A Method of Power Flow Calculation Considering New FACTS and HVDC

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Abstract. Focusing on the influence of new FACTS or HVDC, this paper proposes a method to calculate their power flow of modern power system. The proposed method is carried out by transforming new FACTS or HVDC into equivalent buses like PQ buses in AC. Compared with alternating iterative method and unified iterative method, the proposed method has advantages in convergence property, preparatory work and reusability. This paper used the proposed method, through theoretical deduction of the equations concerning DC system, to complete the power flow calculation of system with HVDC. Through case studies, the results proved that the proposed method has good convergence property and faster computing speed than unified iterative method.

1. Introduction

In modern power system and energy internets, more and more power electronic devices and new ways of transmission or structures are applied. These new components will increase the buses which have different characters. The global energy internet must be enough stable, and have large transmission capacity, which needs electrical network automation providing the base.

The application of FACTS has been considered as an essential trend to improve the stability of system and enlarge the capacity of power transmission [1]. The development and use of FACTS controllers in power transmission system have led to many applications, not only to improve the voltage and transient angle stability of the existing power networks but also to provide operation flexibility of power systems, as presented in [2].

In recent years, China has built ten High Voltage Direct Current Transmission (HVDC) and four Ultra High Voltage Direct Current Transmission (UHVDC), which are under operation, and there will be more HVDC to be put into operation, according to the plan of State Grid Corporation of China.

These new components will increase the difficulty of network modeling and pose increased challenge to the analysis of stability of power system. Power flow calculation (PFC), is a fundamental calculation of other important research. Thus, how to create a unified structure for PFC needs considering carefully.

Faced with new components (FACTS or HVDC) in AC power system, the usual ways to calculate the power flow are with unified iterative method and alternating iterative method. Sheykholeslami has used the unified iterative method to complete the PFC, focusing on the presence of Dynamic Flow Controller in [3]. Paper from [4] has presented the process of a unified iterative solution of PFC. It considers the wind farms and FACTS devices. For HVDC, researchers have completed the PFC
through unified iterative method in [5, 6] and paper from [7] improved the unified power flow algorithm by focusing on the changes of buses type.

It should be mentioned that the software OpenDSS has completed much work on the PFC about distribution networks including converter-interfaced DGs. In this paper, the method EPQ is not same with the solution of OpenDSS. The differences rely on below: the EPQ is a method for the entire system, including the FACTS themselves, and the method needs to calculate the operation parameters of FACTS at the same time. The EPQ does not transform the FACTS into pure PQ buses and it will consider the relations between FACTS and AC system which may make the parameters in AC system influence the power injected into AC system. Its purpose is to cope with many different FACTS at an entire system, not only for one type of devices.

This paper mainly consisted of two parts. First part, presented in section 2, proposed a method, named EPQ, to calculate the power flow, and compared it with the alternative iterative method and unified iterative method. Second part, presented in section 3, used EPQ method, after theoretical deduction and analysis of the LCC station, to calculate the power flow of system with HVDC, which is practiced in a case.

2. Methods of power flow calculation
In this part, a method for PFC considering new FACTS is proposed, and the comparison of the traditional two method of PFC with the method is completed.

2.1 Alternating iterative method
For the alternating iterative method, its main advantage against unified iterative method is that, in the iteration the elements and its construct methods of Jacobian matrix are not changed, so this method only needs modifying the power equations. If the numerical oscillation or divergence occurs, the method does not convergence. This method no longer has the quadratic convergence, which is the characteristic of the traditional Newton-Raphson method for computing power flow.

2.2 Unified iterative method
For the unified iterative method, its main advantages rely on its characteristic of quadratic convergence which is preserved from traditional Newton-Raphson. This method combines power equations from the original system and the new equations from new components including control equations and basic equations, to create the Jacobian matrix to complete the PFC. These equations are nonlinear and the unified iterative method uses the principle of the traditional Newton-Raphson method. Thus, this method has quadratic convergence. However, compared with the original PFC, unified iterative method needs expanding the Jacobian matrix for the new variables and the equations of these variables. New variables from new components need considering setting the initial values, while the iterative convergence relays on the initial values. The new equations differ from the original power equations and there may be some situations where modified matrix is pathological and unsolved, which need further processing [8]. Thus, this method requires much work to be done to complete the calculation.

2.3 Equivalent PQ Buses method
Through transforming the new FACTS or HVDC into equivalent PQ buses (EPQ) in AC system, this method can complete the PFC conveniently. The EPQ could be controlled by variables from AC system but not from new FACTS or HVDC on expression, as shown in Fig. 1.

![Figure 1. The schematic of EPQ method.](image-url)
New FACTS is controlled by its own control strategies and basic characteristics from its structure. They also have some restricts on the operation range. EPQ method should analyze the new FACTS, get the basic equations and control equations, and furtherly analyze the reactive and active power injected into devices. Purpose of EPQ is to get an expression of reactive and active power which only concerns variables from AC system, or variables from the control strategies and basic characteristics that can be determined before PFC, as shown in Fig. 2.

Figure 2. Influence of EPQ method on the variables in PFC.

The detailed process will be presented through using the HVDC with LCC stations as example in this paper. In [9], VSC converter has been equivalent to a controllable voltage source in series with transformer impedance to complete PFC. Thus, the proposed method has built some foundation on the past research, but it is not concluded and proposed systematically.

2.4 Comparison of PFC Method

As shown in Table 1, unified iterative method and EPQ method have quadratic convergence, while the alternating iterative method’s convergence has not mathematical proof and in practice its convergence do not better than unified iterative method. To apply certain method to complete the PFC, the alternating iterative method nearly do not need doing external work after modeling the new FACTS, while unified iterative method needs designing the structure of Jacobian, setting the initial values and considering the influence of control strategy on the Jacobian. The EPQ method need to do the theoretical deduction to get the expression of reactive and active power, which may be very difficult, and according to the results of the theoretical deduction, the relation between injected power of new FACTS and the variables from AC system should be analyzed to modify the Jacobian. But after this work is done, even if new FACTS was added into network, the unified iteration just need do the same work for new FACTS based on previous work. Alternating iterative method also just analyzes the new FACTS. But unified iteration needs reconsider the structure of Jacobian and considering the influence of control strategy on the Jacobian. For example, literature [6] focused on the PFC of system incorporating HVDC with LCC and VSC station, while the PFC of system with one type of HVDC, LCC or VSC station, has been completed in the other paper before. Thus, faced with more new FACTS, there will be more work to be done again.

| Comparison | Alternating iteration | Unified iteration | EPQ |
|------------|-----------------------|------------------|-----|
| Convergence| No mathematical proof | Quadratic        | Quadratic |
| Preparation| Little                | Much             | Much |
| Reusability| High                  | Low              | High |

Table 1. Comparison of three methods for PFC.

Here the difference of alternating iterative method and EPQ method should be explained further, because that, under certain situation the two method has the same process. In the whole iteration of PFC, the EPQ do not change the variables from new FACTS while the alternating iterative method do. Usually the active and reactive power injected into new FACTS in the alternating iterative method will change with the variables changing. The difference is shown in Fig. 3.
Figure 3. Difference of alternating iteration and EPQ. (a) is the process of alternating iteration and (b) is the process of the iteration of EPQ.

3. EPQ METHOD FOR HVDC

In this part, the EPQ method is applied in a system with HVDC using LCC stations.

3.1 Captions/numbering

The relations concerning LCC station are given in (1).

\[
\begin{align*}
V &= KU \cos \theta - XI \\
V &= \gamma KU \cos \phi \\
I_a &= \gamma KI
\end{align*}
\]  

(1)

where all parameters in this paper are per unit quantities. \(V\) and \(I\) respectively denote the voltage and current in DC system; \(U\) denotes the voltage of AC bus connected with transformer. \(K\) is the value of transformer ratio; \(\theta\) represents the converter commutation control angle; \(X\) indicates the equivalent converter reactance; \(\gamma\) is a parameter corresponding to the commutation effect, usually set as 0.995; \(\phi\) is the power factor angle. Equivalent structure of LCC station is shown in Fig. 4, where \(\delta\) denotes the phase angle of AC bus.

![Equivalent Structure of LCC station](image)

For LCC station, the operating condition of each converter depends on two individual control variables, D-axis control variable and E-axis control variable [6]. Under practical operation condition, most transformers' ratio (\(K\)) is usually set with specified integers which correspond to alternative tap positions. In calculation, when constant \(\theta\) is used and calculation is done, \(\theta\) should be recalculated by rounding the ratio of transformer to nearest available integer and turning constant \(\theta\) into constant \(K\). Then the constant quantities for control strategy are elaborated and shown in Table 2.

| D-axis Control | E-axis Control |
|----------------|---------------|
| \(P, V, I\)    | \(K, \theta\) |

where \(P\) is the active power. Moreover, \(P, V\) and \(I\) are defined as D-axis control variables, while \(K\) and \(\theta\) belong to E-axis control variables.

3.2 Transform HVDC to Equivalent Nodes

The discussion of different control strategies’ effect on Equivalent PQ Buses will be divided into two parts.
3.2.1 D-axis control strategies of HVDC

For an entire DC system, there must be at least one inverter choosing constant voltage as its D-axis control, and under this condition, not matter whether other converters’ D-axis control strategy are constant $P$ or $I$, the voltage and injected active power can be calculated by (2).

$$I_k = \sum g_{kj} V_j; \quad P_k = I_k V_k \quad (2)$$

where, $n$ is the number of converters and $g$ is the equivalent conductance.

Therefore, the voltage and injected active power of HVDC system in static status can be obtained based on the admittance matrix of HVDC.

3.2.2 E-axis control strategies of HVDC

(1) When E-axis control is constant $\theta$, the power injected by DC into AC could be expressed as (3). $Q_k$ could be obtained through combining (1) and (3), and deviation of power equations can be expressed as (5).

$$P_k = V_k I_k; \quad Q_k = V_k I_k \tan \phi_k \quad (3)$$

$$Q_k = P_k \sqrt{\gamma^2 \left(V_k^2 + P_k^2 \right) \left[V_k^4 \cos^2(\theta_k)\right]} - 1 \quad (4)$$

$$\begin{cases}
P_a = P_a - U_i \sum_{j=1}^{n} {U_j \left[ G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}\right]} - (\pm P_k) = 0 \\
Q_a = Q_a - U_i \sum_{j=1}^{n} {U_j \left[ G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}\right]} - (Q_k) = 0
\end{cases} \quad (5)$$

where, $P_a$, $Q_a$ are scalar values, positive, the sign $\pm$ is + for rectifier and $-$ for inverter, and $\delta_{ij} = \delta_{ij} - \delta_{ij}$. Compared with Jacobian used in AC PFC, new Jacobian for PFC using Equivalent PQ Buses needn’t modifying.

(2) When E-axis control is constant $K$, $Q$ could be obtained through combining (1) and (3), as shown in (6). Deviation of power equations are expressed by (5), while Jacobian need modifying by using (8).

$$Q = P \sqrt{\gamma^2 K^2 U^2 \left[\gamma^4 - 1\right]} \quad (6)$$

$$dQ/dV = \gamma^2 K^2 PU \sqrt{V^2 \gamma^2 K^2 U^2 - V^4} \quad (7)$$

$$I_a = 2 U_i^2 B_{ij} - \gamma^2 K^2 PU \sqrt{V^2 \gamma^2 K^2 U^2 - V^4}$$

$$- U_i \sum_{j=1, j\neq i}^{n} {U_j \left[ G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}\right]} \quad (8)$$

where, subscript $i$ indicates the AC bus number, $V$ denotes the voltage of DC connected with AC bus $i$.

3.3 Process of the PFC

The process of the PFC in system with HVDC is shown in Fig. 5, in which initializing variables usually choose the flat start. After analysing the control strategies of LCC station, the DC system can be transformed into PQ buses and Jacobian will be modified to use common AC power flow calculation.
3.4 Study Case of PFC with HVDC

3.4.1 Convergence property of two methods
The calculation data source is the 22 buses system of China Electric Power Research Institute, and data could be got from [10]. By adding the DC part to original system, this paper got the grids for the case, as shown below in Fig. 6.

Equivalent converter reactance: two LCC’ equivalent reactance both are 0.013. Control parameter of rectify: active power is 1.5 and commutation control angle is 24.07 degree. Control parameter of inverter: DC voltage is 0.9384 and commutation control angle is 23.92 degree.
| Variables | Times |
|-----------|-------|
| \( U(12) \) | 1 | 2 | 3 | 4 | 5 |
| 1.1251 | 1.0533 | 1.04 | 1.0454 | 1.0454 |
| \( \delta(12) \) (rad) | -0.2594 | -0.2406 | -0.24 | -0.2435 | -0.2435 |
| Maxdelt | 10.3402 | -2.769 | -0.23 | 0.0023 | 3.4e-07 |

Table 3. Results of case using unified iterative method.

| Variables | Times |
|-----------|-------|
| \( U(12) \) | 1 | 2 | 3 | 4 | 5 |
| 1.1236 | 1.0531 | 1.04 | 1.0454 | 1.0454 |
| \( \delta(12) \) (rad) | -0.2322 | -0.2388 | -0.24 | -0.2435 | -0.2435 |
| Maxdelt | 6 | -2.7555 | -0.23 | 0.0023 | 3.3e-07 |

Table 4. Results of case using unified iterative method.

In Table 3 and 4, the Maxdelt is the max deviation of power equations.

After 5 iterations, the PFC converged separately under unified iterative method and EPQ method, with the condition that convergence precision within \( 10^{-5} \). The processes of iteration of two method are shown in Table 3 and 4, in which Maxdelt is the max deviation of power equations. Through Table 3 and 4, it can be found that the EPQ and unified iterative method both have good convergence property.

3.4.2 Calculation speed of two methods

To compare the two method’s efficiency, this paper transformed the IEEE39-10Gen, IEEE162-17Gen, IEEE300 through adding HVDC apart. Using C# to write programs to compute the PFC, results were shown in Fig. 7. The calculation time is recorded and shown in Fig. 7, where the results of C1 are calculated with EPQ method and results of C2 are for the case using integrated iteration method. The test computer configuration specified as follows. The CPU, memory and storage are Intel Core i5-4200H @ 2.60GHz Dual-Core Quad-threading, 8 GB 1867 MHz and Sandisc SSD 500G. From the results, it can be found that the EPQ consumed less time to complete the PFC than unified iterative method.

![Figure 7. Time consumed for PFC.](image)

4. Conclusion

The development of modern power system and energy internets requires the help of new FACTS and HVDC, which as a new component will increase in types and quantity. In recent years, more researchers devoted time into modelling for new FACTS and calculating the power flow of system with them. When new FACTS is invented and considered to be incorporated into original system, the work of power flow calculation may need redoing. This slows the development of modern power system, the application and research of new FACTS. Therefore, this paper proposed a method (EPQ)
to calculate the power flow calculation. The purpose of the method is to remove the new components from AC system. Compared with the alternating iterative method and unified iterative method, EPQ method has more advantages. In a case, this paper uses EPQ to complete the PFC with HVDC, and results imply that compared with unified iterative method, EPQ has same convergence property and faster speed of computation.

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