A Routing Algorithm Based on Weighted Graph for Power Distribution Network

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Abstract. Smart power distribution network refers to the network that realizes information transmission among the power generation, transmission, transformation, consumption. With the rapid development of the power distribution network, the network topology becomes more and more complex. The scheduling of measurement, protection and control information can be realized by routing selection. However, the traditional routing algorithm cannot be applied due to its poor adaptability to the structural of the modern intelligent power system. In order to meet the requirements of low latency and high reliability in data communication of power distribution network, this paper utilize the weighted graph theory to describe the power distribution network. Then, an intelligent routing algorithm is proposed based on the analysis of the connectivity, delay, reliability and other parameters. Simulation results show that the proposed routing scheme is feasible and effective, which can also realize the load balancing of the power distribution network.

Keywords: Power distribution network · Routing algorithm · Weighted graph theory · Load balancing

1 Introduction

Power grid is one of the important part of national energy industry comprehensive transportation system [1]. Smart grid use digital information network to optimize the power grid control, including energy resources development, conversion, transmission and distribution, power supply, scheduling [2, 3]. The power distribution network is part of the grid system, which is a two-way communication network platform, using a variety of smart sensors, automation equipment, electronic devices to realize the optimization of information transmission and the reasonable use of resources [4]. The smart power distribution network belongs to the bottom of the power system, which is directly connected to the user and meets the customer demand for electricity [5]. In order to ensure the reliability of the power distribution network system, the network architecture needs to be designed in combination with the structural characteristics of the distribution network and the communication requirements of the power grid network. In intelligent power distribution network, the distribution network is composed

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of a number of local communication subnets. There are a lot of sensor nodes in every communication subnet [6]. The wireless sensor nodes have formed a wireless sensor network in a local geographic area, using multiple hops links. Therefore, it is necessary to study reliable routing algorithm in smart distribution network, which can not only meet the data transmission requirements of low delay, but also realize the load balance of the whole network [7]. In recent years, more and more researchers have been starting their projects on routing design of power distribution network and there have been some important studies.

Wang et al. [8] considered the energy constraints of clustered power distribution network and proposed an improved routing protocol to achieve a global optimization in energy consumption for all cluster head nodes, which reduce the effects of hot spots in some nodes near the sink node and prevent the hot head nodes to be overloaded for data communication. But the latency of the link was not considered. The authors in [9] thought that it was a challenge to decrease the risk of different services efficiently in power distribution network. One of the method was route distribution. They proposed a routing optimization mechanism based on load balancing for power communication networks to address the abovementioned problems. Although the load balance was achieved, the reliability of the network was reduced because of the unevenly distributed network structure. The authors in [10] presents a routing algorithm to long the network lifetime oriented to the intelligent power distribution network, which can balance the energy consumption of network node, and extend the network lifetime. Similarly, the stability of this network architecture with fewer nodes was not analyzed. In order to solve the above shortcomings, this paper considers the optimal path selection problem. In particular, the transmission delay, network reliability and load balancing are analyzed in particularly.

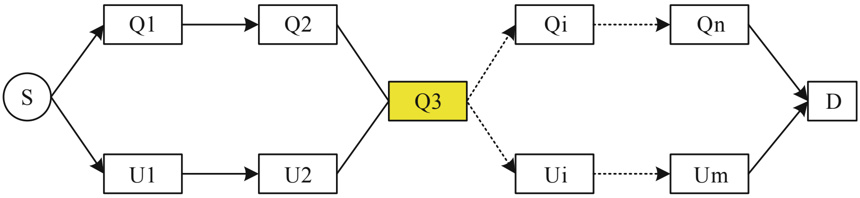
In this paper, we study the problem of routing design for power distribution network. The rest is arranged as follows. Section 2 presents the mathematical model and proposes the routing algorithm. Section 3 displays the simulation results and analysis. We then conclude our work in Sect. 4.

2 Mathematical Model

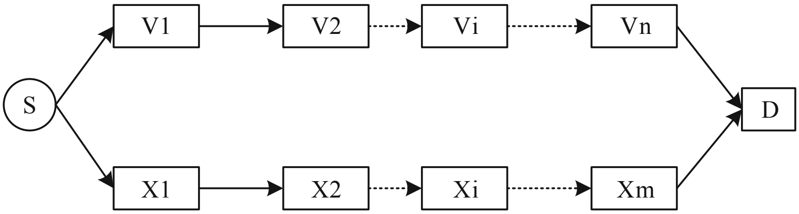
In the topology of power distribution network, path stability is affected by the interference of wireless channel, path correlation, influence of geographical location, and energy efficiency of nodes, etc. In this section, the influence of node energy efficiency and path correlation on path stability is studied.

2.1 The Probability of Link Fracture

It is assumed that two links transmit information together and the probability of failure of each node is $p(0 \le p \le 1)$. Generally speaking, the routing scheme can be divided to two methods, as shown in Fig. 1. If there are no public nodes in the path, the probability of link fracture is p_0:



(a) Link with public node



(b) Link with no public node

Fig. 1. The comparison of two routing methods.

$$\begin{aligned} P_0 &= P_{1-break}(V_1V_2\ldots V_n)P_{2-break}(X_1X_2\ldots X_m) \\ &= [1-(1-p)^n][1-(1-p)^m] \end{aligned} \tag{1}$$

If there is a common node in the link, the probability of link fracture is:

$$\begin{aligned} P_1 &= P_{1-break}(Q_1Q_2\ldots Q_n)P_{2-break}(U_1U_2\ldots U_m) \\ &= [1-(1-p)^{n-1}][1-(1-p)^{m-1}]+p \end{aligned} \tag{2}$$

The stability comparison of these two paths is shown as $f_1(p)$:

$$\begin{aligned} f_1(p) &= P_1 - P_0 \\ &= \left[1-(1-p)^{n-1}\right]\left[1-(1-p)^{m-1}\right]+p-[1-(1-p)^n][1-(1-p)^m] \\ &= p-p(1-p)^{n-1}-p(1-p)^{m-1}+p(2-p)(1-p)^{n+m-2} \\ &= p\left[1-(1-p)^{n-1}-(1-p)^{m-1}+(2-p)(1-p)^{n-1}(1-p)^{m-1}\right] \\ &\geq p\left[1-(1-p)^{n-1}-(1-p)^{m-1}+(1-p)^{n-1}(1-p)^{m-1}\right] \\ &= p\left[1-(1-p)^{n-1}\right]\left[1-(1-p)^{m-1}\right] \\ &\geq 0 \end{aligned} \tag{3}$$

where $P_1 > P_0$. So the stability of node-independent routing is higher than that of link-independent routing when public node is 1. When comparing the link stability with k public nodes, The stability comparison of two paths is shown as $f_k(p)$:

$$\begin{aligned}
f_k(p) &= P_k - P_0 \\
&= \left[1-(1-p)^{n-k}\right]\left[1-(1-p)^{m-k}\right] + kp - \left[1-(1-p)^{n-1}\right]\left[1-(1-p)^{m-1}\right] - p \\
&= p - p(1-p)^{n-k} - p(1-p)^{m-k} + [1-(1-p)^{2k-2}](1-p)^{n-k}(1-p)^{m-k} \\
&= p\left[1-(1-p)^{n-k} - (1-p)^{m-k} + 2(k-2) - C_{2k-2}^{2}p + C_{2k-2}^{3}p^2 - \cdots - p^{2k-3}\right] \\
&\geq p\left[1-(1-p)^{n-k} - (1-p)^{m-k} + (1-p)^{n-k}(1-p)^{m-k}\right] \\
&= p\left[1-(1-p)^{n-k}\right]\left[1-(1-p)^{m-k}\right] \\
&\geq 0
\end{aligned} \tag{4}$$

where $P_k > P_1 > P_0$. It can be seen that the more nodes are public, the less stable the link is, so node-independent routing has the better stability. Therefore, the multi-path routing algorithm proposed in this section will adopt the node-independent model.

2.2 The Model Construction of Network Topology

In intelligent power distribution network, the distribution network is composed of a number of local communication subnets. There are a lot of sensor nodes in every communication subnet. The wireless sensor nodes have formed a wireless sensor network in a local geographic area, using multiple hops links. The multiple wireless sensor networks are connected to form the whole intelligent power distribution network. We use V to express the set of nodes in intelligent distribution network communication network, E to express the set of communication paths, T to express the set of the delay weights in communication paths, R to express the set of reliability weights in links, Thus, the whole network can be described by one connected graph $G(V, E)$, which can express the communication effectiveness between nodes as Fig. 2 shows.

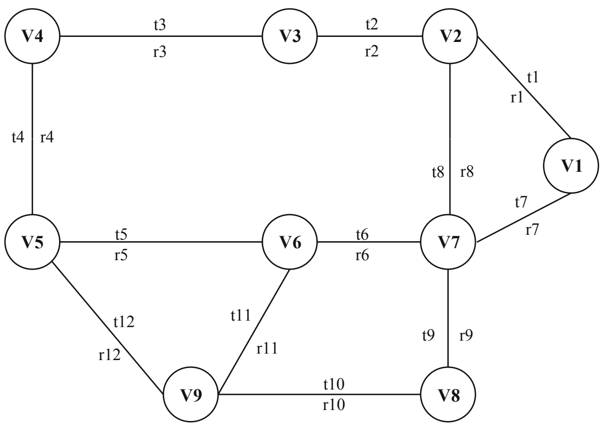


Fig. 2. The connected graph of intelligent power distribution network.

Meanwhile, an adjacency matrix can be denoted by $E = (e_{ij})_{N\times N}$ to express the availability between nodes, which can be formulated as:

$$e_{ij} = \begin{cases} 1 & (v_i, v_j) \in E \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where $e_{ij} = 1$ express there is a transmission link and $e_{ij} = 0$ means no available link. We define adjacency matrix $T = (t_{ij})_{N\times N}$ to express the delay weight of nodes as:

$$t_{ij} = \begin{cases} tw_{ij} & (v_i, v_j) \in E \\ \infty & \text{otherwise} \end{cases} \tag{6}$$

The reliability weights of links can be expressed as $R = (r_{ij})_{N\times N}$:

$$r_{ij} = \begin{cases} rw_{ij} & (v_i, v_j) \in E \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Considering in the power distribution network, there are strict requirements on reliability and real-time of data communication. Therefore, the analyses of alternative links for delay and reliability is necessary, so as to choose the link both satisfying the low latency and reliability for data transmission.

2.3 The Weight Analysis of Network Model

In the power distribution network, the communication delay between nodes mainly includes (1) path transmission delay; (2) node switching delay; (3) random jitter delay. The delay index between path nodes can be expressed as t_{ij}:

$$t_{ij} = \frac{A_{ij}}{c} + Bt_v + \Delta t \tag{8}$$

where t_{ij} represents the communication delay between nodes v_i and v_j, A_{ij} express the communication distance, c represents the data transmission rate, B represents the number of nodes passed between two nodes, t_v is denoted as the time consumed by node switching equipment, and Δt represents the random jitter delay.

The path can be regarded as a combination of links and nodes, so the delay weight value of the path T_{L_k} is the sum of the delay weight values of all nodes:

$$T_{L_k} = \sum_{i=1}^{n-1} \frac{l_{e_i}}{c} + nt_{v_i} + \Delta t \tag{9}$$

The link reliability r_{ij} of smart distribution network can be expressed as the average of network node availability over a period of time. The value of r_{ij} can be calculated from the data collected by the sensor:

$$r_{ij} = \frac{\mu}{\mu + \lambda} \tag{10}$$

where λ represents the failure rate and μ represents the repair rate. Then, the link reliability L_k of the path can be expressed as:

$$R_{L_k} = R_{v_n} \prod_{i=1}^{n-1} (R_{e_i} R_{v_i}) \tag{11}$$

where R_{L_k} represents the reliability value on path L_k; R_{v_n} represents the reliability value of the node n in path L_k; R_{v_i} represents the reliability value of the node i passing through path L_k, and n represents the number of nodes in path L_k. R_{e_i} represents the reliability value of the link i passing through the L_k.

2.4 The Path Selection Scheme

The congestion often occurs in the power communication network because of the sudden and unbalanced distribution of power services. Therefore, in order to reduce congestion, it is necessary to study routing strategies, optimize network resources and realize reasonable distribution of network traffic to ensure the performance of power communication network. Based on the analysis of the connectivity, delay, reliability and other parameters mentioned above, we can transform the path selection problem into the optimization problem, utilizing the directed connected graph theory. The objective function is Z:

$$Z = \min\left[\sum_{k \in K} AT_k + B\omega\right] \tag{12}$$

where:

$$T_k = \sum_{l=1}^{L_k} \frac{S_l}{c} \eta_{ij}^{kl} + nt_v + \Delta t \tag{13}$$

$$\eta_{ij}^{kl} = \{ {1 \atop 0} \tag{14}$$

$$L_k = \{ {1 \atop 2} \tag{15}$$

$$n = \sum_{(i,j) \in E} \eta_{ij}^{kl} \tag{16}$$

$$\omega = \max\left[\sum_{k=1}^{K} \sum_{l=1}^{L_k} \eta_{ij}^{kl} \lambda_k / C_{ij}\right] \tag{17}$$

The aim of the objective function is to find the minimum value of the latency and the maximum utilization of the traffic link. K represents the number of business requests in the network, T_k represents the sum of the delay of main path and alternative path in the k flow, S_l represents the length of path l, n is the number of nodes from node i to node j; ω represents the maximum link utilization rate, λ_k represents the traffic of the k flow, C_{ij} represents the link capacity, and A and B are two constant coefficients. There are other constraints including:

$$\sum_{j(i,j)\in E} \eta_{ij}^{k} - \sum_{j(i,j)\in E} \eta_{ji}^{k} = \begin{cases} 1 & k \in K, l \in L_k, i = s_k \\ -1 & k \in K, l \in L_k, i = t_k \\ 0 & k \in K, l \in L_k, i \neq s_k, t_k \end{cases} \tag{18}$$

$$\sum_{k\in K} \sum_{t\in L_k} \lambda_k \eta_{ij}^{kl} \leq C_{ij}\omega \quad (i,j) \in E \quad \omega \geq 0 \tag{19}$$

$$n = \sum_{(i,j)\in E} \eta_{ij}^{kl} \leq h_k \;\; k \in K \quad l \in L_k \tag{20}$$

$$\sum_{i\in S, j\notin S} \left(\eta_{ij}^{kl} + \eta_{ji}^{kl} \right) = 2 \quad \forall S \in N, S \notin \emptyset \tag{21}$$

The formula (18) represents flow conservation. Formula (19) represents the maximum link load constraint. Formula (20) represents the hop number constraint of the path l of k business flow. Formula (21) are reliability constraints.

It can be seen from the above mathematical model that the selection of communication path by the algorithm in this section is based on connectivity, delay, reliability and load balancing. In this paper, we use genetic algorithm to optimize the path-finding process to find the optimal path that meet the requirements.

3 Simulation Analysis

3.1 Simulation Environment and Parameters

The simulation environment of the routing algorithm are Matlab 2017a and Qualnet 2014. The 100 nodes in the network are randomly generated in the Qualnet simulator to establish the power distribution network. The transmission bandwidth of every link between two adjacent nodes is allocated 200 M. The network traffic distribution takes the normal distribution and generates randomly in the network. Then we connect the Qualnet with Matlab to obtain the dataset, where our weight-based routing (WBR) algorithm and other current main methods including minimum spanning tree algorithm (MST) and greedy algorithm (GRA) are carried out.

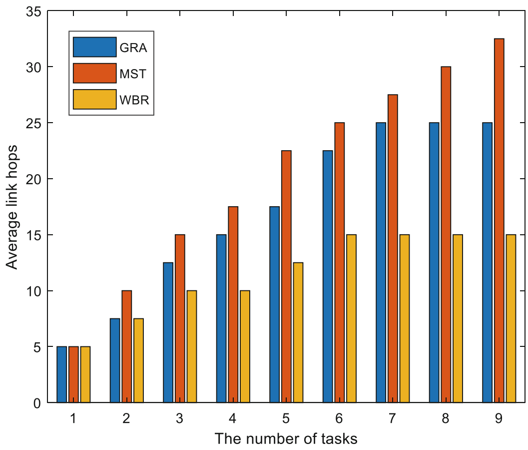


Fig. 3. The comparison of average link hops.

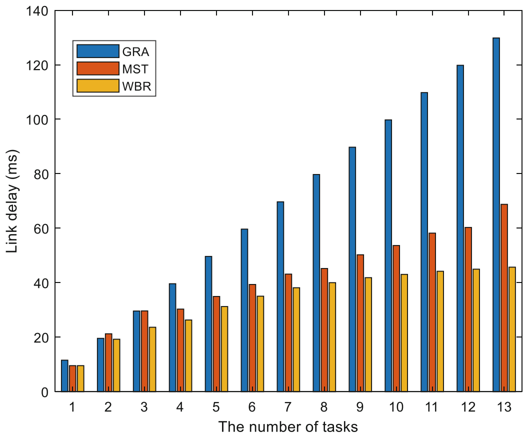


Fig. 4. The comparison of link delay.

The average link hops can reflect the network size and delay to some extent. Figure 3 shows the change of average link hops of three methods with the increase of the number of tasks. It can be seen that the MST As the number of tasks increases, the average link hops of the three methods also increase. The average link hop number of MST method is always the highest among the three kinds, followed by GRA. The WBR method is the least. This is because the network reliability is considered in link planning in WBR scheme. More hops will increase data packet loss rate and reduce network reliability. Therefore, the link in WBR scheme has fewer hops, which guarantees the quality of data transmission (Fig. 4).

Similarly, the link delay is measured for three methods with the increase of the number of tasks. It can be seen that the link delay is relatively low for three methods at the beginning. However, as the number of tasks increases, the link delay of GRA algorithm far exceeds the other two methods. This is because the GRA algorithm pursues the shortest path for data transmission, but does not consider the network load balancing. All data is transferred over fewer paths, overloading the node cache and causing maximum link latency.

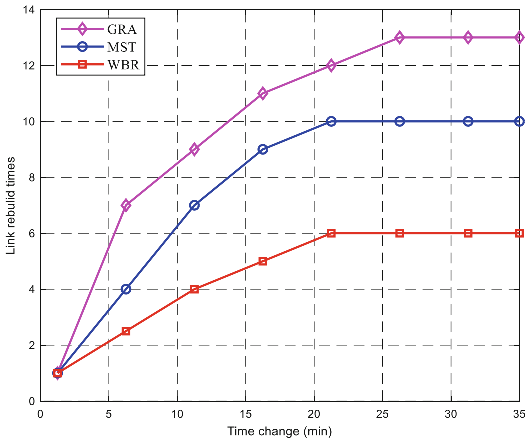


Fig. 5. The comparison of network availability.

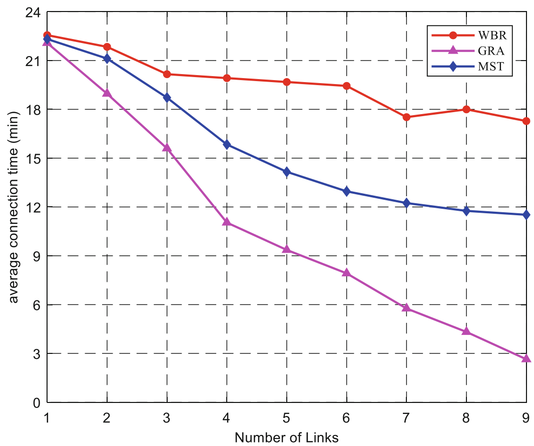


Fig. 6. The comparison of network robustness.

The stability of the network can be expressed by the availability and robustness of the network. Figures 5 and 6 respectively show the availability and robustness of the network. From the two figures, we can find that the link rebuild time of WBR is the smallest of three methods. This is because the reliability is served as one parameter to guide the link deployment. Meanwhile, the average connection time of WBR is the longest of the three methods, which shows a good network robustness.

From the analysis above, we can find that the proposed routing scheme has better performance in link delay and network availability and robustness, which will also realize the load balance of the whole network.

4 Conclusion

In this paper, a weight graph based routing scheme is proposed to improve the performance of delay and availability in smart power distribution network. The routing planning problem is changed to an optimization problem to carry out link selection. Simulation results show that compared with other methods, the proposed algorithm can effectively improve the network performance.

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