Improved power flow algorithm for hybrid AC/DC grid with reactive power control

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Abstract: With the development of high-voltage direct current (HVDC) projects, hybrid AC/DC power grid will be the main characteristic of China’s power grid. As a result, improving the accuracy of power flow result has the important significance of the planning, operation and dispatching of the power grid. This study introduces an improved load flow calculation method, based on reactive power compensation and control strategy of the HVDC converter configuration. The proposed method dealt with the effect of reactive power exchange between AC and DC grids, as well as actual situation. In the end, Jiangsu power grid is used to verify the correctness of the method and the simulation results show the effectiveness in different operation modes of HVDC.

1 Introduction

As a mature and reliable long-distance and high-capacity power transmission technology, high-voltage direct current (HVDC) transmission plays an important role in optimising the allocation of energy resources in China. Dozens of HVDC transmission projects would be built in China before 2020, so that multiple-circuit HVDC transmission drop-points would be inevitably replaced at the same AC receiving-end and the power grid structure under the condition of complex AC/DC multiple series would be formed. The security and stability of the power system are calculated and analysed based on accurate power flow calculation results. Since the HVDC transmission scale is constantly expanded, the power flow should be further calculated in convergence and accuracy. For example, the HVDC transmission system not only increases the number of variables of the power flow calculation, but also further enhances the nonlinearity of the power flow calculation. Therefore, there are often the phenomena of convergence difficulty and even no convergence in the calculation of the large-scale AC/DC hybrid power grid. In addition, HVDC transmission was with multiple operation modes, complex and changeable control methods, especially DC reactive power and voltage control strategy, which directly determined the change rule of the reactive power and voltage between AC and DC power grids and affect the accuracy of power flow calculation results. So, it is urgent to improve the convergence of the algorithm based on the guarantee of the accuracy of the power flow results.

The current research on the power flow calculation of AC/DC power grid focuses on the improvement of the convergence. According to different iterative methods, it can be roughly divided into two categories: unified iterative method and alternative iterative method. The alternative iterative method can make full use of the existing research results of AC power flow calculation and thus attract much attention. Paper [8] adjusted the dividing line of AC/DC systems and thus reduced the iterative frequencies; paper [9] put forward an AC/DC grid power flow calculation method, which could meet the requirements of engineering calculation accuracy and improved the calculation efficiency. However, the above literatures ignored the influence of HVDC reactive power control on the power flow results. With a view of the power flow calculation characteristics of HVDC distribution network, paper [10] introduced the AC/DC power flow model with augmented Cartesian coordinates and solved through the Newton method. However, the model was just suitable for distribution networks. Paper [11] added HVDC electric current as the state variable to the power flow calculation and established the AC/DC hybrid power flow model. However, the convergence was poor in the case of multiple-circuit DC access. Paper [12] classified the distributed power supply and realised the power flow information interaction between various AC/DC subsystems through the converter. Paper [13] analysed the characteristics of the subway hybrid network and adjusted the iterative process of DC power flow to reduce the iterative times. On the basis of the characteristics of droop control, paper [14] successfully calculated the power flow of the low-voltage hybrid micro-grid through the virtual impedance technique. However, it was just suitable for voltage-source converter DC transmission. On the basis of forward-back substitution, paper [15] put forward a power flow calculation method applied to the hybrid distribution networks with distributed power supply and energy storage equipment, which was suitable for different converter control modes. However, it did not refer to the reactive power and voltage control mode.

To adequately consider the influence of DC reactive power control characteristics on the power flow results in the power flow calculation of AC/DC hybrid power grid, this paper proposed a kind of method that takes into account the improvement of the reactive power compensation allocation, reactive power and voltage control strategy of the DC converter station during calculation. On the basis of the existing achievements, on the basis of the influence of different control strategies, the decoupling algorithm is employed to deal with the reactive power compensation capability and control strategy of the DC converter station during calculation. As a result, both convergence and calculation accuracy could be ensured and results are much more identical with the actual power grid operation.

2 Power flow model with HVDC transmission

Taking the double-end DC system, Fig. 1 as an example, the power flow model of DC transmission is shown in formulae (1)–(5)

\[ U_{ir} = \frac{3\sqrt{2}}{\pi} n_k k R U_{ir} \cos \alpha - \frac{3}{\pi} n_k X_{kr} I_d \]  

(1)
In the formulas: \( U_d \) is the DC voltage; \( U_i \) is the AC bus voltage; \( n \) is the bridge number; \( k \) is the ratio of transformation of the converter transformer; \( \psi \) is the firing angle of rectifier side; \( \gamma \) is the extinguishing angle of inverter side; \( X_c \) is equivalent commutation reactance; \( I_d \) is DC line current; \( P_d \) is the DC active power; \( Q_d \) is the reactive loss; \( Q_C \) is the reactive compensation capability; the subscripts \( R \) and \( I \), respectively, represent rectifier side and inverter side.

Formulæ (1)–(5) constitute the power flow equation of DC transmission. The four variables of \( U_d \), \( I_d \), \( k \), and \( \cos \alpha (\cos \psi) \) are added to the single DC converter station. According to the operation situation of HVDC actually put into operation in China, the rectifier power \( P_{dR} \) and the voltage \( U_{dR} \) are usually fixed. On the basis of this, the DC current \( I_d = P_{dR}/U_{dR} \) can be calculated. Then, the DC voltage \( U_{dR} \) at the inverter side and the active power \( P_{dI} \) injected into the receiving system could get through formulæ (4) and (5). Finally, they are substituted into formulæ (6)–(9) to calculate the capacity and the reactive power of DC transmission.

### 3 Reactive power control of DC converter station

The reactive power control of DC converter station means that the DC converter station controls the reactive power in the DC transmission control system. It allocates the input capacity of the reactive power compensation equipment, and controls the reactive power exchanged between the converter and the AC system within the specified range (reactive power control mode) or AC bus voltage of the converter station within the specified range by means of the converter station. The former aims to ensure the reactive power balance of the AC system. Moreover, the latter is used to improve the voltage stability of the receiving-end grid.

The DC converter station is usually equipped with the following reactive control strategies: absolute minimum filter capacity control, minimum/maximum voltage control, minimum filter capacity control, reactive power exchange control and AC bus voltage control. Among them, the following three control strategies have a greater influence on the reactive power distribution of power grid:

(i) **Absolute minimum filter capacity control strategy:** This control strategy aims to avoid the minimum reactive compensation capability, which is required by the other operating AC filter harmonic overload when the partial AC filter banks overload are moved due to the fault. If the condition is not met, in order to prevent the AC filter being damaged, the DC system will reduce the active power to meet the conditions of the absolute minimum filter banks.

(ii) **Reactive power exchange control strategy:** The control strategy is applied to control the reactive power exchange amount between the converter station and the AC system within the upper and lower set limits. To prevent the frequent switching of the reactive power compensation equipment, the difference between the upper and lower limits of the set reactive power exchange should be greater than the capability of the maximum reactive power equipment group. If the exchange value of the exchanged reactive power exceeds the upper limit, the reactive power compensation equipment is switched off.
and lower limits, a group of reactive equipment will be put in or removed.

(iii) AC bus voltage control strategy: The control strategy is used to control the AC bus voltage of the converter station within the upper and lower set limits. To prevent the frequent switching of the reactive power compensation equipment, the difference between the upper and lower limits of the set AC bus voltage should be greater than the voltage variation when the single group reactive power is switched. If the AC bus voltage exceeds the upper and lower limits, a group of reactive compensation equipment will be removed or put in.

The above three control strategies are: (i) > (ii) > (iii) in the priority level. In the actual operation of the DC converter station, strategy (i) is the basic control strategy and needs to be put into operation at all times. Strategy (ii) and (iii) are usually chosen by the operators according to the operation of the AC power grid. Strategy (i) is with the highest priority, so it should first ensure itself and then switch and control the reactive power compensation equipment according to strategies (ii) and (iii) in the actual operation.

4 Calculation method of the AC/DC power flow considering the characteristics of reactive power control

4.1 Processing method of reactive power control strategy

The key to improve the accuracy of the calculation results of the AC/DC grid power flow is to accurately calculate the reactive power capability of the reactive control strategy of the DC converter station. This paper puts forward the following processing methods with a view of the above three DC reactive control strategies:

(i) Absolute minimum filter capacity control strategy

\[
Q_c = \begin{cases} 
Q_{c,\text{abs}} & \text{if } Q_c < Q_{c,\text{abs}} \\
Q_c & \text{if } Q_c \geq Q_{c,\text{abs}} 
\end{cases}
\]  

(16)

In the formula, \(Q_{c,\text{abs}}\) is the minimum reactive compensation switching capability required by the absolute minimum filter capacity control strategy. Two groups of filters are usually set.

(ii) Reactive power exchange control strategy

\[
Q_c = \begin{cases} 
Q_c + \left[Q_{c,\text{ex},\text{min}} - \Delta Q_d\right]/Q_s \times Q_s & \text{if } \Delta Q_d < Q_{c,\text{ex},\text{min}} \\
Q_c - \left[Q_{c,\text{ex},\text{max}} - \Delta Q_d\right]/Q_s \times Q_s & \text{if } \Delta Q_d > Q_{c,\text{ex},\text{max}} \\
Q_c & \text{if } Q_{c,\text{ex},\text{min}} \leq \Delta Q_d \leq Q_{c,\text{ex},\text{max}} 
\end{cases}
\]  

(17)

In the formula, \(Q_{c,\text{ex}}\) is the reactive power exchanged between the AC/DC power grids; \(Q_c\) is the capability of a single filter; \(Q_{c,\text{ex},\text{min}}\) and \(Q_{c,\text{ex},\text{max}}\) are respectively the minimum and maximum values of the AC/DC exchange reactive power required by the strategy; \(\lceil \cdot \rceil\) is the first integer greater than the value.

(iii) AC bus voltage control strategy

\[
Q_c = \begin{cases} 
Q_c + \left[\frac{\Delta Q}{\Delta U} \cdot (U_{i,\text{min}} - U_i)/Q_s\right] \times Q_s & \text{if } U_i < U_{i,\text{min}} \\
Q_c - \left[\frac{\Delta Q}{\Delta U} \cdot (U_i - U_{i,\text{max}})/Q_s\right] \times Q_s & \text{if } U_i > U_{i,\text{max}} \\
Q_c & \text{if } U_{i,\text{min}} \leq U_i \leq U_{i,\text{max}} 
\end{cases}
\]  

(18)

In the formula, \(\Delta Q/\Delta U\) is the sensitivity of AC side bus reactive power to voltage; \(U_{i,\text{max}}\) and \(U_{i,\text{min}}\) respectively are the maximum and minimum voltages of the AC side bus required by the strategy.

4.2 Calculation method of improving the AC/DC grid power flow

This paper introduces the calculation method to improve the AC/DC decoupling power flow based on the control characteristics of the reactive power in the DC converter station as shown in Fig. 2.

![Fig. 2 Flowchart of algorithm](image)

In the formula, \(\partial Q/\partial U\) is the sensitivity of AC side bus reactive power to voltage; \(U_{i,\text{max}}\) and \(U_{i,\text{min}}\) respectively are the maximum and minimum voltages of the AC side bus required by the strategy.

5 Case studies

As an important part of the power grid in Eastern China, Jiangsu power grid has built 49,500 kV substations and 565,220 kV substations and been with the maximum tracking load of about $4$ million, and put into operation the two-circuit DC Jinsu and Longzheng with the respective rated power 7200 and 3000 MW as of the end of 2015. It is estimated that after the two HVDC of northern Shanshi–Nanjing (8000 MW) and Ximeng–Taizhou (10,000 MW) are successively put into operation in 2017.

To verify the effectiveness of the algorithm, the section takes the operation of four HVDCs of Jiangsu power grid as an example and makes the simulation calculation in different DC powers. By
comparing to the calculation result of the traditional AC/DC decoupling power flow, the details are obtained as follows.

The main parameters of four-circuit DC transmission are shown in Tables 1 and 2.

### 5.1 Power flow calculation of different reactive control strategies

When the four HVDCs operate at full power, the simulation calculations are, respectively, carried out in the following four reactive control strategies:

*Example 1:* four HVDCs are all set as the reactive power exchange control strategy.

*Example 2:* four HVDCs are all set as the voltage control strategy.

*Example 3:* Jinsu and Longzheng DCs are set as the reactive exchange control strategy.

*Example 4:* Jinsu and Longzheng DCs are set as the voltage control strategy and Nanjing and Taizhou are set as the reactive exchange control strategy.

In Tables 3–6, the traditional decoupling method, that is, the existing AC/DC decoupling power flow calculation method [9], makes the comparative analysis of the calculation results based on the two methods:

(i) After the four HVDCs’ result is solved through the traditional AC/DC decoupling power flow calculation method, the reactive power of Nanjing DC inverter station into AC side grid is $382.9 \, \text{MVar}$ and exceeds $-250 \, \text{MVar}$, the reactive exchange range of the AC/DC power grid; the AC bus voltage

| Table 1 Data of four HVDCs |
|-----------------------------|
| HVDC | Converter | Single filter, MVar | Group numbers | Exchange reactive power between AC and DC grid, MVar | Voltage range of AC buses, kV |
| Jinsu | R | 215 | 20 | $-150$–$150$ | 500–525 |
| | I | 270 | 16 | $-170$–$170$ | 500–525 |
| Longzheng | R | 140 | 11 | $-120$–$120$ | 500–525 |
| | I | 136 | 15 | $-110$–$110$ | 500–525 |
| Nanjing | R | 285 | 14 | $-200$–$200$ | 495–525 |
| | I | 306 | 14 | $-250$–$250$ | 495–525 |
| Taizhou | R | 240 | 20 | $-200$–$200$ | 495–531 |
| | I | 255 | 17 | $-220$–$220$ | 495–531 |

| Table 2 Data of four HVDCs’ transformers |
|------------------------------------------|
| HVDC | Converter | UN | Tap | $\Delta \gamma$, % |
| Jinsu | R | 535/171.3 | $-6/+22$ | 1.25 |
| | I | 505/160.7 | $-3/+25$ | 1.25 |
| Longzheng | R | 525/210.4 | $-6/+25$ | 1.25 |
| | I | 525/200.4 | $-6/+23$ | 1.25 |
| Nanjing | R | 535/171.9 | $-6/+23$ | 1.25 |
| | I | 555/159.8 | $-6/+24$ | 1.25 |
| Taizhou | R | 535/171.9 | $-6/+24$ | 1.25 |
| | I | 505/159.8 | $-5/+25$ | 1.25 |

| Table 3 Result of AC/DC power flow in test system 1 |
|--------------------------------------------------|
| HVDC | Inverter-side voltage, kV | Exchange reactive power between AC/DC grid, MVar | Transformer tap |
| | Proposed method | Traditional method | Proposed method | Traditional method | Proposed method | Traditional method |
| Jinsu | 515.9 | 520.3 | $-141.0$ | $-108.7$ | 4 | 4 |
| Longzheng | 519.7 | 524.7 | $-98.0$ | $-84.2$ | 1 | 2 |
| Nanjing | 501.4 | 525.9 | $-42.7$ | 382.9 | 1 | 5 |
| Taizhou | 528.3 | 536.3 | $-94.0$ | $-38.4$ | 6 | 7 |

| Table 4 Result of AC/DC power flow in test system 2 |
|--------------------------------------------------|
| HVDC | Inverter-side voltage, kV | Exchange reactive power between AC/DC grid, MVar | Transformer tap |
| | Proposed method | Traditional method | Proposed method | Proposed method | Proposed method | Traditional method | Proposed method |
| Jinsu | 516.1 | 520.3 | $-139.3$ | $-108.7$ | 4 | 4 |
| Longzheng | 521.1 | 524.7 | $-94.1$ | $-84.2$ | 1 | 2 |
| Nanjing | 519.7 | 525.9 | 354.7 | 382.9 | 4 | 5 |
| Taizhou | 518.6 | 536.3 | $-421.6$ | $-38.4$ | 4 | 7 |

| Table 5 Result of AC/DC power flow in test system 3 |
|--------------------------------------------------|
| HVDC | Inverter-side voltage, kV | Exchange reactive power between AC/DC grid, MVar | Transformer tap |
| | Proposed method | Traditional method | Proposed method | Proposed method | Proposed method | Traditional method | Proposed method |
| Jinsu | 514.2 | 520.3 | 148.4 | $-108.7$ | 3 | 4 |
| Longzheng | 520.7 | 524.7 | 42.18 | $-84.2$ | 1 | 2 |
| Nanjing | 496.0 | 525.9 | 55.5 | 382.9 | 0 | 5 |
| Taizhou | 505.3 | 536.3 | $-698.8$ | $-38.4$ | 2 | 7 |
of Taizhou DC inverter station is 536.3 kV and exceeds 500–525 kV, the AC bus voltage control range.

(ii) According to the AC/DC power flow calculation methods considering the control characteristics of DC reactive power proposed in this paper, the exchange reactive power of Nanjing DC and AC power grids and the AC bus voltage of Taizhou inverter station can be controlled within a reasonable range.

(iii) The calculation method of the AC/DC power flow proposed in this paper can adopt different reactive control strategies in the different DC systems, that is, it is with good adaptability. It can effectively and successfully control the reactive voltage, improve the accuracy of the power flow results, and be more accord with the actual operation of the AC/DC power grid.

5.2 Power flow calculation under different active power operation modes

The section calculates the power grid in different active power operation modes of Jinsu and Longzheng DCs and makes a comparative analysis of the existing results based on the fixed reactive power compensation capability methods. The details are shown in Tables 7 and 8.

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**Table 6** Result of AC/DC power flow in test system 4

| HVDC | Inverter-side voltage, kV | Exchange reactive power between AC/DC grid, MVar | Transformer tap |
|------|--------------------------|---------------------------------|-----------------|
|      | Proposed method | Traditional method | Proposed method | Proposed method | Traditional method | Proposed method |
| Jinsu | 515.9 | 520.3 | −141 | −108.7 | 4 | 4 |
| Longzheng | 519.7 | 524.7 | −98 | −84.2 | 1 | 2 |
| Nanjing | 501.4 | 525.9 | −42.7 | 382.9 | 1 | 5 |
| Taizhou | 528.3 | 536.3 | −94 | −38.4 | 6 | 7 |

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According to the analysis of the calculation results based on the method proposed by this paper and the traditional decoupling method, it can be seen that:

(i) As the active power that Jinsu DC and Longzheng DC transmit gradually decreases, the reactive exchange power exceeds the DC reactive exchange control range obtained based on the traditional decoupling power flow algorithm and the AC bus voltage of the inverter station becomes high, which are inconsistent with the actual power grid operation.

(ii) In the AC/DC power flow calculation, when the active power that Jinsu and Longzheng transmit, respectively, reduces to 720 and 300 MW, one or two groups of filters should be put into according to the reactive control strategies. However, the reactive control strategy (i) is with the highest priority, so two groups of filters should be put into operation, which leads to the reactive power of the AC/DC power grids exchange exceeds the upper and lower limits.

(iii) According to the calculation method of the AC/DC power flow described in this paper, when both Jinsu and Longzheng adopt the reactive power control strategy and the DC active power is relatively large, the reactive exchange power of the AC/DC power grid can be ensured in the control range and be in line with the actual AC/DC grid operation.

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**Table 7** Result of AC/DC power flow in constant reactive control mode of Jinsu HVDC

| Transmission power, MW | AC buses voltage, kV | Exchange reactive power between AC/DC grid, MVar | Transformer tap |
|------------------------|----------------------|---------------------------------|-----------------|
|                        | Proposed method | Traditional method | Proposed method | Proposed method | Traditional method | Proposed method |
| 7200                   | 515.9 | 520.3 | −141.0 | −108.7 | 4 | 4 |
| 5760                   | 514.1 | 520.4 | −46.2 | 266.4 | 5 | 7 |
| 4320                   | 517.7 | 526.1 | 151.1 | 439.0 | 6 | 8 |
| 2880                   | 511.6 | 519.5 | 160.1 | 437.5 | 6 | 8 |
| 1440                   | 504.6 | 511.7 | 21.0 | 292.7 | 6 | 7 |
| 720                    | 510.5 | 510.2 | 228.7 | 230.1 | 7 | 7 |

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**Table 8** Result of AC/DC power flow in constant reactive control mode of Longzheng HVDC

| Transmission power, MW | AC buses voltage, kV | Exchange reactive power between AC/DC grid, MVar | Transformer tap |
|------------------------|----------------------|---------------------------------|-----------------|
|                        | Proposed method | Traditional method | Proposed method | Proposed method | Traditional method | Proposed method |
| 3000                   | 524.7 | 524.7 | −84.2 | −84.2 | 2 | 2 |
| 2400                   | 526.2 | 526.2 | 39.0 | 39.0 | 4 | 4 |
| 1800                   | 522.3 | 527.4 | 70.7 | 210.7 | 5 | 6 |
| 1200                   | 518.1 | 523.0 | 28.8 | 166.5 | 6 | 7 |
| 600                    | 509.4 | 515.0 | 50.6 | 187.0 | 6 | 6 |
| 300                    | 512.8 | 515.9 | 120.0 | 160.8 | 7 | 6 |
6 Conclusions

To consider the influence of ultra-HVDC reactive power control strategy on the power flow calculation results of the AC/DC hybrid grid, this paper proposed a power flow calculation method with the DC reactive control strategy. On the basis of the existing AC/DC decoupling power flow algorithm, the algorithm fully deals with the influence of different reactive control strategies on the exchange reactive power between the AC/DC power grids. Finally, it takes Jiangsu power grid as the simulation example. It is indicated that in the case of the four HVDCs feed-in, it could be able to solve and obtain the power flow results more accordant with the power grid operation.

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