Power flow calculation of AC / DC hybrid distribution network considering energy router

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Abstract. Energy router (ER) is the key equipment in the construction of AC / DC hybrid distribution network in the future. Based on the characteristics of AC and DC ports and topological structure of ER, a steady-state model of ER with multi ports access was established, and a power flow model of AC / DC hybrid distribution network considering ER was constructed. Newton Raphson method combined with alternating iteration method was used to solve the problem. IEEE-33 was selected to calculate and compare the circular distribution network considering ER and the traditional AC distribution network. The results show that ER can improve the voltage level of nodes and reduce network loss in hybrid distribution network.

1. Introduction
In order to meet the development of Energy Internet and realize the effective mixing of AC and DC distribution network, energy router (ER) came into being [1-2]. In the future AC / DC hybrid distribution network, the ER can realize the functions of flexible bidirectional control and adjustment of feeder power flow, independent control of bus voltage, plug and use of new energy and energy storage, dynamic monitoring and adjustment of power grid [3]. Therefore, it is of great significance and engineering value to study the mathematical model and control strategy of AC / DC hybrid distribution network with ER for improving the safety and economy of distribution network. In reference [2], with considering energy storage and distributed energy, the applicability of circular topology and hand-in-hand topology was analyzed and compared. Reference [3] proposed the analytical model of ER in AC network, but did not consider the DC port. In reference [4], the access point and capacity selection of ER are studied. As for power flow calculation of AC / DC network, converter is generally used to transfer power flow parameters, and Newton-Raphson method can be used to solve the problem after considering various constraints [5-7]. Reference [8] studied the DC network and proposes a suitable hybrid distribution network power flow calculation method.

According to the application scenarios, main functions, network topology characteristics, operation level, access and control mode of ER in future AC / DC hybrid distribution network, this paper established the equivalent steady-state power flow calculation model of AC / DC hybrid power grid with ER, gave the power flow calculation method, and calculated and analyzed the performance index of AC / DC hybrid network in each scenario. The results show that the ER can well improve the operating voltage level and reduce the network loss.
2. Power flow model and solution of AC / DC hybrid distribution network

2.1. Voltage Source Converters (VSC)

2.1.1. Model of Voltage Source Converter. Based on the structure of AC distribution network [9], VSC is added in the middle link to transform AC distribution network into AC / DC hybrid distribution network and its model is shown in Figure 1.

![Figure 1. Model of Voltage Source Converter.](image)

The active and reactive power injected into AC node i are $P_{AC,i}$ and $Q_{AC,i}$ respectively. $Y_p$ is converter transformer, $Y_{pf} = G_f + jB_f$. $Y_c$ is converter reactor, whose interface voltage is $U_{f,i}$ and phase angle is $\delta_{f,i}$. $B_f$ is AC filter, which consumes reactive power $Q_f$. $V_c$ is the converter of AC side, equivalent to voltage source of $P_C$ with phase angle of $\delta_C$, and its active and reactive power injected into AC side is $P_c$ and $Q_c$. $I_{DC,i}$ is the converter of DC side, equivalent to the current source of $I_{DC,i}$, connected to the DC network, the bus voltage is $U_{DC,i}$, and the power injected into the network is $P_{DC,i}$. The mathematical model of converter station is as follows:

\[
\begin{align*}
P_{ac,i} &= -U_{ac,i}^2 G_g + U_{ac,i} U_f \left( G_g \cos(\delta_{ac,i} - \delta_f) + B_f \sin(\delta_{ac,i} - \delta_f) \right) \\
Q_{ac,i} &= -U_{ac,i}^2 B_g + U_{ac,i} U_f \left( G_g \sin(\delta_{ac,i} - \delta_f) - B_f \cos(\delta_{ac,i} - \delta_f) \right) \\
P_{ac,i} &= U_{ac,i} G_g + U_{ac,i} U_f \left( G_g \cos(\delta_{ac,i} - \delta_f) + B_f \sin(\delta_{ac,i} - \delta_f) \right) \\
Q_{ac,i} &= U_{ac,i} B_g + U_{ac,i} U_f \left( G_g \sin(\delta_{ac,i} - \delta_f) - B_f \cos(\delta_{ac,i} - \delta_f) \right)
\end{align*}
\]

2.1.2. Loss of VSC. The converter loss $P_{loss}$ consists of fixed loss, linear loss and non-linear loss. The coefficient of the three part loss is obtained from reference [10]. Combined with the AC / DC power exchange equation of the converter, there is (3).

2.1.3. Control mode of VSC. That means master-slave control and droop control [11]. In the master-slave control mode, the network consists of a master converter station with large capacity and a slave converter station. The DC side of the main converter station is used as the slack node, and the power flow calculation is regarded as the balance node. The AC side of converter station has constant reactive power control and constant voltage control mode, which is regarded as PQ or PV node. In droop control mode, the DC side voltage and power of each converter station meet the equation (4), and the final operation state is determined by the initial value $P_C$, $U_{c0}$, control coefficient $k_i$, and network structure.
2.2. AC network

According to the balance equation of power flow of AC side and the different types of nodes [12], for the AC network with n nodes, it is assumed that there are m PQ nodes, n-m-1 PV nodes and one balance node. Then the modified equation of the AC network is as follows:

\[
\begin{bmatrix}
    \Delta P \\
    \Delta Q
\end{bmatrix} = -J \begin{bmatrix}
    \Delta \theta \\
    \Delta U
\end{bmatrix}, \Delta P = \begin{bmatrix} \Delta P_1, \ldots, \Delta P_n \end{bmatrix}^T, \Delta Q = \begin{bmatrix} \Delta Q_1, \ldots, \Delta Q_n \end{bmatrix}^T, \Delta \theta = \begin{bmatrix} \Delta \theta_1, \ldots, \Delta \theta_n \end{bmatrix}^T, \begin{bmatrix}
    \frac{\Delta U}{U_1} \\
    \vdots \\
    \frac{\Delta U}{U_n}
\end{bmatrix} = \begin{bmatrix}
    \frac{\Delta U_1}{U_1} \\
    \vdots \\
    \frac{\Delta U_n}{U_n}
\end{bmatrix}^T
\]

(5)

The Jacobi matrix is divided into four parts. The non-diagonal element and diagonal element is obtained by calculating its partial derivative:

\[
\begin{align*}
H_i &= \frac{\partial \Delta P}{\partial \theta_i} = -U_i \sum \left( G_{ij} \sin \theta_j - B_{ij} \cos \theta_j \right) \\
N_i &= \frac{\partial \Delta Q}{\partial \theta_i} = -2U_i^2 \sum \left( G_{ij} \cos \theta_j + B_{ij} \sin \theta_j \right) \\
K_i &= \frac{\partial \Delta P}{\partial U_i} = -U_i \sum \left( G_{ij} \cos \theta_j + B_{ij} \sin \theta_j \right) \\
L_i &= \frac{\partial \Delta Q}{\partial U_i} = 2U_i^2 \sum \left( G_{ij} \sin \theta_j - B_{ij} \cos \theta_j \right)
\end{align*}
\]

(6)

In the formula, \( \Delta P_i \) and \( \Delta Q_i \) are the power deviation. \( P_{gi} \) and \( Q_{gi} \) are the power generated by the generator. \( P_{di} \) and \( Q_{di} \) are the power consumed by the load. \( P_{ci} \) and \( Q_{ci} \) are the injection power of the converter station. \( G_{ij} \) and \( B_{ij} \) are mutual conductance and mutual admittance. \( \theta_j \) is the phase angle.

2.3. DC network

Each node of DC network contains voltage amplitude \( U_{ci} \) and active power \( P_{ci} \) [13]. The power flow balance equation is as (7).

\[
\Delta P_{ci} = U_{ci} \sum_{j=1}^{n_i} \left( G_{ij} (U_j - U_i) \right) - (P_{sci} + P_{di} - P_{ci})
\]

(7)

\[
\begin{align*}
U_{ci} \frac{\partial \Delta P}{\partial U_{ci}} &= U_{ci} G_{ci} U_{ci} \\
U_{ci} \frac{\partial \Delta P}{\partial U_{ci}} &= P_{ci} - U_{ci}^2 \sum_{j=1}^{n_i} G_{ij} \\
U_{ci} \frac{\partial \Delta Q}{\partial U_{ci}} &= Q_{ci} - U_{ci} \sum_{j=1}^{n_i} U_j \frac{U_c}{K_c}
\end{align*}
\]

(8)

\[
\Delta P_{ci} \text{ is the active power deviation of the node, which is expected to be } 0. P_{sci} \text{ is the active power generated by the generator. } P_{sci} \text{ is the injected power of the converter station. } P_{di} \text{ is the active power consumed by the load of node i. } G_{ij} \text{ is the mutual conduction and } n_i \text{ is the number of nodes.}
\]

After partial derivation of the equilibrium equation, the Jacobi matrix elements are obtained as (8).

When droop control is adopted in converter station, DC side power \( P_c \) and voltage \( U_c \) meet (4), and (8) should be modified to (9).

2.4. Energy router

2.4.1. Topology and model of ER. Based on the power electronic architecture, the AC port of the ER can be equivalent as shown in Figure 2. Suppose that the AC network node i is connected with the AC port of ER, and the voltage of AC node i is \( U_i \), which corresponds to the new AC node h of ER,
and its voltage is $U_i \angle \theta_i$. The AC port series reactance and converter loss is $Y_{ac} = G_{ac} + jB_{ac}$, and the port parallel capacitance is $B_{ac}$, the power injected into AC port $i$ is as (10). The active power of injection node $h$ is as (11).

$$
\begin{align*}
\text{active power} &= (G_{ac} \cos \delta_i + jB_{ac} \sin \delta_i)U_i U_h \sin \delta_i (10) \\
\text{active power} &= (G_{ac} \cos \delta_i - jB_{ac} \sin \delta_i)U_i U_h - (B_{ac} + B_{ac})U_i^2 (11)
\end{align*}
$$

The internal loss is equivalent to the equivalent impedance of the port, $P_{he,ac}^{\text{loss}}$ and $P_{he,dc}^{\text{loss}}$ are the same. $k_h$ is the voltage ratio of ER’s AC port. The voltage of new AC node $h$ and DC bus voltage in ER meets the requirement:

$$
U_h = k_h E_{ac} (12)
$$

**Figure 2.** Equivalent model of AC port of ER. **Figure 3.** Equivalent model of DC port of ER.

As for the DC port in ER, the port model is shown in Figure 3. Suppose that the primary side is connected to the DC bus of ER, the voltage is $E_l$, the secondary side is connected to the DC network, the voltage is $E_{l'}$. $P_{kl,ac}$ and $P_{kl,dc}$ are the active power on both sides of the port. $R_{kl}$ is the internal loss, and $n$ is the equivalent transformation ratio. It meets (13).

$$
\begin{align*}
\text{active power} &= \frac{E_i E_j}{R_{kl}} (nE_{l'}^2 - \frac{nE_{l'} E_i}{R_{kl}}) \quad (13) \\
\Delta P_{ac,loss} &= \sum_{k=1}^{x} P_{he,ac}^{\text{loss}} + \sum_{l=1}^{y} P_{he,dc}^{\text{loss}} (14)
\end{align*}
$$

If the number of AC ports and DC converter type ports in the ER are $x$ and $y$ respectively, and the static loss of the converter is ignored, the running loss is as follows:

2.4.2. Control mode of ER. PV nodes are usually absent in distribution network, so the control strategy of ER focuses on adjusting control coefficient and compensating reactive power to maintain active power injection and voltage stability. When the control strategy is adopted, the corresponding node can be regarded as PV node. The equation of control of AC port of ER is:

$$
\begin{align*}
\omega_{Pi}^{ac}(P_{Pi}^{ac} - P_{IN}^{ac}) + \omega_{EI}^{ac}(E_{de,ac} - E_{de,ac,b}) &= 0 \\
\omega_{Pi}^{ac}(Q_{Pi}^{ac} - Q_{IN}^{ac}) + \omega_{EI}^{ac}(U_{l'} - U_{l'}) &= 0
\end{align*}
$$

In the AC port, $P_{IN}^{ac}$ and $Q_{IN}^{ac}$ are the preset values of active and reactive power of node $i$. $E_{de,ac}$ and $E_{de,ac,b}$ are the DC bus voltage and preset value of ER corresponding to the port. $\omega_{Pi}^{ac}$ and $\omega_{PI}^{ac}$ are the coefficients of AC active and reactive power control. $\omega_{EI}^{ac}$ and $\omega_{EI}^{ac}$ are the control coefficients of the DC and AC voltage respectively, taking 0 or 1.

When ER is constant active power control mode, the corresponding node is equivalent to voltage point for DC part in ER. When the DC port is connected to the network node $l$, the governing equation of port $l$ can be obtained as (16). $P_{IN}^{de}$ and $E_{IN}$ are the rated values of active power and port DC voltage respectively. $\omega_{PI}^{de}$ and $\omega_{PI}^{de}$ are the corresponding control coefficient. At this time, the active power of ER’s DC side is as (17).

$$
\begin{align*}
\omega_{Pi}^{de}(P_{Pi}^{de} - P_{IN}^{de}) + \omega_{EI}^{de}(E_{l'} - E_{IN}) &= 0 \\
P_{k,de}^{ac} &= P_{k,de} - \left(\frac{P_{k,de}^2}{E_{l'}}\right) R_{kl}
\end{align*}
$$
3. Power flow calculation of AC / DC hybrid distribution network considering energy router

3.1. Evaluation index of AC / DC network operation

1) Average deviation degree of voltage in hybrid network

It is defined as the average value of node voltage deviation during stable operation, which is expressed as:

\[ d = \frac{\sum_{i=1}^{n_{ac}} d_{ac,i} + \sum_{i=1}^{n_{dc}} d_{dc,i}}{n_{ac} + n_{dc}} \]

\[ d_{ac,i} = \frac{U_{ac,i} - U_{ac,n} \times 100\%}{U_{ac,i}} \]

\[ d_{dc,i} = \frac{U_{dc,i} - U_{dc,n} \times 100\%}{U_{dc,i}} \]

(18)

In the formula, the AC part includes: total number of AC nodes \( n_{ac} \), voltage deviation degree \( d_{ac,i} \) at AC node \( i \), rated voltage \( U_{ACN,i} \) and actual voltage \( U_{ACR,i} \). DC part includes: total number of DC nodes \( n_{dc} \), voltage deviation degree \( d_{dc,i} \) at DC node \( i \), rated voltage \( U_{DCN,i} \) and actual voltage \( U_{DCR,i} \).

2) Mixed network loss

It is defined as the sum of losses of AC and DC networks.

\[ \Delta P = \Delta P_{ac} + \Delta P_{dc}, \Delta P_{ac} = \sum_{i=1}^{n_{ac}} \sum_{j=1}^{n_{ac}} \Delta P_{ac,i,j}, \Delta P_{dc} = \sum_{i=1}^{n_{dc}} \sum_{j=1}^{n_{dc}} \Delta P_{dc,i,j} \]

\[ \Delta P_{ac,i,j} = \frac{(U_{ac,i} - U_{ac,j})^2}{R_{ac,i,j}} \]

\[ \Delta P_{dc,i,j} = \frac{(U_{dc,i} - U_{dc,j})^2}{R_{dc,i,j}} \]

(19)

In the formula, \( \Delta P_{ac} \) and \( \Delta P_{dc} \) are AC and DC network losses respectively, \( \Delta P_{ac,i,j} \) is AC line loss, \( P_{AC,i,j}, Q_{AC,i,j}, U_{AC,i,j} \) are active and reactive power and voltage amplitude at AC node \( i \). \( R_{ac,i,j} \) is branch resistance between AC nodes. \( \Delta P_{dc,i,j} \) is DC line loss, \( U_{DC,i,j} \) and \( U_{DC,i,j} \) are voltage values of DC nodes \( i \) and \( j \). \( R_{dc,i,j} \) is branch resistance between DC nodes.

3.2. Constraints of power flow calculation

3.2.1. AC system and DC system

AC system needs to consider node voltage constraint, generator power constraint and power constraint between nodes. The constraints of node voltage and line current should be considered in DC system

\[ \begin{align*}
    U_{el,\min} < U_{ei} < U_{el,\max} \\
    -I_{el,\max} < I_{ei} < I_{el,\min}
\end{align*} \]

(20)

In the formula, \( U_{el,\max} \) and \( U_{el,\min} \) are the upper and lower limits of the AC side port voltage of the converter. \( I_{el,\max} \) is the upper limit of the converter current.

3.2.2. VSC

3.2.3. Constraints of energy router

For the energy exchange bus of ER, the upper and lower limits of total switching power should be satisfied.

\[ \begin{align*}
    \sum_{j=1}^{N} P_{j} \leq P_{E,\max} \\
    \sum_{j=1}^{N} P_{j} \leq P_{E,\min}
\end{align*} \]

(21)

In the formula, \( P_{E,\max} \) and \( P_{E,\min} \) are the upper and lower limits of exchange power of the primary side, and \( P_{E,\max} \) and \( P_{E,\min} \) are the upper and lower limits of exchange power of the secondary side.
3.3. Calculation process
Calculation process of the hybrid system is shown in Figure 4.

4. Example analysis

4.1. Power flow calculation of AC / DC distribution network

4.1.1. Circular AC / DC distribution network. On the basis of IEEE-33 AC distribution network, the converter station is added between node 4 and node 5, node 22 and node 23 respectively, and electrical connection is made to establish the electrical connection between node 24 and node 32, and node 17 and 32, so as to obtain circular AC / DC distribution network, as shown in Figure 5. Among them, the branch resistance from converter station I to node 5 is the same as the original node 4-5, the branch resistance between node 5-17 and node 25-32 is the same as the AC line resistance, and the node active power remains unchanged. As for the converter station, R_TF = 0.0015, x_TF = 0.1121, R_C = 0.0001, X_C = 0.1643 (all standard values).

Converter station I is the main converter station. It uses DC side constant voltage control method, AC side reactive power injection is 80 kVar, Converter station II is from the converter station, AC side active power injection is -300 kW, and reactive power injection is 60 kVar. The calculation results of current flow are shown in Figure 6 and Table 1.

It can be seen that the average deviation of voltage and loss can be effectively reduced by using circular AC / DC network. The average deviation of voltage is reduced by 1.31%. The network loss is 17.79% lower than the traditional network. The circular AC / DC network not only meets the power demand of DC load, but also improves the stability of system operation and optimizes the economy of system operation.

Table 1. Comparison of different networks.

| Result of power flow calculation | Traditional AC network | Circle Topology |
|---------------------------------|------------------------|----------------|
| Average deviation degree of voltage amplitude(%) | AC part: 3.72 | 1.38 |
| DC part | / | 1.03 |
| Line loss(MVA) | AC part: 0.018117 | 0.008612 |
| DC part | / | 0.003649 |
| VSC | / | 0.002625 |
4.2. Considering the energy router

4.2.1. ER in the terminal part
As is shown in Figure 7. The ER has two ports connected to the annular AC/DC hybrid distribution network, including two AC ports and one DC port, corresponding to AC node 21 and DC node 13 respectively. The fixed loss of active power of the energy exchange bus of the ER is 80 kW, and the maximum of reactive power compensation that the port can provide is 20 kVar.

At this time, the 21 nodes corresponding to Figure 7 can be equivalent to the PV node. The results of the tidal current calculation are compared with the original circular topology as shown in Figure 8.

![Figure 7. Terminal part considering ER.](image)

![Figure 8. Comparison of Terminal part.](image)

The results show that the participation of ER can effectively raise the overall voltage level of the system. In the original annular AC/DC hybrid distribution network topology, the lowest voltage of DC network node is node 13. After the participation of ER at the end of the original network, since node 13 and node 21 achieve electrical connection with adjacent nodes through ER. The minimum voltage node of the DC network node is transferred to node 15, which is 2.21% higher than that of the original circular network node 17.

4.2.2. ER in the middle part
As is shown in Figure 9. Under rated load operation, the voltage amplitude of the network after the original network and the ER participate in the network optimization control is shown in Figure 10. It can be found that the application of ER in the middle of distribution network can also increase the voltage of nodes.

Comparing these three scenarios with a circular network yields in Table 2. It can be seen that the application of ER in the middle link of annular AC/DC hybrid distribution network can also raise the voltage at the end of the branch. After the ER participates in network optimization, the average deviation of network voltage and network loss are reduced, and the operation status of the whole AC/DC hybrid distribution network is improved.

![Figure 9. Middle part considering ER.](image)

![Figure 10. Comparison of middle part.](image)

| Table 2. Comparison of different networks. |
|------------------------------------------|
| Result of power flow calculation          | Circular | ER in terminal part | ER in middle part |
|------------------------------------------|----------|---------------------|-------------------|
| Average deviation degree of voltage      |          |                     |                   |
| amplitude(%)                             | AC part  | 1.387               | 1.288             | 1.314             |
|                                          | DC part  | 1.033               | 1.024             | 1.025             |
|                                          | AC part  | 0.0008612           | 0.008051          | 0.007875          |
|                                          | DC part  | 0.003649            | 0.003138          | 0.003438          |
|                                          | VSC      | 0.002625            | 0.002547          | 0.003138          |
|                                          | Total loss| 0.014886            | 0.013736          | 0.014451          |
| Line loss(MVA)                           |          |                     |                   |
|                                          | AC part  |                     |                   |
|                                          | DC part  |                     |                   |
|                                          | VSC      |                     |                   |
|                                          | Total loss|                   |                   |
5. Conclusions
a. Compared with the AC distribution network, the operation level of the circular AC / DC hybrid distribution network has significantly improved, and the loss has been lower.
b. ER can improve the problems of low terminal node voltage and high line voltage drop of radial line by establishing circular network composed of node electrical connection.
c. After the intermediate link of AC / DC hybrid network is connected with ER, the network operation status is better and the loss is lower. ER has great development potential and in the follow-up work, the optimization effect of ER after energy storage and electric vehicle access will be further studied.

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