

Optimal reactive power control in a converter station during low-power operation of HVDC

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Abstract: When the high-voltage DC (HVDC) system is operated in low-power transmission, the overplus of reactive power provided by AC filters may still exist apart from satisfying the need of the converter station, restricted by the minimum number of filter banks. This will lead to a large number of surplus reactive power into AC system, affecting the safe and stable operation of power grid. Here, the impacts of the adjustment of on-load tap changer of converter transformer and the adjustment of control angle of the converter station on reactive power consumption are analysed. Taking effects on the adjustment of control devices and the interchange of reactive power into account, a static reactive power optimisation model based on the actual control strategy of reactive power in a converter station is set up, which provides theoretical basis for an optimal control during low-power operation. Taking Tian-Guang HVDC project as an example, the simulation results verify its effectiveness of the proposed method.

1 Introduction

The reactive power compensation and voltage control in converter station are key points for the security and stability of high-voltage DC (HVDC) and ultra-HVDC (UHVDC). The DC converter will consume a large amount of reactive power in the transmission of active power, and the fluctuation of AC voltage occurs due to insufficient or excess reactive power, which might seriously affect the safety of power grid. Owing to the harmonic performance of the converter station and the limitation of AC filters, a certain number of AC filter banks, called absolute minimum filter capacity limit, must be put into the station when HVDC system operates. However, the capacity of AC filters for each group increases rapidly restricted by numerous factors, and 287 Mvar AC filters, for example, has been put into ± 800 kV Bin-Jin DC transmission project. Therefore, when HVDC system runs during the period of low power, the reactive power provided by AC filters will far greater than that consumed by converter, which leads to considerable interchange of reactive power between the converter station and AC system. Meanwhile, the load is usually low in power grid, and excess reactive power exists in AC line under light load during this period. If a large amount of reactive power is injected into AC system at this time, the voltage rise of the converter station and nearby grid will aggravate the difficulty of voltage regulation in local area, which brings great impact to the stability of power grid operation, and DC system might be even forced to stop under specific way.

Domestic and foreign scholars have made great efforts on reactive power control of HVDC power transmission system in low-power operation. In [1], the solution to suppress the voltage rise caused by low-power operation based on the non-linearity of reactive power consumption in a converter station is proposed. The excrescent reactive power can be absorbed by increasing the minimal extinction angle of converter. Two kinds of low load reactive power optimisation (LLRPO) function of HVDC and UHVDC applied in China Southern Power Grid are introduced in [2], and suggestions on LLRPO function improvement in practice are proposed. Wang *et al.* [3] introduce a reactive power control method of 'open loop+closed loop' in a converter station, in which DC voltage is considered as control variable and exchange of reactive power of AC/DC system as feedback variable. Lei *et al.*

[4] and Xiao *et al.* [5] comprehensively analyse and summarise the LLRPO function of Xing-An and Yun-Guang HVDC, separately.

In the aspect of reactive power optimisation of AC/DC system, the existing research focuses on the transmission grid, including power plants, AC substations, and DC converter stations. A multi-objective reactive power optimisation model of AC/DC system is set up considering the minimal active power loss and high-voltage quality in [6], and Li *et al.* [7] take further consideration on the energy-loss characteristics of the converter stations in detail. However, the actual control requirements of a converter station, AC filter requirements, for example, are not taken into account in above. Based on the FACTS device, reactive power optimisation model of AC/DC transmission and distribution network are separately established with specified parameter of a converter station in [8, 9].

It is obvious that there are following problems of previous research: (i) a convincing scheme of device motion or parameter setting cannot be given in the low-power operation of HVDC power transmission system; (ii) the existing research on reactive power optimisation of AC/DC hybrid system is not suitable for a single converter station without considering the actual control requirements. The remainder of this paper is organised as follows. Section 2 analyses characteristics of reactive power and their influence factors in a converter station. Then, a reactive power optimisation model is built. Section 3 is a case study on Tian-Guang HVDC project. Section 4 summarises the paper and gives suggestion on further research.

2 Methodology

2.1 Characteristic analysis of reactive power in converter station

With the operation of HVDC system, the interchange of reactive power between the converter station and AC system is shown in Fig. 1. Specially, adjustable low-voltage reactors or fixed high-voltage reactors are installed near the converter station in some projects, which is not suitable for this paper.

Therefore, the interchange of reactive power between the converter station and AC system is calculated by

$$Q_{\text{exp}} = Q_{\text{d}} - Q_{\text{acf}} \quad (1)$$

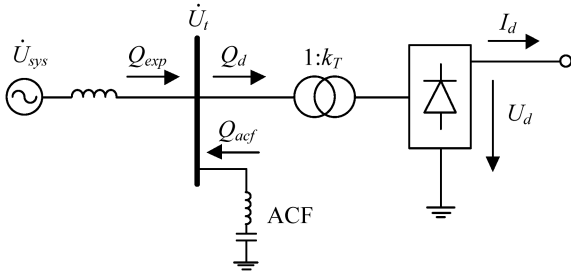


Fig. 1 Diagram of reactive power in a converter station

and

$$Q_d = P_d \tan \varphi = P_d \sqrt{\left(\frac{U_{d0}}{U_d}\right)^2 - 1} \quad (2)$$

$$Q_{acf} = Q_{ACFnom} \times \left(\frac{U_t}{U_{ACFnorm}}\right)^2 \times \left(\frac{f_{ACact}}{f_{ACnorm}}\right)^2 \quad (3)$$

It shows that reactive power is injected into a converter station from AC system when Q_{exp} is positive. The feature of thyristor determines that the converter needs to absorb reactive power from AC system whether it works in rectifier or inverter state. With stable operation of the converter, some expressions are

$$U_d = U_{d0} \cos \theta_d - k_b \cdot \frac{3}{\pi} X_r \cdot I_d \quad (4)$$

$$U_{d0} = k_b \cdot \frac{3\sqrt{2}}{\pi} k_T U_t \quad (5)$$

where Q_{exp} stands for the exchange of reactive power; P_d , Q_d , U_d , U_{d0} , I_d , θ_d , and φ represent active power, reactive power, DC voltage, ideal no-load DC voltage, DC current control angle, and power factor angle of the converter, respectively; X_r , k_b , and k_T , located in the valve side in Fig. 1, stand for commutating reactance, the number of six-pulse converter per pole, and the ratio of converter transformer; Q_{acf} is the reactive power provided by AC filters, $Q_{ACFnorm}$ and $U_{ACFnorm}$ are total rated capacity and rated voltage amplitude of AC filters, and U_t , f_{ACact} , and f_{ACnorm} are the actual voltage, actual frequency, and rated frequency of AC system.

Then Q_d can be achieved from (2) by introducing (4) and (5)

$$Q_d = P_d \sqrt{\left(\frac{1}{\cos \theta_d - (X_r / \sqrt{2} U_t) \cdot (I_d / k_T)}\right)^2 - 1} \quad (6)$$

It is assumed that the voltage U_t of AC bus is constant, reactive power Q_d of the converter station is only related to DC current I_d , control angle θ_d , and converter transformer ratio k_T , when using constant power control.

Owing to

$$P_d = k_p \cdot U_d I_d \quad (7)$$

where k_p stands for the number of poles in the converter station and I_d can be calculated by (4), (5), and (7), which is

$$I_d = \frac{\sqrt{2} U_t}{2 X_r} \cdot k_T \cos \theta_d - \sqrt{\left(\frac{\sqrt{2} U_t}{2 X_r} \cdot k_T \cos \theta_d\right)^2 - \frac{\pi}{3 k_p k_b X_r} P_d} \quad (8)$$

The variation of I_d with θ_d and k_T can be discussed by taking the derivative of the preceding equation (4)

$$\frac{\partial I_d}{\partial \theta_d} = C_1 \sin \theta_d \cdot \left[\frac{1}{\sqrt{1 - (C_2 / (C_1 \cos \theta_d)^2)} - 1} \right] > 0 \quad (9)$$

$$\frac{\partial I_d}{\partial k_T} = C_3 \cdot \left[1 - \frac{1}{\sqrt{1 - (C_2 / (C_3 k_T)^2)} \right] < 0 \quad (10)$$

where

$$C_1 = \frac{\sqrt{2} k_T U_t}{2 X_r} > 0$$

$$C_2 = \frac{\pi P_d}{3 k_p k_b X_r} > 0$$

$$C_3 = \frac{\sqrt{2} U_t \cos \theta_d}{2 X_r} > 0$$

Meanwhile, the ratio of converter transformer shown in Fig. 1 is

$$k_T = \frac{k_{TN}}{1 - p \cdot \Delta U} \quad (11)$$

where k_{TN} is the rated ratio, p represents the tap position, and ΔU stands for the step voltage of converter transformer tap.

Overall, from (6), (9) to (11), it is not difficult to find that: (i) I_d is increasing with the increase in θ_d , and then Q_d is rising; (ii) I_d is increasing with the decrease in p , and then Q_d is rising.

2.2 Reactive power optimisation of converter station during low-power operation

2.2.1 Model for reactive power optimisation of converter station:

The traditional method to increase the reactive power consumption of the converter station is to raise its trigger angle with the maximum limit of 38° due to potential adverse effects referred in [1]. Also, the conclusion summarised in Section 2.1 shows that a proper increase for converter transformer ratio helps to reduce these negative impacts. Hence, an optimal reactive power model for the converter station with minimum number of AC filters during low-power operation is proposed.

In addition, to take the connection of AC and DC system into account, as well as to adapt to the usual method, that per unit system is used for the analysis of AC system, reference values are chosen for a concise form of converter equations as follows:

$$P_{dB} = S_B \quad (12)$$

$$U_{dB} = \frac{3\sqrt{2}}{\pi} k_b k_{TB} U_B \quad (13)$$

where S_B and U_B represent reference power and reference voltage of AC system, P_{dB} and U_{dB} the reference power and reference voltage of DC system, and k_T represents reference ratio of converter transformer. More details can be found in [10]. In addition, the following contents are discussed under per unit system in this section, and the subscript ‘*’ will be deleted for a convenient writing.

2.2.2 Objective function:

The objective function of the model is

$$y = \min \{ w_1 \times |Q_d - Q_{acf}| + w_2 \times (k_T - k_{T0}) + w_3 \times (\theta_d - \theta_{d0}) \} \quad (14)$$

where Q_d and Q_{acf} are computed by (2) and (3); θ_{d0} and k_{T0} represent common status of the converter station under a normal operating condition. The model reflects that a small amount of reactive power interchange with slight adjustment of control angle and converter transformer ratio is expected, and w_1 , w_2 , and w_3 are their weighting coefficients. Furthermore, $|Q_d - Q_{acf}|$ and θ_d are

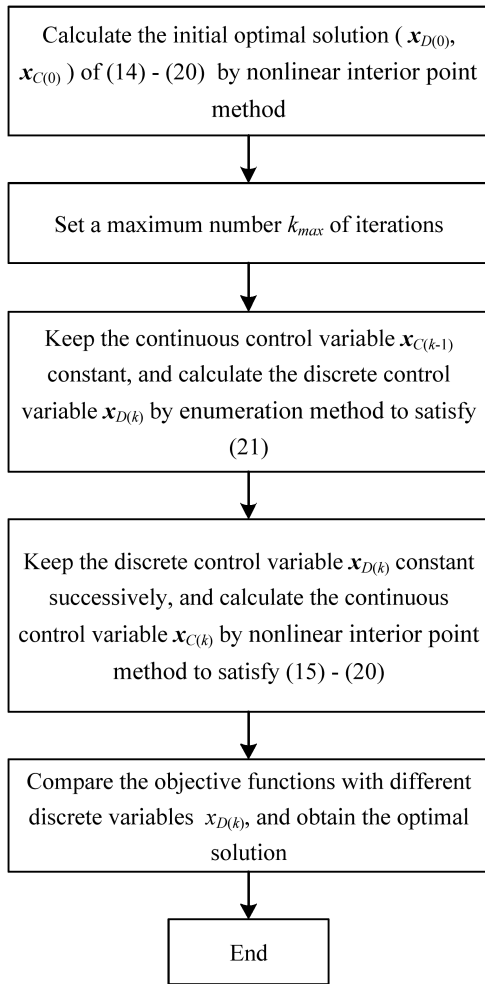


Fig. 2 Hybrid algorithm flowchart

replaced by $(Q_d - Q_{ac})^2$ and $\cos\theta_d$ to reduce the complexity and non-linearity of the model. Hence, the objective function is represented as

$$y = \min \{ w_1 \times (Q_d - Q_{ac})^2 + w_2 \times (k_T - k_{T0}) + w_3 \times (\theta_d - \theta_{d0}) \} \quad (15)$$

2.2.3 Equality constraints:

(i) Nodal power balance equations
For pure AC node i

$$\left. \begin{aligned} \Delta P_i &= P_{is} - U_i \sum_{j \in i} U_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \\ \Delta Q_i &= Q_{is} - U_i \sum_{j \in i} U_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \end{aligned} \right\} \quad (16)$$

where P_{is} and Q_{is} represent the nodal injection active and reactive power for node i , and G_{ij} and B_{ij} the real part and imaginary part of the node admittance matrix element, respectively. U_i indicates the voltage amplitude of node i , and θ_{ij} indicates the phase angle of the two nodes between i and j . It is necessary to point out that node j can be either a pure AC node or a DC node (the converter AC bus).

For DC node i

$$\left. \begin{aligned} \Delta P_i &= P_{is} - U_i \sum_{j \in i} U_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ &\pm U_d I_d = 0 \\ \Delta Q_i &= Q_{is} - U_i \sum_{j \in i} U_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \\ &- U_d I_d \tan \varphi + Q_{ACFnorm} \left(\frac{U_i}{U_{ACFnorm}} \right)^2 = 0 \end{aligned} \right\} \quad (17)$$

where positive and negative signs represent inverters and rectifiers, respectively.

1. ii) Basic equations for the converter station

$$\left. \begin{aligned} \Delta d_1 &= U_d - k_T U_i \cos \theta_d + X_T I_d = 0 \\ \Delta d_2 &= U_d - k_\mu k_T U_i \cos \varphi = 0 \\ \Delta d_3 &= d_3 (U_d, I_d, \cos \theta_d, k_T) = 0 \end{aligned} \right\} \quad (18)$$

where k_μ is the coefficient considering the influence of commutation overlap.

2.2.4 Inequality constraints:

(i) Inequality constraints for state variables

$$\left. \begin{aligned} Q_{expmin} &\leq Q_{exp} \leq Q_{expmax} \\ U_{imin} &\leq U_i \leq U_{imax} \\ U_{dmin} &\leq U_d \leq U_{dmax} \\ I_{dmin} &\leq I_d \leq I_{dmax} \end{aligned} \right\} \quad (19)$$

(ii) Inequality constraints for control variables

$$k_{Tmin} \leq k_T \leq k_{Tmax} \quad (20)$$

$$\cos \theta_{dmin} \leq \cos \theta_d \leq \cos \theta_{dmax} \quad (21)$$

$$k_T \in \{k_{Tmin}, \dots, k_{Tmax}\} \quad (22)$$

where $(\cdot)_{min}$ and $(\cdot)_{max}$ are minimum and maximum values of the variable (\cdot) . Especially, (22) shows that k_T is a discrete variable with a series of values.

2.2.5 Algorithm for reactive power optimisation of converter station: The hybrid algorithm in [11] is applied to the model founded in the preceding section. Similarly, discrete constraints are ignored first and the initial solution can be obtained by non-linear interior point method. Then, the original problem is decomposed into a discrete optimal subproblem and a continuous optimal subproblem. Specially, there is only one discrete variable in the model; hence, the enumeration method in a limited range is used for the discrete variable. Also, the continuous one is solved by non-linear interior point method. Finally, the optimal solution is received by comparing the objective functions with different discrete variables. A hybrid algorithm flowchart is shown in Fig. 2. In this paper, sparse technology is applied in the interior point method and power flow calculation.

3 Results

3.1 Comparison and analysis of different measures to adjust reactive power and voltage in converter station

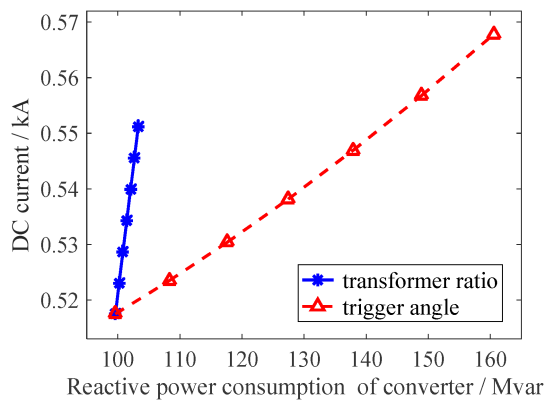
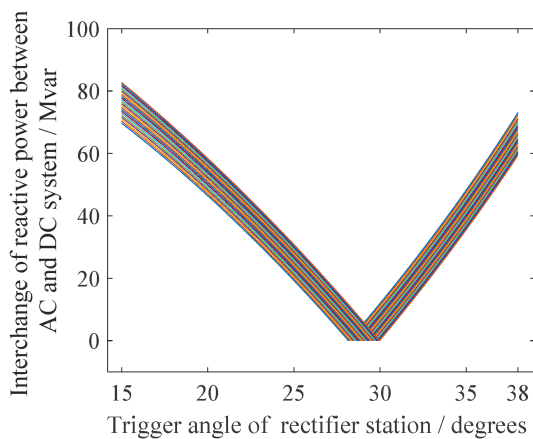
In Section 2.1, the reactive power consumption of converter Q_d is derived with the adjustment of control angle θ and transformer ratio k_T . Taking the rectifier station of Tian-Guang HVDC project as an example, the adjustment of reactive power and voltage is simulated and analysed, and detailed parameters of the test system are referred in [12–15]. Taking the transmission of 270 MW DC power as an example, it is assumed that the equivalent voltage of AC system U_{sys} is 228 kV, and that DC system is operated in single

Table 1 AC/DC variables changing with p adjustment

P	U_t , kV	U_{d0} , kV	U_d , kV	I_d , kA	Q_d , Mvar
0	228.819	558.912	521.749	0.517	99.601
-1	228.807	553.350	516.181	0.523	100.205
-2	228.795	547.896	510.718	0.529	100.813
-3	228.783	542.549	505.356	0.534	101.426
-4	228.771	537.304	500.093	0.540	102.044
-5	228.759	532.158	494.925	0.546	102.666
-6	228.747	527.110	489.851	0.551	103.294

Table 2 AC/DC variables changing with θ_d adjustment

θ_d	U_t , kV	U_{d0} , kV	U_d , kV	I_d , kA	Q_d , Mvar
15	228.819	558.912	521.749	0.517	99.601
17	228.649	558.498	515.766	0.523	108.294
19	228.468	558.056	509.083	0.530	117.586
21	228.275	557.585	501.708	0.538	127.453
23	228.071	557.086	493.651	0.547	137.889
25	227.855	556.558	484.919	0.557	148.906
27	227.627	556.000	475.520	0.568	160.531

**Fig. 3** I_d changing trends with Q_d **Fig. 4** Q_{exp} changing trends with θ_d

pole under constant power control. In low-power operation, AC filters are applied in accordance with the minimum filter requirements.

Supposing that the trigger angle of the converter θ_d is 15° , converter transformer tap position p is adjusted from 0 to -6, and the result of the adjustment, reactive power consumption of converter Q_d , for example, is shown in Table 1.

Supposing that the converter transformer works at rated ratio, i.e. $p=0$, trigger angle increases from 15° to 27° , and the adjustment result is shown in Table 2.

It can be seen from Tables 1 and 2, when 270 MW power transported and two sets of AC filters (1A + 1B) applied, converter station transfers the excess reactive power 60.399 Mvar, calculated as $80 \times 2 - 99.601$, to AC system in initial state, i.e. $\theta_d = 15^\circ$ and $p = 0$. As the converter transformer tap position p is adjusted from 0 to -6, the consumption of reactive power Q_d increases from 99.601 to 103.294 Mvar, and its increment is limited. If the trigger angle of converter θ increases to 27° , the consumption of reactive power is raised to 160.531 Mvar, realising the purpose of zero interchange of reactive power between AC and DC system. In addition, as far as power loss of DC line is concerned, it is not difficult to find in Fig. 3 that comparing with transformer ratio, the regulation of trigger angle has little influence on DC current, that is, the increment caused by trigger angle is small. Therefore, it is clear to be seen that the adjustment of trigger angle is more propitious to increase reactive power consumption, as well as decrease the impact on energy loss, than that of the transformer tap.

However, the trigger angle of converter is restricted by the valve arrester, damper winding, and valve reactor. The ideal no-load direct voltage decreases with the increase in trigger angle, but it may lead to a high step voltage of valve and bring adverse effects. Thus, it is necessary for the converter station to adjust the transformer tap position in order to avoid running under the condition of excessive trigger angle.

3.2 Optimal control results of converter station during low-power operation

Considering decision-makers' respective preference and order of magnitude for different targets, values are assigned to weighting coefficients as follows: $w_1 = 1$, $w_2 = 10$, $w_3 = 100$. Under the normal condition of sample system adopted in Section 3.1, the trigger angle works around 15° with the converter transformer changing in the vicinity of its rated ratio. Hence, the fixed values for parameters in the model are taken as $p_0 = 0$, $\theta_{d0} = 15^\circ$. As it can be seen from Fig. 4, there is little reactive power interchange between AC and DC system when the trigger angle ranges from 28° to 30° as converter transformer ratio varies.

Control variables p and θ_d are optimised by the optimal reactive power model proposed in this paper. Compared with other strategies, the operating parameters of AC/DC system are analysed. The comparison scheme is designed as follows.

- **Strategy 1:** Set the same p and θ_d as those under normal condition, i.e. $p = p_0$, $\theta_d = \theta_{d0}$.
- **Strategy 2:** Set θ_d for the minimum interchange of reactive power, and $p = p_0$.

Table 3 Comparison of different strategies

No	ρ	θ_d	Q_{exp} , Mvar	U_t , p.u.	U_{d0} , kV	U_d , kV	I_d , kA
1	0	15	-73.48	1.04	558.91	521.75	0.517
2	0	29.1	0.13	1.03	553.30	464.42	0.581
3	1	25.8	9.24	1.03	559.06	497.24	0.543

- **Strategy 3:** Set ρ and θ_d based on the proposed reactive power optimisation.

The results of different strategies are shown in Table 3. From the table, it is clear to be seen that strategies 2 and 3 can effectively decrease the interchange of reactive power compared with strategy 1 applying initial parameters. Meanwhile, DC voltage is reduced to far less than its rated value in the case of a long overvoltage operation. Considering the influence of transformer ratio, strategy 3 has an effective suppression of the ideal no-load direct voltage fluctuation. Though reactive power interchange and DC current obtained by the proposed method outweigh those by strategy 2, the limited energy loss can be accepted due to low DC resistance.

The above analysis shows its effectiveness of the proposed method. The method provides a theoretical basis for tuning parameters of the converter station during low operation. However, the choice of weighting coefficients leading to different optimal results may be affected by various factors, which can be focused on for further research.

4 Conclusion

An optimal reactive power control method of the converter station during low-power operation is proposed in this paper. Firstly, the effects of converter transformer ratio and control angle on reactive power and voltage in a converter station are derived theoretically, and the similarities and differences of the two measures are analysed and compared. Then, an optimal reactive power dispatch model of the converter station is established, comprehensively considering its actual strategies and requirements. The optimisation results provide reference for the parameters of the two regulation devices. Finally, the test results on Tian-Guang HVDC verify the effectiveness of the proposed method.

However, there are certain limitations in this paper. Apart from previously mentioned one that weighting coefficients will affect the result, the influence of change in DC control mode and the regulation characteristics of AC system are both not taken into account.

5 Acknowledgments

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