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Power Flow Calculation of Distribution Network With Multiple Energy Routers

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ABSTRACT Energy router is an emerging device based on power electronic technology, which can realize the flexible distribution of electric energy in the power system. Therefore, the use of energy routers to improve the operating conditions of the power system not only has broad development prospects, but also brings economic benefits. In this regard, this paper proposes a steady-state model of a single energy router and considers the loss of the DC/DC transformer, establishes a power flow equation with multiple energy routers, and proposes a distribution network power flow alternate iteration that takes into account multiple energy routers Calculation method. A case study of an improved IEEE-33 system with multiple energy routers under different working conditions is carried out. The calculation results show that the alternate iterative power flow calculation method used in this paper is effective and feasible, and it reasonably reflects that the network analysis model with multiple energy routers can achieve stable operation, and it can improve the node voltage and reduce the active power loss of the grid. It makes the operation of the distribution network more flexible.

INDEX TERMS Multiple energy routers, distribution network, DC/DC transformer, alternate iterative, power flow calculation.

I. INTRODUCTION

Energy is one of the foundations for the survival and development of human society, and the problem of energy shortage is also a key issue that people have paid attention to in recent years. The energy development model based on fossil energy consumption not only has limitations in the total amount, but also causes certain pollution to the environment [1], [2]. In order to solve the problem of energy shortage and environmental protection, countries all over the world will focus on the active research on the development and application of renewable energy [3].

In the traditional power system, power regulation mainly relies on the generator set, which is mostly controlled in a centralized manner by means of electric energy coordination. In addition, the transformer, as a key link in the system, only has the function of voltage conversion but not power adjustment and distribution, which means that a new type of power transformation equipment is urgently needed to meet the needs of energy Internet construction [4]. For this reason, the FREEDM Center of North Carolina State University in the United States proposed the concept of energy routers. This design concept is derived from information routers and switches in the Internet. The energy flow is regarded as the information flow, and the free distribution and transmission of electric energy are realized through the energy router in the grid [6], [7].

At present, the research on energy routers mainly focuses on its structural design [8], [9], transient simulation [10], [11] and optimized control strategy [12]–[14]. In reference [8], the design method of key parameters of energy router is proposed based on the principle of energy balance, and the design of high-frequency transformer inductance, leakage inductance and bus capacitance is analyzed. Based on

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reference [8], a design method of the main circuit of modular multi-interface energy router is proposed in reference [9]. The design methods of energy storage, converter, common DC bus and energy interface are emphatically discussed. Reference [12] established an energy router model based on AC/DC hybrid network based on the traditional AC microgrid energy router model, and analyzed the relationship and limitation of the rectifier stage phasor under different working modes in the case of cascade connection. The simulation shows that the energy router can effectively improve the availability of the microgrid. Reference [11] uses the idea of decentralized and autonomous coordination control to simulate and analyze multi-port energy routers, and realizes the decentralized and autonomous coordination capabilities of energy routers, and improves the reliability and efficiency of transmission. Reference [12] adds a self-storage control strategy to the control of the energy router, which can stabilize the voltage of the energy subnet even when the input power is short of power, and provide short-term energy supply when the network is switched. Reference [13] proposed an energy router model based on AC/DC hybrid microgrid, which can be used for multiple voltage levels. Then, the idea of power coordinated control is used to ensure the stable operation of the AC/DC hybrid network with energy router while meeting the required power for the output part of the grid connected. In [14], an energy layered coordinated control strategy and seamless handover method for energy router are proposed to make the system run more stable.

At present, the research on energy router design, simulation and optimization has gradually matured, but there are still few researches on the establishment of energy router steady-state models and the role played in network operation [15]. The research on the steady-state model of energy routers is mostly limited to the research on the steady-state model of a single energy router, and most of them do not consider the loss calculation models of energy routers. With the continuous development of the power system, the distribution network with a single energy router can no longer meet the needs of the development of the distribution network, and the cooperation and operation of multiple energy routers is the inevitable trend of the future development of the distribution network. Therefore, it is necessary to discuss in depth the power flow calculation method of the distribution network with multiple energy routers to lay the foundation for the flexible operation and optimized control of the power grid with multiple energy routers.

The basic solution methods for power flow calculation of distribution networks with energy routers can be divided into two types: unified solution method and alternating iteration method. The alternating iterative method divides the power flow calculation module into a distribution network module and an energy router module, which are solved separately. Compared with the unified solution method, the alternating iteration method does not need to augment the Jacobian matrix of the distribution network. When calculating the power flow of the energy router module, there is no need to modify the Jacobian matrix of the AC distribution network. Therefore, compared with the unified solution method, the alternating iteration method is easier to implement, less computationally expensive, and more efficient.

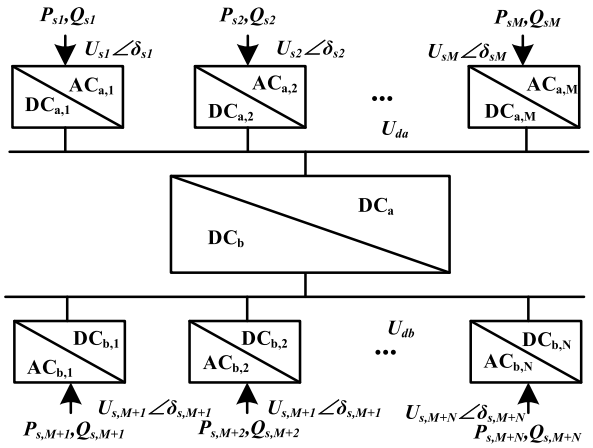

FIGURE 1. Structure diagram of energy router.

In this regard, this paper proposes a general analysis method for power flow calculation of multi-energy router distribution network considering the losses of energy routers. Firstly, the basic steady-state calculation model of a single energy router is established, and the loss model of energy router is taken into account; Secondly, based on the steady-state calculation model of a single energy router, the power flow equation with multiple energy routers is derived; Then, an alternating iteration method is proposed to solve the power flow problem with multiple energy routers; Finally, a case study of the improved IEEE-33 system is carried out to verify the effectiveness of the proposed model.

II. STEADY STATE MODEL OF ENERGY ROUTER

Energy router is a kind of power equipment that integrates information technology and power electronic conversion technology to realize the efficient utilization and transmission of distributed energy. Energy routers are an indispensable part of the realization of energy Internet. A single energy router can no longer meet the needs of the development of the distribution network [16], and the cooperative operation of multiple energy routers has become an inevitable trend of development. Features of multiple energy routers are: 1) Each energy router can provide a standardized plug-and-play interface to complete the safe startup and mode determination of the equipment; 2) Have the ability to detect and isolate faults and formulate energy management plans; 3) Multiple energy routers adopt solid-state transformer type (SST) structure, which can reduce the reactive power loss of the power system by independently setting the bus voltage of each port; 4) It can realize the active control of power flow direction and size, and at the same time complete the optimization of power quality.

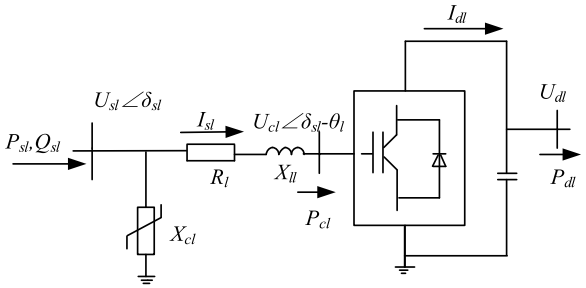

FIGURE 2. Energy router AC/DC converter model.

A. AC/DC CONVERTER MODEL

The equivalent circuit of AC/DC converter is shown as in Fig. 2 [17]. The AC/DC converter model is composed of reactor, bridge, AC filter and DC capacitor. R_l is the loss of l-port converter, U_{cl} is the fundamental voltage of l-port converter. X_l and X_{cl} are the fundamental reactance of l-port converter and AC filter respectively. Let P_{sl} and Q_{sl} denote the active power and reactive power injected into port l from the side of the grid, respectively, the amplitude of the AC grid side voltage is denoted as U_{si}, the corresponding angle is denoted as δ_{sl}, and the phase angle difference between U_{cl} and U_{si} is θ_l. According to different control objectives, the energy router can control the power grid containing the energy router by independently adjusting P_{sl} and Q_{sl}.

For the convenience of description, the conductance and susceptance of AC/DC converter are expressed as

$$\begin{cases} G_l = R_l/(R_l^2 + X_l^2) \\ B_l = X_l/(R_l^2 + X_l^2) \\ G_{cl} = 1/X_{cl} \end{cases} \tag{1}$$

On this basis, according to Kirchhoff's law, the P_s and Q_s injected into port l of the energy router can be expressed as:

$$\begin{cases} P_{sl} = G_l(U_{sl}^2 - U_{sl}U_{cl}\cos\theta_l) + B_l U_{sl}U_{cl}\sin\theta_l \\ Q_{sl} = B_l(U_{sl}^2 - U_{sl}U_{cl}\cos\theta_l) - G_l U_{sl}U_{cl}\sin\theta_l + B_{cl}U_{sl}^2 \end{cases} \tag{2}$$

where U_{si}, G_l and B_l are generally fixed values in the system, it is not difficult to find that the size and flow direction of P_{sl} and Q_{sl} can be controlled by changing θ_l and U_{cl}.

According to the energy conservation theorem, the expression of active power P_{dl} at DC side is as follows:

$$P_{dl} = U_{dl}I_{dl} = G_l(-U_{cl}^2 + U_{sl}U_{cl}\cos\theta_l) + B_l U_{sl}U_{cl}\sin\theta_l \tag{3}$$

where I_{dl} is the current flowing through the DC side, U_{dl} is the voltage at the DC side, and the active power P_{dl} at the DC side is the product of the two.

The relationship between U_{cl} and DC side voltage U_{dl} can be expressed as follows:

$$U_{cl} = k_l U_{dl} \tag{4}$$

where k_l represents the control coefficient of the voltage, and the modulation strategy of the converter and the wiring form of the line determine its value.

$$k_l = \mu M/\sqrt{2} \tag{5}$$

where μ represents the utilization ratio of DC voltage. When sine pulse width modulation is used, its value is $\sqrt{3}/2$, and when space vector modulation is used, its value is 1. M represents the modulation coefficient, and its modulation range is $0 \le M \le 1$. Therefore, When the AC/DC converter adopts space vector modulation, the value range of k_l is $0 \le k_l \le 1/\sqrt{2}$.

B. DC/DC CONVERTER MODEL

The voltage value on each side of the DC/DC converter can be realized by controlling the power electronics. Based on the principle of internal power conservation, the power loss balance constraints of primary and secondary sides in energy router can be expressed as follows:

$$U_{da}I_{da} + U_{db}I_{db} - (P_{sta} + P_{dyn}) = 0 \tag{6}$$

where I_{da} and I_{db} are the sum of the primary and secondary currents; P_{sta} is the static power loss of the DC/DC converter; P_{dyn} is the dynamic power loss of the DC/DC converter. I_{da} and I_{db} can be further expanded into

$$\begin{cases} I_{da} = \sum_{i=1}^{M} I_{di} \\ I_{db} = \sum_{j=M+1}^{M+N} I_{dj} \end{cases} \tag{7}$$

(1) I_{di} and I_{dj} can be expressed as follows:

$$\begin{cases} I_{di} = -G_i(k_i^2 U_{d\phi} - k_i U_{si}\cos\theta_i) + B_i k_i U_{si}\sin\theta_i \\ I_{dj} = -G_j(k_j^2 U_{d\psi} - k_j U_{sj}\cos\theta_j) + B_j k_j U_{sj}\sin\theta_j \end{cases} \tag{8}$$

(2) The static power loss P_{sta} of DC/DC converter is mainly produced by isolated transformer. Its skeleton structure, core material and switching frequency are important factors affecting the static power loss P_{sta}. according to Steinmetz equation, the static power loss characteristics of the transformer in the converter can be expressed as:

$$P_{sta} = FKf^{\alpha}B^{\beta} \tag{9}$$

where K, f^{α} and B^{β} are constants when the core material, structure and switching frequency are selected; F is the flux waveform coefficient.

(3) P_{dyn} is determined by the power provided by both sides of DC/DC transformer, and can be estimated by the following equation [18]:

$$\begin{aligned} P_{dyn} = {} & I_{d\phi}^2 R_{d\phi} + \left(\frac{I_{d\phi}f_{\phi}}{I_{d\phi0}f_{\phi0}}\right)^2 P_{we\phi0} \\ & + \left(\frac{I_{d\phi}}{I_{d\phi0}}\right)^2 \left(\frac{f_{\phi}}{f_{\phi0}}\right)^{0.8} P_{se\phi0} \\ & + I_{d\psi}^2 R_{d\psi} + \left(\frac{I_{d\psi}f_{\psi}}{I_{d\psi0}f_{\psi0}}\right)^2 P_{we\psi0} \end{aligned}$$

$$+\left(\frac{I_{d\psi}}{I_{d\psi 0}}\right)^2\left(\frac{f_\psi}{f_{\psi 0}}\right)^{0.8}P_{se\psi 0} \tag{10}$$

where f is the working PWM frequency of the DC/DC transformer and I is the DC current on both sides of the DC/DC transformer. When the DC/DC transformer operates under I_{d0} and f_0 conditions, P_{we0} is the basic eddy current loss in the winding and P_{se0} is the basic stray loss in metal structure parts. Once the PWM frequency is fixed, the dynamic power consumption can be expressed as follows:

$$P_{dyn} = I_{d\phi}^2 R_{E\phi} + I_{d\psi}^2 R_{E\psi} \tag{11}$$

For the energy router, it is necessary to relax the active power control of one port to meet the power loss balance constraint of the energy router. In this paper, the M port on the secondary side of each energy router is set as the relaxed port.

C. STEADY STATE POWER FLOW MODEL OF MULTIP-LE ENERGY ROUTERS

When the number of energy routers in the system is n, they can be labelled and represented by the set S:

$$S = \{\mathrm{ER}_1, \cdots, ER_t, \cdots, \mathrm{ER}_n\}, t = 1, 2, \cdots, n \tag{12}$$

This article assumes that the port of the energy router adopts the PQ control strategy, and the voltage control coefficient and phase angle difference of the energy router in the power flow analysis are unknown. Assuming that the ER_t contains M_t primary side port, N_t secondary side port, the lth port and AC grid exchange of reactive power, reactive power can be expressed as $P^t sl$, Q^t_{sl}, at this time the energy router port l node power equation is:

$$\begin{cases} \Delta P^t_{sl} = P^t_{sl} - \left(G^t_l(U^t_{sl}U^t_{sl} - U^t_{sl}U^t_{cl}\cos\theta^t_l) + B^t_l U^t_{sl}U^t_{cl}\sin\theta^t_l\right) \\ \Delta Q^t_{sl} = Q^t_{sl} - B^t_l(U^t_{sl}U^t_{sl} - U^t_{sl}U^t_{cl}\cos\theta^t_l) + G^t_l U^t_{sl}U^t_{cl}\sin\theta^t_l \\ -B^t_{cl}U^t_{sl}U^t_{sl} \end{cases} \tag{13}$$

where U^t_{sl} is the AC voltage value connected to the lth port of ER_t and the external power grid, U^t_{cl} is the voltage value of the AC node inside the lth port of ER_t, and the phase angle difference between the two is expressed as θtl; ΔP^t_{sl} and ΔQ^t_{sl} are the deviation of active power and reactive power of ER_t.

The power loss balance of ER_t is:

$$\Delta P^t_l = U_{da}I_{da} + U_{db}I_{db} - (P_{sta} + P_{dyn}) \tag{14}$$

Combining equation (3) and equation (7), we can get equation (15):

$$\begin{aligned} &\Delta P^t_l \\ &= U_{da}\sum_{l=1}^{M_t}\left(-G^t_l\left(k^t_l k^t_l U_{da} - k^t_l U^t_{sl}\cos\theta^t_l\right) + B^t_l k^t_l U^t_{sl}\sin\theta^t_l\right) \\ &\quad + U_{db}\sum_{l=M_t+1}^{M_t+N_t}\left(-G^t_l\left(k^t_l k^t_l U_{db} - k^t_l U^t_{sl}\cos\theta^t_l\right)\right. \\ &\quad \left. + B^t_l k^t_l U^t_{sl}\sin\theta^t_l\right) \\ &\quad - \left(\sum_{l=1}^{M_t}\left(-G^t_l\left(k^t_l k^t_l U_{da} - k^t_l U^t_{sl}\cos\theta^t_l\right) + B^t_l k^t_l U^t_{sl}\sin\theta^t_l\right)\right)^2 \\ &\quad \times R_{E\phi} \\ &\quad - \left(\sum_{l=M_t+1}^{M_t+N_t}\left(-G^t_l\left(k^t_l k^t_l U_{db} - k^t_l U^t_{sl}\cos\theta^t_l\right)\right.\right. \\ &\quad \left.\left. + B^t_l k^t_l U^t_{sl}\sin\theta^t_l\right)\right)^2 R_{E\psi} \\ &\quad - P_{sta} \end{aligned} \tag{15}$$

Equations (13) and (15) constitute the power flow equation of ER_t. In addition to the relaxed port, the P^t_{sl} and Q^{sl}_t of each port can be set as the control target, and the Q^t_{sl} of the relaxed port can also be determined. In this case, ER_t has M_t+N_t-1 active power and M_t+N_t reactive power is known. With a balance constraint of power loss, there are 2*(M_t+N_t) equations that are known. Then there are 2*(M_t+N_t) equations that are unknown, which are M_t+N_t phase angle difference θ^l_t and M_t+N_t voltage control coefficient k^l_t. For example, the active power calculation of the balance node of the power system, after all θ^l_t and k^l_t are obtained, the active power $P^t_{s,M+N}$ of the relaxation port can be determined.

The power flow equation of ER_t can be solved by the Newton-Raphson method, and the iterative equation is (16), as shown at the bottom of the next page: where ΔF^t is the deviation value of the ER_t power flow equations, ΔX^t is the variable of the ER_t power flow equations, and J^t is the Jacobian matrix of the ER_t power flow equations.

The Jacobian matrix J^t can be expressed as:

$$J = \begin{pmatrix} \frac{\partial(\Delta P^t_s)}{\partial k^t} & \frac{\partial(\Delta P^t_s)}{\partial \theta^t} \\ \frac{\partial(\Delta Q^t_s)}{\partial k^t} & \frac{\partial(\Delta Q^t_s)}{\partial \theta^t} \\ \frac{\partial(\Delta P^t_L)}{\partial k^t} & \frac{\partial(\Delta P^t_L)}{\partial \theta^t} \end{pmatrix} \tag{17}$$

Each matrix block in the equation represents the partial derivative of the deviation value of the power flow equation system to the variable. The specific expression is as follows:

$$\begin{cases} \partial(\Delta P^t_s)/\partial k^t = G^t U_d U_s\cos\theta^t - B^t U_d U_s\sin\theta^t \\ \partial(\Delta P^t_s)/\partial\theta^t = -G^t k^t U_d U_s\sin\theta^t - B^t k^t U_d U_s\cos\theta^t \\ \partial(\Delta Q^t_s)/\partial k^t = B^t U_d U_s\cos\theta^t + G^t U_d U_s sin\theta^t \\ \partial(\Delta Q^t_s)/\partial\theta^t = -B^t k^t U_d U_s\sin\theta^t + G^t k^t U_d U_s\cos\theta^t \\ \partial(\Delta P^t_L)/\partial k^t = U_d(-G^t(2k^t U_d - U_s\cos\theta^t) + B^t U_s\sin\theta^t) \\ -2R_E(-G^t(2k^t U_d - U_s\cos\theta^t) + B^t U_s\sin\theta^t) \\ (-G^t(k^t k^t U_d - k^t U_s\cos\theta^t) + B^t k^t U_s\sin\theta^t) \\ \partial(\Delta P^t_L)/\partial\theta^t = U_d(-G^t k^t U_s\sin\theta^t + B^t k^t U_s\cos\theta^t) \\ -2R_E(-G^t k^t U_s\sin\theta^t + B^t k^t U_s\cos\theta^t) \\ (-G^t(k^t k^t U_d - k^t U_s\cos\theta^t) + B^t k^t U_s\sin\theta^t) \end{cases} \tag{18}$$

According to the initial conditions given by the system, the combined equations (16)-(18) can perform power flow calculation and analysis on ER_t.

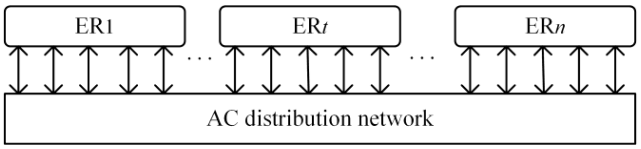

FIGURE 3. Network diagram with multiple energy routers.

III. POWER FLOW CALCULATION METHOD FOR MULTIPLE ENERGY ROUTERS

A. POWER GRID MODEL OF MULTIPLE ENERGY ROUTERS

A schematic diagram of an AC power grid with multiple energy routers is shown in Figure 3. There are n multi-port energy routers for energy exchange with the AC power grid.

The model of the AC distribution network is a nodal power equation reflecting the relationship between nodal power, nodal voltage and phase angle:

$$P_{grid,i} = V_i \sum_{j \in i} V_j \left(G_{ij} \cos(\theta_{ij}) + B_{ij} \sin(\theta_{ij})\right) \quad (19)$$

$$Q_{grid,i} = V_i \sum_{j \in i} V_j \left(G_{ij} \sin(\theta_{ij}) - B_{ij} \cos(\theta_{ij})\right) \quad (20)$$

In the equation, $P_{grid,i}$ and $Q_{grid,i}$ represent the reactive power and active power of AC distribution network at node i, respectively. The voltage of V_i and V_j at nodes i and j, G_{ij} is the conductance of node admittance matrix, B_{ij} is the admittance of node admittance matrix, and θ_{ij} is the phase angle difference between nodes i and j.

B. ALTERNATING ITERATION METHOD

The power flow of the AC distribution network power flow model with multiple energy routers can be solved by alternately solving the power flow equations between the AC grid and each energy router. The specific process is as follows:

1) The active power initialization of the balanced port: the initial active power injection of the slack port can be estimated according to the given value of the active power of other ports, as shown in equation (21).

$$P^t_{s,M_t+N_t} = -\sum_{l=1}^{M_t+N_t-1} P^t_{s,l} \quad (21)$$

For the internal parameters of the energy router, the initial values can be set as follows:

$$\theta^t_{l,0} = \arctan(P^t_{sl}/(U^t_{sl}U^t_{sl}/X^t + U^t_{sl}U^t_{sl}/X^t_c - Q^t_{sl})) \quad (22)$$

$$k^t_{l,0} = P^t_{sl}X^t/U^t_{sl}U^t_d \sin\theta^t_{l,0} \quad (23)$$

2) AC system power flow calculation: According to the active power and reactive power values of the energy router ports, the equivalent injected power of the AC distribution network nodes is updated. Assuming that the node h of the AC distribution network is connected to the port l of ER_t, the equivalent injected power of the node h of the AC distribution network is the sum of the original power of the AC system and the exchange power of the same port l. The equation can be expressed as:

$$\begin{cases} P_{grid,h} = P_{grid,h0} + P^t_{sl} \\ Q_{grid,h} = Q_{grid,h0} + Q^t_{sl} \end{cases} \quad (24)$$

After updating the equivalent injected power of the AC distribution network, the U^t_{sl} value of each node is updated accordingly, and the P-Q fast decomposition method is used to calculate the power flow of the AC distribution network.

3) Energy router port power flow calculation: Solve the variables θ^t l and k^t_l of ER_t by combining equations (16)-(18), update the active power $P^{t\_new}_{s,M+N}$ of the ER_t relaxation port, and calculate all energy router variables.

4) Convergence judgment: Calculate the changes in active power injected into the relaxation ports of all energy routers after this iteration. If it is small enough, terminate the iteration and give the result. Otherwise, turn to step 2).

$$\begin{aligned} \max\{&abs(P^{1\_new}_{s,M_1+N_1} - P^1_{s,M_1+N_1}), \\ &\ldots, abs(P^{t\_new}_{s,M_t+N_t} - P^t_{s,M_t+N_t}) \\ &, \ldots, abs(P^{n\_new}_{s,M_n+N_n} - P^n_{s,M_n+N_n})\} < \varepsilon \end{aligned} \quad (25)$$

IV. CASE STUDY

In this paper, an improved ieee-33 node system with three energy routers is verified and analyzed [19]. The example topology is shown in Figure. 4. A two-port energy router is connected between nodes 12 and 30, a four-port energy router is connected between nodes 18, 22, 25 and 34, and a three-port energy router is connected between nodes 4, 26 and 19. Nodes 30, 34 and 19 are set as the relaxation ports of their energy router respectively, and the remaining nodes of energy router are controlled by PQ. The output of generators is extracted from the example files from Matpower version 6. The basic capacity of IEEE-33 node power distribution system is 10MVA. The rated voltage level of IEEE-33 distribution network is 12.66KV. The distribution network system consists of 33 nodes, 32 branches and 1 root node. The total load of distribution network is 5084.26+j2547.32KVA. The detailed parameters of the network can be referred to [20]. The capacity of the three energy routers is set to 0.5MVA. For the convenience of analysis and comparison, the original impedance values of AC / DC converter ports of all energy routers are the same. Each port impedance parameter

$$\begin{cases} \Delta F^t = J^t \Delta X^t \\ \Delta F^t = [\Delta P^t_{s,1}, \ldots, \Delta P^t_{s,M_l+N_l-1}, \ldots, \Delta Q^t_{s,1}, \ldots, \Delta Q^t_{s,M_l+N_l}, \Delta P^t_L] \\ \Delta X^t = [k^t_1, \ldots, k^t_{M_l+N_l}, \theta^t_1, \ldots, \theta^t_{M_l+N_l}] \end{cases} \quad (16)$$

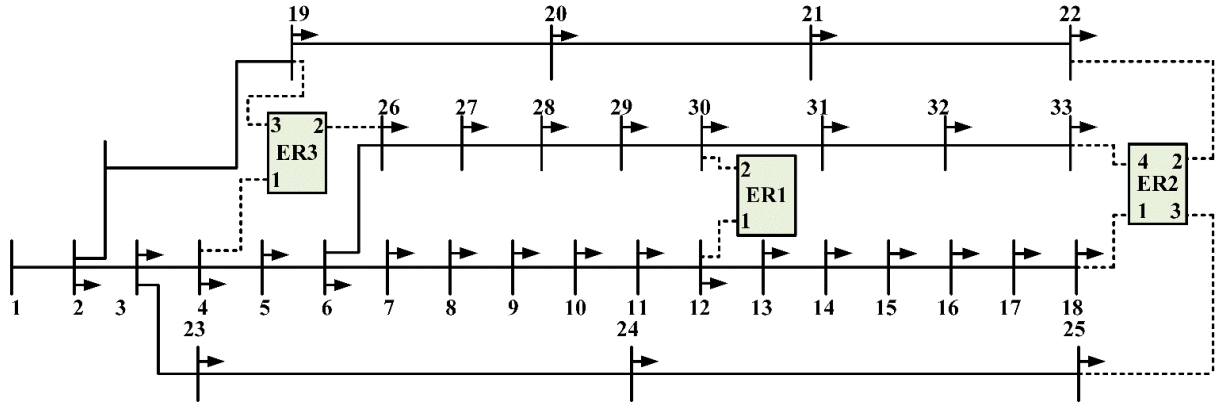

FIGURE 4. IEEE-33 node network topology with multiple energy routers.

R is set to 0.002p.u., X is set to 0.037p.u., and X_c is set to -18.2617p.u.. In this case, the convergence threshold ε is 10^{-6}, and the unit values of the DC side voltage U_d are 1.5, 2 and 1.8 respectively.

A. VERIFICATION OF POWER FLOW CALCULATION RESULTS

According to the alternating iterative algorithm proposed in this paper, the power flow calculation of the AC distribution network with multiple energy routers is shown in Table 1. The system is iterated alternately, the running time is 22.49s, the number of iterations of the AC distribution network using the P-Q decomposition method is 12, and the number of iterations of the power flow of the energy router port is 15739. In the case, the initial values of $P^1_{s,M1+N1}$, $P^2_{s,M2+N2}$ and $P^3_{s,M3+N3}$ of the three energy routers balanced ports are -0.10MW, 0MW and -0.03MW respectively, and the update times are 44. The network loss of the system is 0.178MW. At this time, the values of balanced ports $P^{1\_new}_{s,M1+N1}$, $P^{2\_new}_{s,M2+N2}$ and $P^{3\_new}_{s,M3+N3}$ remain unchanged at -0.098MW, -0.003MW and 0.032MW, respectively. At the end of the alternate iteration process, the U_s, θ, and k obtained from the power flow calculation are substituted into equations (12) and (14). The calculation results show that the values of ΔP^t_{sl}, ΔQ^t_{sl} and ΔP^t_l are almost zero, which shows that the algorithm proposed in this paper is correct and effective. After adding multiple energy routers to calculate the power flow of distribution network, the minimum voltage of all nodes should be larger than the minimum value of original power flow voltage without energy router, and the maximum voltage per unit value of all nodes should be less than 1.05p.u..

B. ANALYSIS OF DIFFERENT CASE RESULTS

In order to verify the correctness of power flow calculation of distribution network under multiple energy routers and compare the impact of energy routers on the system under different conditions, three different cases are set up in this paper, and the results are shown in Table 2. Case 1 is to verify the correctness of the power flow calculation results, and the results are given in Table 1. Case 2 is to further increase the voltage on the basis of case 1. Case 3 is to reverse the active power of case 1 (for example, port 3 of energy router 2 provides active power to the system in case 1, and the system provides active power to it in case 3). It should be pointed out that when the energy router is not considered, the system power loss is 0.203MW.

TABLE 1. Calculation results of energy router.

ER	Port No	P_s(MW)	Q_s(MW)	U_s(p.u.)	k	θ(°)
1	1	0.100	-0.10	0.935	0.625	0.243
	2	-0.098	-0.10	0.930	0.622	-0.230
2	1	-0.100	-0.08	0.928	0.465	-0.237
	2	0.050	-0.07	0.992	0.496	0.107
	3	0.050	-0.06	0.970	0.485	0.111
	4	0.003	0.05	0.924	0.460	-0.008
3	1	0.050	-0.05	0.977	0.543	0.109
	2	-0.080	-0.05	0.953	0.530	-0.183
	3	0.032	0.05	0.997	0.552	0.055

TABLE 2. Calculation results in different cases.

Case No.	ER	Port No.	P_s(MW)	Q_s(MVar)	U_s(p.u.)	k	θ(°)
Case 2	1	1	-0.100	-0.10	0.946	0.632	-0.226
		2	0.102	-0.10	0.936	0.625	0.247
	2	1	-0.100	-0.10	0.939	0.471	-0.229
		2	0.100	-0.10	0.992	0.497	0.216
		3	0.100	-0.10	0.972	0.487	0.225
		4	-0.098	-0.10	0.933	0.467	-0.229
	3	1	-0.100	-0.10	0.980	0.545	-0.211
		2	-0.100	-0.10	0.958	0.534	-0.220
		3	0.202	-0.10	0.997	0.554	0.426
Case 3	1	1	-0.100	-0.10	0.926	0.619	-0.236
		2	0.102	-0.10	0.921	0.615	0.255
	2	1	0.100	0.08	0.905	0.450	0.239
		2	-0.050	0.07	0.991	0.493	-0.119
		3	-0.050	0.06	0.969	0.483	-0.123
		4	0.002	-0.05	0.916	0.458	0.005
	3	1	-0.050	0.05	0.975	0.540	-0.121
		2	0.080	0.05	0.946	0.523	0.175
		3	-0.028	-0.05	0.997	0.554	-0.060

TABLE 3. Power flow calculation results of line in case 3.

Bus No.	From Node	To Node	P_s(MW)	Q_s(MVar)	P_{loss} (MW)	Q_{loss} (MVar)
1	1	2	3.93	2.45	0.012	0.01
2	2	3	3.54	2.2	0.054	0.03
3	3	4	2.5	1.62	0.021	0.01
4	4	5	2.41	1.48	0.02	0.01
5	5	6	2.33	1.44	0.041	0.04
6	6	7	1.1	0.51	0.002	0.01
7	7	8	0.9	0.4	0.005	0
8	8	9	0.69	0.3	0.004	0
9	9	10	0.63	0.28	0.004	0
10	10	11	0.56	0.26	0.001	0
11	11	12	0.52	0.23	0.001	0
12	12	13	0.56	0.29	0.004	0
13	13	14	0.49	0.25	0.001	0
14	14	15	0.37	0.17	0.001	0
15	15	16	0.31	0.16	0.001	0
16	16	17	0.25	0.14	0.001	0
17	17	18	0.19	0.12	0	0
18	2	19	0.28	0.18	0	0
19	19	20	0.22	0.19	0.001	0
20	20	21	0.13	0.15	0	0
21	21	22	0.04	0.11	0	0
22	3	23	0.89	0.52	0.003	0
23	23	24	0.8	0.46	0.005	0
24	24	25	0.37	0.26	0.001	0
25	6	26	1.13	0.87	0.003	0
26	26	27	0.99	0.8	0.003	0
27	27	28	0.93	0.77	0.011	0.01
28	28	29	0.86	0.74	0.007	0.01
29	29	30	0.73	0.66	0.004	0
30	30	31	0.42	0.16	0.001	0
31	31	32	0.27	0.09	0	0
32	32	33	0.06	-0.01	0	0

TABLE 4. Calculation results of line power flow under initial power flow.

Bus No.	From Node	To Node	P_s(MW)	Q_s(MVar)	P_{loss} (MW)	Q_{loss} (MVar)
1	1	2	3.92	2.44	0.012	0.01
2	2	3	3.44	2.21	0.052	0.03
3	3	4	2.36	1.68	0.02	0.01
4	4	5	2.22	1.59	0.019	0.01
5	5	6	2.14	1.55	0.038	0.03
6	6	7	1.1	0.53	0.002	0.01
7	7	8	0.89	0.42	0.005	0
8	8	9	0.69	0.32	0.004	0
9	9	10	0.62	0.3	0.004	0
10	10	11	0.56	0.27	0.001	0
11	11	12	0.52	0.24	0.001	0
12	12	13	0.45	0.21	0.003	0
13	13	14	0.39	0.17	0.001	0
14	14	15	0.27	0.09	0	0
15	15	16	0.21	0.08	0	0
16	16	17	0.15	0.06	0	0
17	17	18	0.09	0.04	0	0
18	2	19	0.36	0.16	0	0
19	19	20	0.27	0.12	0.001	0
20	20	21	0.18	0.08	0	0
21	21	22	0.09	0.04	0	0
22	3	23	0.94	0.46	0.003	0
23	23	24	0.85	0.41	0.005	0
24	24	25	0.42	0.2	0.001	0
25	6	26	0.95	0.97	0.003	0
26	26	27	0.89	0.95	0.003	0
27	27	28	0.82	0.92	0.011	0.01
28	28	29	0.75	0.89	0.008	0.01
29	29	30	0.63	0.81	0.004	0
30	30	31	0.42	0.21	0.002	0
31	31	32	0.27	0.14	0	0
32	32	33	0.06	0.04	0	0

It can be seen from Table 1 and Table 2 that the energy router will play a certain role in raising the node voltage after participating in the network optimization control. After the IEEE-33 node distribution network introduces multiple energy routers, the network loss of the system when the energy router runs in Case 2 is only 0.137MW, which is 32.51% lower than before the energy router is added.

At the same time, it should be pointed out that the active power loss of the system increases to 0.212MW when the energy router is running in Case 3. It can be clearly seen that when the energy router is not well controlled, it will lead to a substantial increase in the active power loss of the system. Table 3 is the power flow calculation result of the line power and network loss in case 3, and Table 4 is the power flow calculation result of the power and network loss under the initial power flow. When the active power and reactive power of the energy router port are set improperly, as the active power and reactive power transmitted in the line increase, the line network loss further increases. It can be clearly seen that poor control of energy routers will worsen the power flow distribution of the system.

The node voltage of the system under different working conditions is shown in Figure.5. Compared with the initial power flow and case 1, it is not difficult to find that the coordinated optimal control of multiple energy routers can support the node voltage, especially the voltage of node 18 and node 33 has been improved., Furthermore in order to

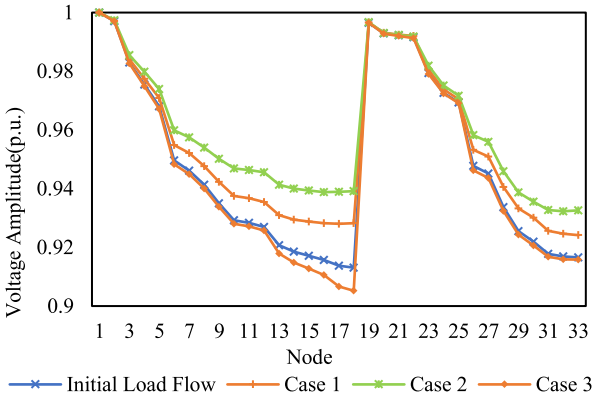

FIGURE 5. Node voltage under different conditions.

reduce power loss while not exceeding the maximum voltage of the original network, by controlling energy routers to work in Case 2, the system power loss can be significantly reduced. Energy routers help to optimize the system power flow distribution.

V. CONCLUSION

In this paper, a steady-state power flow model of distribution network with multiple energy routers is established. Based on IEEE-33 system, the effect of operation state of distribution network with multiple energy routers is verified. The results show that the alternating iteration power

flow calculation method with multi energy router is correct and feasible. Through the coordinated operation of multiple energy routers, controlling the voltage of each port and the interactive power of distribution network can improve the minimum voltage of the system, reduce the active power loss of the system, and improve the operation state of the distribution network. Poor control measures cannot coordinate the operation of multiple energy routers, affecting the operation of the distribution network.

This paper discusses the power flow calculation method of distribution network with multiple energy routers, and how to realize the optimal operation of distribution network with multiple energy routers is the focus of the next work.

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