Sequential Power Flow Calculation of AC/DC Hybrid System Considering Converter Station Loss and Its Capacity Constraints

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Abstract. In the power flow calculation of AC/DC hybrid distribution network, the loss and capacity of the converter station have a great influence on the power flow calculation, and the AC/DC alternately solves the power flow, which has the disadvantage of poor convergence performance. In this paper, the power flow model of AC/DC hybrid distribution network with VSC is established. The loss mechanism of the converter station is analyzed and the capacity limit of the converter station is fully considered. The sequential power flow algorithm with VSC AC-DC hybrid distribution network is proposed. Its convergence performance is improved. In the improved 33-node AC/DC hybrid power distribution network with multiple types of DG, the correctness, effectiveness and algorithm fastness of the algorithm are verified.

1. Introduction
In recent years, the development of distributed energy with multiple advantages such as environmental protection and economy has become increasingly mature, so a large number of distributed power supply devices are connected to the power grid. In addition, such as electric vehicles, LED lighting and many energy storage devices are connected to the grid in a DC mode. The establishment of a DC distribution network can reduce the commutation links, reduce system losses, and improve power utilization. However, the access of a large number of distributed power sources has changed the unidirectional flow mode into a two-way flow mode, which has a serious impact on the distribution network. The impact on network loss is a very important content, and the power flow calculation is the main means of affecting quantitative analysis. Due to the mature operation technology of the AC power distribution system and the relatively perfect control and protection mechanism, the main power supply carrier of the current distribution network still adopts the AC power grid, which cannot be replaced in a short time [1-3]. AC/DC hybrid system as its excessive link will become an important research content in the future [4-5].

In [6], the Zbus Gaussian method is used to study and calculate the power flow of AC/DC hybrid network, which has good adaptability to the three-phase unbalanced distribution network. However,
when calculating the power flow of the algorithm, the balance node needs to be calculated separately. If the power fluctuation is large, the voltage fluctuation of the balance node is likely to be too large, and the power flow does not converge. The literature [7-8] is based on the traditional Newton-Raphson power flow method. The alternating iterative method is used to calculate the power flow of the AC-DC hybrid system. The calculation is accurate and effective, but the influence of the converter station loss on the power flow is not reasonably considered. In [9], considering the power characteristics and reactive power control characteristics of DC converter stations, an improved power flow calculation method for AC and DC power grids is proposed. Although this algorithm is applicable to power flow calculation of different reactive power control strategies, it does not consider converter station loss vs. influences. In [10], the augmented Cartesian coordinate model is used and the Newton method is used to solve the problem, which greatly improves the computational efficiency. In the proposed method, although the Jacobian matrix is sparse, the number of nonlinear equations is almost the traditional model. 2 times the complexity is added to a certain extent. In the alternating iterative power flow calculation method of AC/DC hybrid system proposed in [11], the AC side three-phase unbalance modeling is considered, which effectively reduces the influence of distributed power supply access on AC voltage distribution and three-phase unbalance. However, the literature converts the converter station into a generator node. The equivalent generator of each converter station needs to calculate the initial value for each iteration. The power flow calculation is greatly affected by the initial value. In [12-13], considering the VSC control method and loss model, based on the previous pushback method, the corresponding power flow calculation method is proposed, which can be applied to the power flow calculation problem in AC/DC distribution systems with different types of DG. In [14], the commutator AC bus current is used as the coordination variable. By improving the AC network and DC network iterative equations, a bidirectional iterative method is proposed, which reduces the shortcomings of the iterative method and the uniform iteration method is not easy to expand.

Based on the above literature, this paper proposes a general calculation method for sequential power flow algorithm for solving the AC-DC hybrid distribution network with VSC. The algorithm comprehensively considers the loss of the converter station and the capacity limitation of the converter station, and improves the convergence for the shortcomings of the AC/DC system when it is alternately iterative. It has the characteristics of simple programming and rapid convergence.

2. AC-DC hybrid network power flow model

![Figure 1. VSC-Station equivalent circuit model](image)

Figure 1 shows the equivalent circuit model of the converter station [15]. The VSC is regarded as a controllable voltage source. The voltage vector is $U_C \angle \delta_C$. Admittance is expressed as $Y_C = G_C + jB_C$. Filter susceptance is expressed as is expressed as $jB_{f}$, the transformer interface filter admittance is $Y_T = G_T + jB_T$, the AC side grid connection point and The DC side output voltages are respectively
$U_{AC} \angle \delta_{AC}$ and $U_{DC}$, and the filter node voltage and the transformer interface voltage are respectively $U_N \angle \delta_N$ and $U_T \angle \delta_T$.

2.1. AC system power flow calculation

The active power and reactive power of the injected AC system are calculated as shown in equations (1)-(2)

$$
P_{AC} = -U_{AC}^2 G_T + U_{AC} U_T [G_T \cos(\delta_{AC} - \delta_N) + B_N \sin(\delta_{AC} - \delta_N)]
$$

(1)

$$
Q_{AC} = U_{AC}^2 B_T + U_{AC} U_T [G_T \sin(\delta_{AC} - \delta_N) + B_N \cos(\delta_{AC} - \delta_N)]
$$

(2)

If the MTDC network has n converters connected, the active power injected into the AC network by the converter is expressed as

$$
P_{AC,n} = \sum_{j=1}^{n-1} P_{AC,j}
$$

(3)

The matrix is expressed as

$$
P_{AC} = [P_{AC1}, P_{AC2}, P_{AC3}, ..., P_{AC,n-1}, 0, ..., 0]^T
$$

(4)

Where: $P_{AC,n}$ represents the active power of the nth DC balanced node converter, except for $P_{AC,n}$, the remaining n-1 converter control modes are constant power control. The zero element is expressed as the line power that is not connected to the AC network.

The active power and reactive power from the VSC through C are expressed as follows

$$
P_{C} = U_C^2 G_C - U_{AC} U_C [G_C \cos(\delta_{AC} - \delta_C) - B_C \sin(\delta_{AC} - \delta_C)]
$$

(5)

$$
Q_{C} = -U_C^2 B_C + U_{AC} U_C [G_C \sin(\delta_{AC} - \delta_C) + B_C \cos(\delta_{AC} - \delta_C)]
$$

(6)

When calculating the AC network power flow separately, it is considered that the parameters of the DC system and the converter station are constant. At this time, the active and reactive power of the AC system is expressed as

$$
P_1(u, \delta) = U_i \sum_{j=1}^{m} U_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} (\delta_i - \delta_j)]
$$

(7)

$$
Q_1(u, \delta) = U_i \sum_{j=1}^{m} U_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)]
$$

(8)

Where: m represents the total number of nodes.

AC network active and reactive unbalance calculations are calculated as follows

$$
\Delta P_i = P_{AC,i}^G - P_{AC,i}^{load} - P_1(u, \delta) + P_{AC,i}
$$

(9)

$$
\Delta Q_i = Q_{AC,i}^G - Q_{AC,i}^{load} - Q_1(u, \delta) - Q_{AC,i}
$$

(10)
Where: \( P_{\text{AC},i}^G \) and \( Q_{\text{AC},i}^G \) respectively represent the active power and reactive power of the generator; \( P_{\text{AC},i}^{\text{load}} \) and \( Q_{\text{AC},i}^{\text{load}} \) respectively represent the active and reactive loads of the AC system; \( P_{\text{AC},j} \) and \( Q_{\text{AC},j} \) respectively represent the active and reactive power injected into the VSC.

Using the cattle pull method to solve the nonlinear equations to solve the AC system node voltage and phase angle, the calculation is as follows

\[
\begin{bmatrix}
\Delta \delta \\
\Delta U \\
\hline
U
\end{bmatrix} = -[J]^{-1} \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]  

(11)

2.2. DC system power flow calculation

DC network power is calculated as follows

\[
P_{\text{DC},i} = -(P_{\text{ci}} - P_{\text{loss}}) = \Gamma U_{\text{DC},i} \sum_{j=1, i\neq j}^{q} G_{ij} (U_{\text{DC},i} - U_{\text{DC},j}), \forall i \leq n
\]

(12)

Where: \( \Gamma \) indicates the DC network polarity configuration, \( \Gamma=1 \) indicates a single point configuration, and \( \Gamma=2 \) indicates a two-point configuration.

The DC network conductance matrix is calculated as follows

\[
G_{\text{DC}} = \begin{bmatrix}
G_{11} & G_{12} & \cdots & G_{1q} \\
G_{21} & G_{22} & \cdots & G_{2q} \\
\cdots & \cdots & \cdots & \cdots \\
G_{q1} & G_{q2} & \cdots & G_{qq}
\end{bmatrix}
\]

(13)

\[
G_{ij} = \sum_{j=1, i\neq j}^{q} g_{ij}, G_{i} = -g_{ij}, i \neq j
\]

(14)

Where: \( q \) represents the total number of DC nodes.

DC network current

\[
I_{\text{DC}} = G_{\text{DC}} U_{\text{DC}}
\]

(15)

\[
I_{\text{DC},j} = \sum_{j=1, i\neq j}^{P} G_{\text{DC},ij} (U_{\text{DC},i} - U_{\text{DC},j})
\]

(16)

The DC network power imbalance is calculated as follows

\[
\Delta P_{\text{DC}} = \left( U_{\text{DC}} \frac{\partial P_{\text{DC}}}{\partial U_{\text{DC}}} \right) \frac{\Delta U_{\text{DC}}}{U_{\text{DC}}}
\]

(17)
2.3. Converter station control mode
The VSC converter station with turn-off device IGBT and current vector control enables flexible control of active and reactive variables. There are usually seven control modes [16], as shown in Table 1.

| mode | Active control | Reactive power type control | AC busbar side equivalent | DC busbar side is equivalent |
|------|----------------|-----------------------------|---------------------------|-----------------------------|
| 1    | set $\delta$   | $U_{AC}$                     | $PQ$                      | $P$                         |
| 2    | set $P_{AC}$   | $Q_{AC}$                     | $PQ$                      | $P$                         |
| 3    | set $P_{AC}$   | $Q_{AC}$                     | $PV$                      | $U$                         |
| 4    | set $U_{DC}$   | $Q_{AC}$                     | $PQ$                      | $U$                         |
| 5    | set $U_{DC}$   | $U_{AC}$                     | $PV$                      | $U$                         |

2.4. Converter station loss model

AC filter side node voltage

$$U_N = I_{AC}X_L + U_{AC}$$

(18)

The converter station loss actually contains three parts, namely the converter transformer iron loss, converter reactor loss and converter loss, the first two parts of the loss is small, calculated as follows

$$P_{loss,Ti} = r_{Ti} \left| I_{AC,i} \right|^2$$

(19)

$$P_{loss,Ci} = r_{Ci} \left| I_{Ci} \right|^2$$

(20)

Where: $r_{Ti}$ represents the converter transformer resistance; $r_{Ci}$ converter reactance resistance.

The total loss is obtained by quadratic curve fitting method [17], and the calculation formula is as follows (23)

$$P_{loss} = a + bI_C + cI_C^2$$

(21)

Where: a, b, c are the fitting coefficients.

The total loss of the converter station is

$$P_{loss,n} = P_{loss,Ti} + P_{loss,Ci} + P_{loss}$$

(22)

2.5. Converter station capacity limit

The VSC capacity will be affected by the DC access point output voltage, and the converter capacity needs to meet the following conditions:

$$P_C^2 + \left( Q_C - \frac{U_C^2}{X_L} \right) \leq 3U_C^2I_C^2$$

(23)

Where: $I_C$ is the DC access point current and $X_L$ is the reactance of the AC filter.

The upper limit of the article is set to 1.05 (standard value), and the upper and lower voltage limits are set to 0.85 (standard value) and 1.20 (standard value), respectively.
3. Sequential AC-DC hybrid network power flow calculation method

3.1. Improvement of convergence performance

There are many ways to improve the convergence performance, such as the sensitivity matrix, the bidirectional power flow iteration method adopted in [14].

In the iterative process using the alternating iterative method, the following premise is made: the AC power flow calculation result is used as the voltage value of the AC bus of the converter station in the DC power flow calculation, and the DC power flow calculation result provides the converter station for the AC power flow calculation in the next iteration. The value of active power and reactive power, according to this law cycle until convergence. However, the DC power in the AC power flow calculation is a known constant. The AC voltage in the DC power flow calculation is a known constant. Although the AC/DC system is decoupled, the iterative calculation will cause the convergence speed to slow down or not converge. Improved by $\frac{\partial P_{AC}}{\partial U_{AC}}$ and $\frac{\partial Q_{AC}}{\partial U_{AC}}$ in the Jacobian matrix in the AC part of the current. Derived from equations (19)-(24)

$$\frac{\partial P_{AC}}{\partial U_{AC}} = \frac{I_{AC}}{U_{AC}} [b + 2(r_c + c)I_c + 2r_I I_{AC}]$$

$$\frac{\partial Q_{AC}}{\partial U_{AC}} = \frac{2I_{AC}}{U_{AC}} [X_T I_{AC} + B_N X_T (U_N - I_c X_c)] - 2X_L B_N I_c$$

Where: $X_T$ is the reactance of the converter transformer; $X_c$ is the reactance of the smoothing reactor.

3.2. Steps for the calculation of the power flow of the sequential AC-DC hybrid network

The specific calculation steps of the sequential AC-DC hybrid system power flow algorithm mentioned in the paper are as follows:

1. Step 1: Convert all named value data to standard value data.

2. Step 2: Assume that there is no power loss in the DC network and the converter station, and calculate the active power estimation value of the injected AC network by Equation (3).

3. Step 3: Select the network type. If it is an AC network, go to step 4. If the DC network goes to step 6.

4. Step 4: Exchange network power flow calculation. The active and reactive power calculations are as shown in equations (7) and (8), and the active and reactive power imbalances are calculated as equations (9) and (10). The node voltage and phase angle are calculated using equation (11).

5. Step 5: Calculate the power of the converter station and its loss. Power calculation (1), (2), the loss is calculated as equations (19)-(22).

6. Step 6: DC network power flow calculation. The power calculation is as shown in equation (12), the DC line admittance matrix is as shown in equations (13) and (14), and the current calculation is as shown in equations (15) and (16). The calculation formula of the DC network power imbalance is Equation (17).

7. Step 7: Determine the network characteristics. If the head end is an AC power grid, go to Step 8. If it is a branch AC power grid, go to Step 4. If it is a DC network, go to Step 5.

8. Step 8: Calculate the active power $P_{AC}$ injected into the AC network from the VSC side C. After all the unknowns in the DC and AC networks have been calculated, a separate calculation is required, which depends on the DC balance node power $P_{DC, n}$ and its converter loss $P_{loss, n}$. When performing iterative calculations, it is considered that the AC network voltage and reactive power injection are constant.
$$P_{c,n} = -\left(P_{DC,n} + P_{loss,n}\right), \forall i \leq n$$  (26)

Step 9: Inverter capacity verification. Detect whether the inverter has a reactive power limit. If a limit occurs, correct the node type that has exceeded the limit to the PQ node type, and go to step 8 to re-iterate the calculation. If no limit occurs, go to the next step.

Step 10: Convergence criterion. The difference in active power injected into the AC network at the converter side C is used as a convergence criterion.

$$\max \left| P_{c,n}^k - P_{c,n}^{k-1} \right| < \varepsilon$$  (27)

Where: $k$ is the number of iterations; $\varepsilon$ is the convergence precision.

If the calculation does not converge, return to step 2 to update the AC and DC network values for the current iteration.

4. Examples and Analysis

In order to verify the correctness and versatility of the VSC AC-DC hybrid network sequential power flow algorithm, the modified IEEE33 node system is simulated, as shown in Figure 2.

The modified topology can access different types of DGs. The power reference value, the AC voltage reference value, and the DC voltage reference value are 100 MVA, 12.66 kV, and 1.5 kV, respectively. The resistance and leakage reactance of all converter transformers are taken as 0.0015 + j0.1121 p.u. The filter susceptance is j0.045 p.u, and the reactor impedance is 0.0001 + j0.1643 p.u. In this topology, node 6 in the AC network is a balanced node with a voltage of 1.05 p.u, and node 1 of the DC network is a balanced node with a voltage of 1.05 p.u. The model adopts a flat start, the voltage and phase angle of the remaining AC busbars are 1.0 p.u and 0, respectively, and the DC bus voltage is 1.0 p.u. The DG of the access system includes solar power generation (PV), wind power generation (WF), fuel cell (FC), and gas turbine (GT), and the access capacities are 0.5 MW, 0.5 MW, 0.3 MW, and 0.3 MW, respectively.

The following two types of DG access schemes are set to simulate and simulate the network power flow and its loss.

1: All DGs are connected on the AC network side, and the PV, WF, FC, and GT access locations are nodes 26, 7, 22, and 17, respectively.

2: By DG output type, the DG is in the AC and DC networks. The PV, WF, FC, and GT access locations are nodes 20, 7, 2, and 17, respectively.

In order to verify the correctness of the article method, the paper uses the traditional Newton-Raphson method to calculate, and uses the article algorithm to calculate the two schemes separately.

![Figure 2. Improved 33-node AC-DC hybrid system diagram](image-url)
Table 2. The power of key nodes.

| Node Power                                | Algorithm          | Plan 1                  | Plan 2                  |
|-------------------------------------------|--------------------|-------------------------|-------------------------|
| DC balanced node power/pu                 | The article algorithm | -0.4184                | -0.3700                |
|                                          | Traditional algorithm | -0.4186               | -0.3704               |
| Total VSC node power/pu                   | The article algorithm | -0.4172-j0.0452        | -0.3816-j0.0612        |
|                                          | Traditional algorithm | -0.4166-j0.0449        | 0.3807-j0.0614         |
| AC system injection power/pu              | The article algorithm | -0.4440+j0.0053        | -0.3918+j0.0050        |
|                                          | Traditional algorithm | -0.4443+j0.0049        | 0.3921+j0.0049         |

Table 2 shows the DC balance node power, VSC node power, and injected AC system injection power values. Since the traditional algorithm does not reasonably take into account the loss of the converter station and does not consider the power capacity limitation of the converter station, there is a certain difference in the power calculation result, and the maximum error value of the VSC node power reaches 0.0009 pu.

It can be seen from Table 3 that compared with the scheme 1, the total network loss of the scheme 2 is reduced by 0.0206 pu compared with the scheme 1. The main reason is the reduction of distributed power converters, although the converter station losses have increased but the overall reduction. The converter station loss accounts for 24.3% of the total loss of the AC-DC hybrid network and cannot be ignored.

Table 4 shows the performance comparison between the traditional algorithm and the article algorithm before and after the improvement. The algorithm of the article has reduced the number of iterations and the calculation time compared with the traditional algorithm. Considering the loss and capacity constraints of the converter station, and improving the convergence performance of the Jacobian matrix, the iteration time and the number of times without considering the above factors are reduced to some extent. The number of iterations of the AC network is reduced in the two different schemes. The iteration time is significantly reduced before the improvement.

Table 3. The Loss.

| Wastage                        | Plan 1        | Plan 2        |
|--------------------------------|---------------|---------------|
| AC line/pu                     | 0.0019        | 0.0029        |
| The DC line/pu                 | 0.0188        | 0.0208        |
| Converter station loss/pu      | 0.0140        | 0.0135        |
| DG converter loss/pu           | 0.0231        | 0.0000        |

Table 4. Comparison of algorithm performance.

| Plan   | Algorithm        | The number of iterations | Take/ms |
|--------|------------------|--------------------------|---------|
|        |                  | AC network | DC network |         |
| Plan 1 | The article algorithm | 6          | 3          | 30      |
|        | Traditional algorithm | 7          | 3          | 33      |
| Plan 2 | The article algorithm | 5          | 3          | 26      |
|        | Traditional algorithm | 8          | 4          | 35      |

5. Conclusion
Power flow calculation is an important basic algorithm for realizing AC/DC hybrid distribution network simulation, analysis and calculation, operation planning and optimization. The example analysis shows that:

1) The converter station loss accounts for a considerable proportion of the overall system loss, which has an important impact on the power flow calculation and must be fully considered.
2) By summarizing and analyzing the separation of the AC network and the DC network and the poor convergence performance, the Jacques matrix elements are improved to improve the convergence performance and computational efficiency.

3) The algorithm can be applied to AC and DC hybrid network power flow calculations coexisting with multiple DGs.

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