Research on probabilistic optimal power flow of distribution system with multilayer structure based on energy router

Dong Weijie¹, Hu Lijuan¹, Sheng Wanxing¹, Liu Keyan¹, Meng Xiaoli¹, Deng Pan¹

¹Power Distribution Department, China Electric Power Research Institute, Beijing 100192, People’s Republic of China
E-mail: hulijuan@epri.sgcc.com.cn

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Abstract: The core connotation of global energy interconnection is to realise the large-scale utilisation and sharing of renewable energy, especially distributed renewable energy. In order to realise energy sharing over a wide area and stabilise the impact of intermittent and random output distributed renewable energy on distribution network (DN) under global energy interconnection, a multilayer structure based on energy router for DN is proposed first. Then a multi-objective optimal power flow (OPF) model for the multilayer structure DN is established, which is aimed at the lowest cost of power generation, the minimum pollutant treatment cost and the minimum active power loss. This paper proposes the steady-state power flow model of the energy router embedded DN and formulates the model of OPF problem. Case studies are carried out on a modified IEEE 33-bus distribution system. The role of the energy router on improving the system voltage level is discussed. The results show that the energy router is able to regulate bus voltages of the system, and system operation status is greatly improved.

1 Introduction

With the continuous construction of energy Internet construction, intelligent, economical and safe way to achieve the distribution network (DN) will be of more and more attention [1, 2]. For the traditional DN, due to open-loop operating conditions, the system voltage level deviation from the network operation and management become increasingly prominent problem [3]. At the same time, large-scale distributed renewable power and electric vehicles and other DN unit scale development, further exacerbated the DN voltage limit, two-way trend and other issues [4]. Increased demand for diversification also provides more intelligent requirements for system protection and control [5]. Therefore, the efficient fast voltage control method of DN has received more and more attention [6, 7].

At this stage, the overall optimisation of the DN voltage level can be achieved through a variety of means:

(i) The voltage amplitude of the specified node is boosted by introducing the reactive power compensation device;
(ii) Adjust the voltage conversion ratio by adjusting the transformer tap.

This paper focuses on the specific application of the energy router in the voltage and power control of the distribution system.

At present, the scientific research institutions for the energy router research focused on the realisation of power electronic architecture and transient simulation and so on. The research on the establishment of the steady state model of the energy routers and the role of the energy routers in the network operation are still rare.

2 Mathematical model and control strategy of energy router

2.1 Topology of the energy router and the equivalent model

Fig. 1 shows the topology of the energy router based on the power electronics architecture. The interface between the energy router and the AC network is divided into a primary port and a secondary port. Each port can be regarded as an AC–DC rectifier. The DC outlet terminals of all ports on each side are connected to a unified energy exchange bus. The primary and secondary sides are switched by DC–DC energy conversion devices.

The power of each of the AC–DC ports corresponds to the power electronics structure shown in Fig. 2. For each port of the energy router, the power loss of the port can be equivalent by the admittance $g_l^H + jb_l^H$, the parallel reactive power loss is equivalent by the charge $b_l^H$. When the active and reactive power of port is injected through the relevant conductance and electricity, the reactive power is absorbed by the rectifier device, and the active power is transmitted to the DC bus of the energy router, which is involved in the energy balance of the bus.

In the above analysis, the energy injection $P_l^H$ and reactive power $Q_l^H$ injected into the port of the energy router can be expressed as follows:

$$P_l^H = g_l^H U_l^2 - (g_l^H \cos \delta_l + b_l^H \sin \delta_l) U_l U_l^D$$  \hspace{1cm} (1)

$$Q_l^H = -(b_l^H + g_l^H) U_l^2 + (b_l^H \cos \theta_l - g_l^H \sin \theta_l) U_l U_l^D$$  \hspace{1cm} (2)

Energy router port and DC bus for energy exchange of active power $P_l^D$ is

$$P_l^D = E_l U_l^D - g_l^H (U_l^D)^2 + (g_l^H \cos \delta_l - b_l^H \sin \delta_l) U_l U_l^D$$  \hspace{1cm} (3)

Wherein the DC side voltage $E_l$ and the AC port voltage $U_l^D$ satisfy the following relationship:

$$E_l = w_i U_l^D$$  \hspace{1cm} (4)

In the above equation, $w_i$ is the equivalent integrated voltage control coefficient. Its specific value is related to the voltage utilization efficiency of the DC side and the modulation angle of the rectifier.
3 Virtual node and virtual association matrix

3.1 Virtual node

Equations (1)–(5) and the system’s own exchange trend equations together constitute the energy flow model of the DN. However, based on the established mathematical model, the AC part and the DC part are independent of each other, and the solution needs to be carried out step by step, which is inefficient in the actual process. At the same time, through the analysis (1) and (2) can be found, its expression and AC flow equation is similar. Therefore, in the analysis of this paper, consider the establishment of a unified trend model, in order to achieve the integration of the network analysis. To achieve this goal, we first define the virtual node and the virtual correlation matrix to describe the coupling between the port of the energy router and the network node. For the internal structure of the energy router port described in Fig. 2, by defining a virtual node, the port model described in this figure can be equivalent to the form shown in Fig. 3.

The energy router input port in Fig. 3 is defined as a virtual node in the network. For each port of the energy router, port, part of the rectifier input port can be included in the overall network through the form of a virtual node. For a N-node AC network that contains the K-port energy router, the total number of network nodes is \(N + K\) after the introduction of the virtual node.

After introducing the concept of the virtual node, the dimension of the network admittance matrix is also increased accordingly.

Specifically, if the i port of the energy router is connected to the i node of the AC network, the extension of the port to the original network admittance matrix through the virtual node can be represented by

\[
[Y] = \begin{bmatrix}
Y^* & Y \\
Y & Y^*
\end{bmatrix}
\]

Before the introduction of the virtual node, the admittance matrix of the system is \(Y\) in (5). The new admittance matrix will be raised one dimension, the original admittance matrix \(Y\) in the new admittance matrix corresponding part of the \(Y^*\), the extended part of the column vector \(\mathbf{y}\), row vector \(\gamma\), and element \(y_{ij}\).

\[
Y^* = Y + g_i^H + jh_l^H + jg_l^H
\]

In column vector \(\mathbf{y}\) only the elements of row \(i\) are \(-g_i^H - jh_l^H\), and the remaining elements are 0, and the concrete structure is as follows:

\[
\mathbf{y} = \begin{bmatrix}
0 \\
-g_i^H - jh_l^H \\
0 \\
\end{bmatrix}
\]

The row vector \(\gamma^T\) is the transpose of the column vector \(\gamma\).

For \(Y^*\), it is defined as: \(-g_i^H - jh_l^H\). Introduce the virtual node one by one in the above way and realise the expansion of the network admittance matrix, and finally get the \(N + K\) order network admittance matrix including K-port energy router and N-node communication network.

3.2 Virtual correlation matrix and adjoint correlation matrix

After defining the virtual node, the correlation between the DC power \(P_i^D\) of the energy router and the active power \(P_i\) of the node in the AC network is given by

\[
P_i^D = P_{N+1}, \quad i = 1, 2, \ldots, K
\]

After introducing the concept of the virtual node, the virtual association matrix \(F\) and the adjoint correlation matrix \(H\) can be further introduced to serve the establishment of a unified network power analysis model including the energy router.

For N-node networks involving the K-port energy routers, \(F\) is the K-row \(N + K\) column matrix, and the relevant element definitions are given by

\[
F_{ii} = \begin{cases}
1, & \text{if port } L \text{ is connected to node } i \\
0, & \text{others}
\end{cases}
\]

The associated matrix \(H\) is a K-row \(N + K\) column matrix, and the associated elements are defined as follows:

\[
H_{ii} = \begin{cases}
1, & \text{if port } L \text{ is connected to node } i \\
0, & \text{others}
\end{cases}
\]

According to the definition of the adjoint correlation matrix \(H\) and the numbering of the virtual nodes, we can see that the element distribution of \(H\) is as shown in the following equation:

\[
H = \begin{bmatrix}
0 & 1
\end{bmatrix}
\]

Combining the virtual correlation matrix \(F\) and the adjoint correlation matrix \(H\), the correlation between the power, voltage and phase angle of the relevant DC side and the AC side in (1)–(5)
can be described by

\[ U_i = \sum_{j=1}^{N+K} F_{ji} U_j \]  \hspace{1cm} (12)

\[ P_i^0 = \sum_{j=1}^{N+K} H_{ji} P_j \]  \hspace{1cm} (13)

\[ U_i^0 = \sum_{j=1}^{N+K} H_{ji} U_j \]  \hspace{1cm} (14)

\[ \delta_i = \sum_{j=1}^{N+K} (F_{ji} - H_{ji}) \]  \hspace{1cm} (15)

4 Consider the power flow model of DN

4.1 DN load analysis model

This is obvious that the voltage of each node in the transmission network is near the nominal voltage. In particular, the relationship between the actual power and voltage of the load node can be described by (17) and (18)

\[ P_i = (\alpha_i U_i^2 + \beta_i U_i + \gamma_i) P_{i0} \] \hspace{1cm} (16)

\[ Q_i = (\alpha_i U_i^2 + \beta_i U_i + \gamma_i) Q_{i0} \] \hspace{1cm} (17)

where \( P_{i0} \) and \( Q_{i0} \) denote the active and reactive loads of the nodes at the rated voltage, respectively. The voltage coefficients \( \alpha_i, \beta_i \) and \( \gamma_i \) represent the ratio of the constant impedance load, the constant current load and the constant power load of the node, and for all nodes.

4.2 Integrated power flow analysis model of distribution network considering energy router

Combined with the analysis of the previous two parts, the integrated model of DN analysis for energy routers is summarised as follows.

(i) Network node active power injection equation

\[ \Delta P_i = (\alpha_i U_i^2 + \beta_i U_i + \gamma_i) P_{i0} - U_i \sum_{j=1}^{N+K} U_j (B_{ji} \sin \theta_j) + G_{ji} \cos \theta_j \]

\[ = 0 \] \hspace{1cm} (18)

(ii) Network node reactive power injection equation

\[ \Delta Q_i = (\alpha_i U_i^2 + \beta_i U_i + \gamma_i) Q_{i0} - U_i \sum_{j=1}^{N+K} U_j (G_{ji} \sin \theta_j) - B_{ji} \cos \theta_j \]

\[ = 0 \] \hspace{1cm} (19)

(iii) Energy router port active power control equation

The variables described in the form of the virtual correlation matrix and the adjoint matrix are substituted into (1) and in (13)–(16), then the active power of the port can be expressed as follows:

\[ \Delta P_i^0 = P_i^0 - g_i^0 \left( \sum_{j=1}^{N+K} F_{ji} U_j \right)^2 \]

\[ \sum_{j=1}^{N+K} F_{ji} U_j \sum_{j=1}^{N+K} H_{ji} U_j \left( g_i^0 \cos \left( \sum_{j=1}^{N+K} F_{ji} - H_{ji} \right) \right) \]

\[ + \sum_{j=1}^{N+K} F_{ji} U_j \sum_{j=1}^{N+K} H_{ji} U_j \left( g_i^0 \sin \left( \sum_{j=1}^{N+K} F_{ji} - H_{ji} \right) \right) \theta_j \]

\[ = 0 \] \hspace{1cm} (20)

(iv) Energy router switching power balance equations (12)–(15) into (4), then the active power balance equation of the energy router can be expressed as follows:

\[ \Delta P_S = \sum_{j=1}^{K} \left( g_i^0 \left( \sum_{j=1}^{N+K} H_{ji} U_j \right)^2 \right) \]

\[ + \sum_{j=1}^{K} \left( \sum_{j=1}^{N+K} F_{ji} U_j \sum_{j=1}^{N+K} H_{ji} U_j \left( g_i^0 \sin \left( \sum_{j=1}^{N+K} F_{ji} - H_{ji} \right) \right) \theta_j \right) \]

\[ - \sum_{j=1}^{N+K} \left( \sum_{j=1}^{N+K} F_{ji} U_j \sum_{j=1}^{N+K} H_{ji} U_j \left( g_i^0 \cos \left( \sum_{j=1}^{N+K} F_{ji} - H_{ji} \right) \right) \right) \]

\[ + \Delta P_m = 0 \] \hspace{1cm} (21)

Equations (18)–(21) constitute the power flow analysis model of the DN. Consider the \( N \)-node DN system, where the \( PQ \) nodes \( N-1 \) provide independent (18) and (19) \( N-1 \). The \( K-1 \) parts of the energy router take a constant port power and a constant corresponding node voltage control mode, providing (20) for a total of \( K-1 \). Finally, the network contains an energy router’s total active power balance equation (21), then the model has a total of \( 2N+K-2 \) equations.

5 Optimisation model of distribution network operation of fusion energy router

5.1 Optimisation model of distribution network operation of fusion energy router

In the DN optimisation operation analysis, in order to enhance the minimum operating voltage of the system to optimise the target, the relevant mathematical description is given by

\[ \text{Max}(\text{Min}(U_i)) \] \hspace{1cm} (22)

5.2 Restrictions

(i) Equality constraints: For all system nodes including virtual nodes, it is necessary to satisfy the node injection power balance relationship

\[ \Delta P = 0 \] \hspace{1cm} (23)

\[ \Delta Q = 0 \] \hspace{1cm} (24)
where the specific description forms of $P, Q$ are given by (18) and (19).

(ii) Inequality constraints: For all the lines in the network and all the ports of the energy router, it is necessary to meet the upper and lower limits of the line trend, which is defined in the form of line flow

$$S_{\text{min}}^2 \leq S_y^2 = \left( G_y^2 + B_y^2 \right) U_i^2 \left( U_i - U_j \cos \theta_{ij} \right)^2 \left( \frac{U_i}{U_j} \right)^2 + \left( U_i \sin \theta_{ij} \right)^2 \leq S_{\text{max}}^2$$ \quad (25)

where the admittance is derived from the elements in the extended admittance matrix constructed by the formula (6).

Overall switching power upper and lower bounds

$$P_{\Phi, \text{min}} \leq \sum_{i=N+1}^{N+k_a} P_i \leq P_{\Phi, \text{max}}$$ \quad (26)

$$P_{\Psi, \text{min}} \leq \sum_{i=N+1}^{N+k_a} P_i \leq P_{\Psi, \text{max}}$$ \quad (27)

5.3 Case study

For the case where the energy router is applied to the bifurcation point of the DN branch, an example is used to verify the comparison using the distribution system shown in Fig. 4.

It can be found that the energy router applied to the DN branch bifurcation point can also play the effect of lifting the end of the branch (Fig. 5).

As can be seen from Fig. 6, after the energy routers participate in network optimization, the power flow of some heavy load lines in the system is reduced, while the active loss of most lines is reduced, the total network loss of the system is reduced by 17.18%, and the running state is improved.

6 Conclusion

In this paper, the results show that the average voltage of the system is increased by 0.92% at the load level of 0.5 time base load to 1.5 times base load, and the energy router is used to optimise the running status of the DN. In this paper, the results show that when the energy router is applied to the end of distribution network, the average voltage of the system increases by 0.92% ~ 3.43% at the load level of 0.5 ~ 1.5 times the base load. The average voltage of the system is increased by 1.02% under rated load, and the total network loss is decreased greatly.

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8 References

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