc}} + Q_{\text{cref}} < 0 \\ Q_{\text{cref}} - Q_{\text{exc}} \geq Q_{\text{csc}} \end{cases} \tag{9}$$

(ii) Meanwhile, considering Q_{exc} is increased by $Q_{\text{filt}N}$ after one AC filter unit switched on, the reactive power of the SC should be reset to $-(Q_{\text{exc}} - Q_{\text{filt}N})$.

(iii) (ii) If the following conditions are met, one AC filter will be switched off:

$$\begin{cases} Q_{\text{exc}} = Q_{\text{filt}} - Q_{\text{dc}} + Q_{\text{cref}} \\ Q_{\text{cref}} = -Q_{\text{csc}} \end{cases} \tag{10}$$

(iv) Meanwhile, considering Q_{exc} is reduced by $Q_{\text{filt}N}$ after one AC filter unit switched off, the reactive power of the SC should be reset to $Q_{\text{filt}N} - Q_{\text{exc}}$.

4 Simulation results and evaluation

Simulation with proposed control strategy is carried out by PSCAD/EMTDC for a 2000 MW PMSG wind farm by LCC-HVDC links. The power output of the wind farm fluctuates as well as the reactive power demand at the converter stations. The corresponding parameters of the studied system are given in Table 1. At the inverter side, only AC filters are employed as RPCD for simplification.

The wind velocity varies during the simulation as shown in Fig. 4, which contains the component of gust wind, ramp wind and noise wind. Initially, the wind speed is set to its rating 11.3 m/s. After 1 s, there is a sudden drop from 11.3 to 9 m/s and then it continues to decrease to 7.5 m/s and fluctuates between 7.5 and 9 m/s. Then another 1 s later, it suddenly increases to 11.3 m/s and exceeds its rating to 13.5 m/s within 1.5 s, then the wind speed experiences the fluctuation between 8 and 11.3 m/s during 3.5 s.

Table 1 Parameters of the simulated system in PSCAD

P_{dN} (rated capacity of HVDC)	2000 MW (monopole)
U_{dc} (DC voltage of HVDC)	±660 kV
U_{ac} (AC bus voltage)	345 kV (rectifier), 500 kV (inverter)
Q_{csc} (capacity of the SC)	150 MVar
S_m (capacity of the converter transformer)	1200 MVA (rectifier), 1150 MVA (inverter)
X_m (commutated reactance of the converter transformer)	12.18 Ω (rectifier), 10.92 Ω (inverter)
Q_{filtN} (smallest group capacity of AC filters)	200 MVar (rectifier), 180 MVar (inverter)

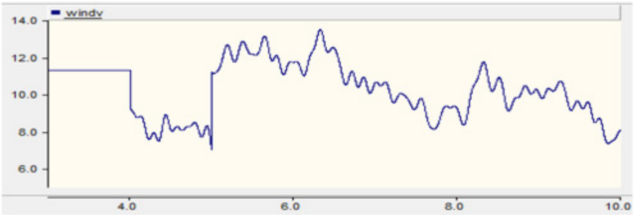

Fig. 4 *Simulation result of wind speed*

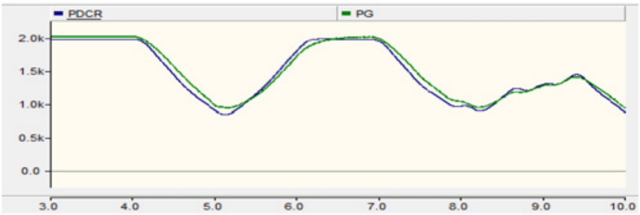

Fig. 5 *Power output of the wind farm and DC power*

(i) (i) *Active power output:* The power output of wind farm P_G and DC power P_{DCR} are shown in Fig. 5. The power output of the wind farm varies with the wind speed. At the steady state, the value is 2000 MW, and it decreases to 800 MW when the wind speed is reduced to 9 m/s. Then it rises to 2000 MW and then drops and fluctuates. The DC power keeps up with the wind power output with a slight delay around 0.1 s.

(ii) (ii) *Reactive power output:* The reactive power output of the wind farm is controlled to zero in the simulation. The simulation result of reactive power demand at the rectifier side is shown in Fig. 6. Due to the change of DC transmission power, the reactive power demand of the rectifier Q_{conv} also varies.

The reactive power supplied by AC filters and the SC follows the fluctuation of reactive power demand. The reactive power supplied by AC filters and the SC is shown in Fig. 7. The reactive power generated by AC filters is stair-stepping while the control of the SC is continuous. The simulation result of reactive power exchange is shown in Fig. 8. If it is not superior to the capacity of the SC, only the SC acts quickly to maintain the reactive power balance. Otherwise, the AC filter(s) will be switched. According to the simulation result in Fig. 8, the reactive power exchange is controlled to be relatively small (no more than 160 MVar) and the adjustment is continuous.

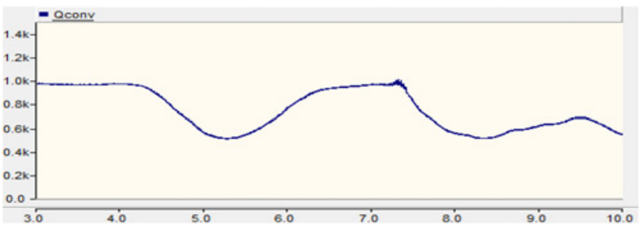

Fig. 6 *Reactive power demand at the rectifier*

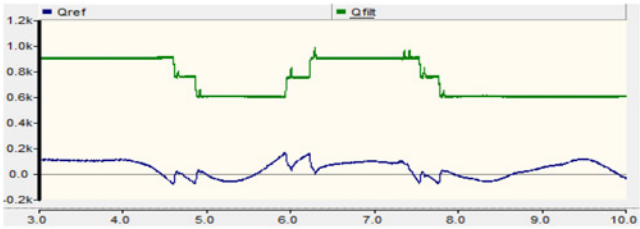

Fig. 7 *Reactive power supplied by RPCDs*

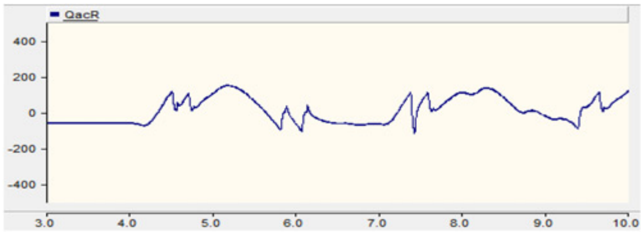

Fig. 8 *Reactive power exchange*

5 Conclusion

This paper has presented the coordinated RPC strategy in large-scale wind power system with LCC-HVDC connection. The RPC with AC filters and a SC as RPCDs has been proposed and related controllers have been integrated. The load centre at the inverter side is considered as a strong system and the response is desirable.

The capacity of the SC has been determined by the continuous adjustment requirement and the cost saving is also taken into account. The installed SC acts before AC filters to satisfy fast-varying reactive power demand to maintain the reactive power balance. While the reactive power exchange is beyond the capacity of the SC, AC filters will be switched and the SC will co-operate as well. Simulation of a 2000 MW wind farm by LCC-HVDC link has been carried out in PSCAD/EMTDC. Simulation results have verified the effectiveness of proposed strategy.

6 Acknowledgement

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