A Relay Station Deployment Algorithm for Smart Grid Based on Delay Optimization

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Abstract. Power line communication (PLC) technology can make full use of the existing distribution network physical network for data transmission in smart grid, with low cost, flexibility, high coverage, network reliability advantages. In order to extend the communication distance of PLC network and improve the reliability of network, it is necessary to research the networking and deployment methods of PLC network and establish a reasonable optimization model for different environments and business requirements. Therefore, in order to solve the problem of PLC relay deployment under the business scenario of power communication network, this paper proposes an algorithm of PLC network relay station deployment for time delay optimization. The graph theory is used to describe and define the reliability of the network. In order to reduce time delay, the reliability and transmission power are defined as constraints. The mathematical model of relay station deployment is proposed. The improved genetic algorithm is designed and the relay station deployment algorithm based on the improved genetic algorithm is proposed. The performance of the algorithm is verified by simulation results.

Keywords: Power line communication · Smart grid · Relay station

1 Introduction

The power distribution and utilization communication network mainly completes special-purpose user acquisition (i.e. load control system), residential user acquisition, line monitoring, distribution automation and other services [1–4]. At present, a hybrid network with a wireless public network as the main solution and a combination of optical fiber and wireless private network is generally adopted as a secondary solution [5–8]. However, the current wired optical fiber and wireless transmission methods have certain limitations, and cannot meet the “full coverage, full acquisition” requirements of the power collection service [9–13].

It is a common practice for multi-city power companies to lease GPRS wireless public network to carry out electricity distribution business. Due to the mature

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development of the wireless public network, the leased public network channel has the advantages of less initial investment and short construction period, which can meet the requirements of rapid deployment and business development of the distribution service [12–15]. However, with the large-scale development of power distribution services, the commonly used GPRS wireless public network has gradually exposed many problems, such as low acquisition success rate, low controllability, reliability, and real-time performance, no priority for different power services and so on.

The fiber optic private network has a high cost and long construction period. The wireless private network has high investment, complicated deployment, and limited frequency resources, if the total number of dedicated base stations required to achieve full coverage is large [2–5]. Therefore, at present, the integration of wireless private network and wired private network is adopted in most areas to deploy power distribution services. The architecture is shown as Fig. 1.

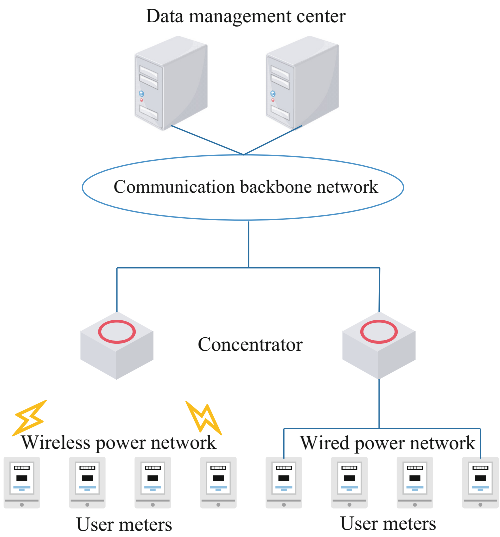

Fig. 1. Wireless and wired power private network architecture.

PLC technology can make full use of the physical network of the existing distribution network for data transmission, is a common communication technology in the distribution network. In this section, the PLC network networking and deployment method under the scenario of distribution power communication network is studied [8–11]. The main problem to be solved is to expand the communication range of PLC network, improve the reliability of network, and ensure that the time delay requirements of distribution power communication network are met [12–15].

In this paper, considering the characteristics of PLC relay network routing, network reliability, delay characteristics and channel characteristics of PLC and other factors, a PLC relay station deployment algorithm for delay optimization is designed. Under the scheme of selecting the relay station, the network routing selection will also be determined, and the average transmission delay, reliability, average transmission energy and other indicators will change accordingly. The relay station selection scheme is proposed as chromosome coding sequence, the performance index of the corresponding network after the relay station deployment is abstracted as multi-objective deployment model, and the optimal chromosome is selected by improved genetic algorithm to obtain the final relay station deployment scheme.

2 PLC Relay Station Deployment for Delay Optimization

2.1 PLC Network Model

The PLC power communication network model is shown as Fig. 2. PLC data relay terminals in the network need to transmit the collected data to the upper control center, which will transmit the control information to each data terminal in the network through the same path. PLC network consists of data terminal and relay station. Data terminal refers to the communication node of PLC network, which is connected with the collection terminal of smart grid to collect and transmit the information of distribution communication network. Relay stations are data terminals with relay functions. On the one hand, they assume the functions of data terminals in the covered area; on the other hand, they forward the transmitted data on the data terminals with relay connection to the control center. Answer points apply the hierarchical idea, that is, the network is divided into multiple levels, the lower data terminals communicate directly with the upper answer points, and the answer points interact with the control center for data. All data terminals and relay stations in the PLC network can be coordinated two-way data exchange, without the control of the upper control center.

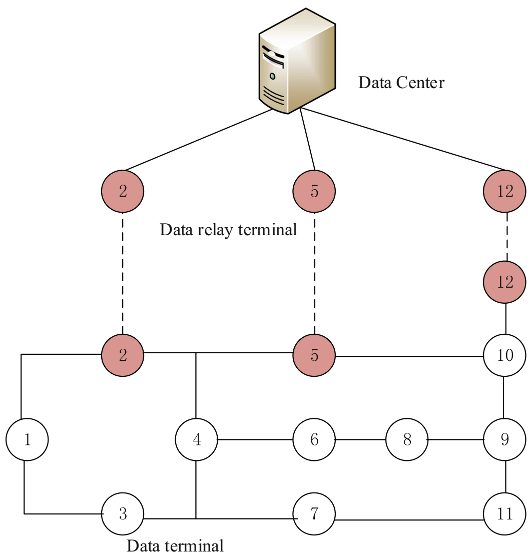

Fig. 2. PLC power communication network model.

2.2 Relay Station Deployment Model

The PLC network in this section is represented by undirected graph $G(V, L)$, where the vertices represent each communication node and the edges represent the communication links between nodes. Define the total number of all nodes in the PLC network as N. Set Q represents the vertex set of data terminal, set S represents the vertex set of relay station, and its relationship is as follows:

$$q \in Q \subseteq V, s \in S \subseteq V, Q \cup S = V \tag{1}$$

Define the set of all communication links in PLC network as L, and the set of routing from all data terminals to all relay stations as L_0. $L_{e,r}$ represents the routing set from data terminal e to relay station r, and the following formula can be obtained:

$$L_{e,r} \subseteq L_0 \tag{2}$$

We define $L_h = \{l_1, l_2, \ldots, l_n\}$ to represent the route from data terminal q to relay station s, and the route length is n, then we can get:

$$L_h \in L_{e,r} \tag{3}$$

Reliability of PLC Network. We define $b_{e,r}$ P as the reliability of route L_h, and the reliability of route is the reliability product of each link constituting the route:

$$b_{e,r} = \prod_{I \in p_h} b_I \tag{4}$$

The network consists of N routes. The reliability of the network is the average of the N routes. At the same time, the reliability of the data terminal link where the relay station is located is 1. The definition parameter $a_{e,r}$ represents the routing selection. When $a_{e,r} = 1$, route L_h is selected. When $a_{e,r} = 0$, route L_h is not selected. The number of relay stations is defined as M, and the proportion of network optional relay stations is determined by parameter α, which is related to the maximum number of hops allowed by the network. From the above parameters, the reliability of PLC network is expressed as:

$$R = \frac{1}{N}\sum_{e=1}^{N}\sum_{r=1}^{M} b_{e,r} \cdot a_{e,r}, l_h \in L_{e.r} \subseteq L_0 \tag{5}$$

In order to ensure that each data terminal belongs to only one relay station and there is only one route between it and the relay station, the following constraints are proposed:

$$\sum_{r=1}^{M} a_{e,r} = 1, \forall q \in Q \tag{6}$$

Link Quality. We measure link quality using link maximum transmission speed. Link quality parameters describe the transmission quality of PLC network links, the higher the link quality, the smaller the transmission delay. Under the same physical parameters such as transmission frequency and bandwidth, the link quality is affected by the transmitted signal power at the sending end, and the transmitted power will affect the average transmission energy of the link and network. We define i is the data terminal number of link sender and j is the data terminal number of link receiver. The channel capacity of link $T_{i,j}$ is defined as:

$$C_{i,j} = \int_{B_1}^{B_2} \log_2\left(1 + \frac{L_{i,j}\left|H_{i,j}(f)\right|^2}{(B_2 - B_1)N(f)\Gamma}\right) df \tag{7}$$

In formula (7), B_1 and B_2 are the lowest and highest values of channel frequency band respectively. $T_{i,j}$ is the signal transmission power from node i to node j, $N(f)$ is the channel noise, Γ is the fixed ratio between the channel capacity and the achievable rate, which is related to the channel SNR, encoding and modulation mode. $H_{i,j}(f)$ is the frequency response of link $T_{i,j}$. In the same PLC network, the link channel has the characteristics of flat fading, and the link quality function $M_{i,j}$ of PLC is defined as the maximum channel capacity:

$$M_{i,j} = C_{i,j}(L_{i,j\max}) \tag{8}$$

Where, $L_{i,j\max}$ is the maximum signal transmitting power of link $T_{i,j}$.

Transmission Delay. Assuming that there are N routes in the PLC network, the transmission delay T_a of the average single node in the network and the energy E_a of average transmission data of each node in the network are respectively expressed as:

$$T_a = \frac{1}{N}\sum_{e=1}^{N} T_{er} \quad E_a = \frac{1}{N}\sum_{e=1}^{N} E_{er} \tag{9}$$

Where T_{er} is the total transmission delay and E_{er} is the total transmission energy.

Based on the above conclusions, if the threshold of network average reliability is φ and the threshold of network average transmission energy is ψ, the mathematical model of relay station deployment target and constraint conditions can be obtained, as shown in formula (10):

$$\min T_a = \frac{1}{N}\sum_{e=1}^{N}\sum_{r=1}^{M} T_{e,r} \cdot w_r$$

$$s.t.\begin{cases} R = \frac{1}{N}\sum_{e=1}^{N}\sum_{r=1}^{M} b_{e,r} \cdot a_{e,r} \geq \varphi \\ \sum_{r=1}^{M} a_{e,r} = 1, \forall q \in Q \\ E_a = \frac{1}{N}\sum_{e=1}^{N} E_{er} \leq \psi \\ M \leq \alpha \cdot N \end{cases} \quad (10)$$

The problem of relay station deployment belongs to NP hard problem, and heuristic algorithm is a common method to solve this kind of problem. Among heuristic algorithms, genetic algorithm is a common algorithm to solve network deployment problems because of its simple implementation and strong adaptability to multi-objective optimization problems. However, genetic algorithm is prone to fall into the local optimal solution, and the local search ability is not good after the population evolution approaches the optimal interval. In order to solve these problems, the selection, crossover and mutation operations are optimized in this section, and an improved genetic algorithm is designed, which not only improved the genetic diversity of the population at the early iteration stage, but also reduced the degree of change to the excellent genes at the later stage. The flow chart is as follows:

3 Simulation

In order to verify the effectiveness of relay station deployment algorithm, Matlab is used to carry out simulation experiments on PLC network with at least 20 nodes. The link reliability is randomly selected within the range of [0.9, 0.99], and the initial value of network reliability threshold φ is set as 0.9. In the simulation, 0.01 is added to 0.99 at a time. The maximum proportion of nodes occupied by relay stations $\alpha = 0.3$. The size of a single packet is 200bit, and the data generated by the node obeys the $\lambda = 1p/s$ Poisson distribution. The transmitting power of each node's uplink is between 10 mW and 20 mW, and the average transmission energy threshold ψ of the network is up to 39 mJ. Channel noise is Gaussian white noise, $\Gamma = 10$. Population size is 100 and maximum evolutionary algebra is 300, and the chromosome length is set as 20. Maximum crossover probability L_c and maximum mutation probability L_m are 0.6 and 0.2 respectively. Minimum crossover probability L_{cm} and minimum mutation probability L_{mm} are 0.2 and 0.02, respectively (Fig. 3).

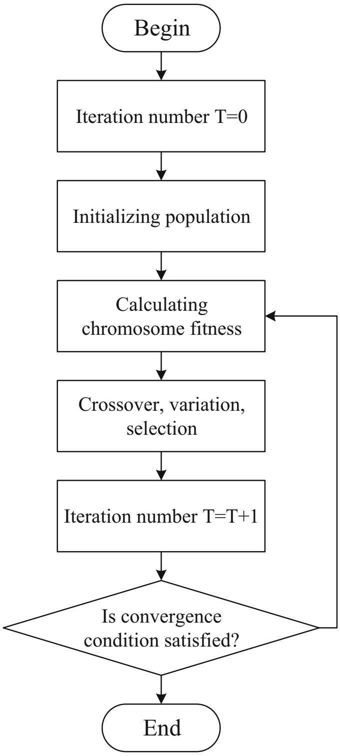

Fig. 3. The flow chart of relay station deployment based on genetic algorithm.

Figure 4 verifies the relationship between network reliability and the number of network relays. As known from Fig. 4, with the increase of network reliability, the number of relay stations increases significantly when the energy threshold restriction is not done. However, when the network reliability exceeds 0.97, the number of network relay stations increases slowly, which becomes obvious with the increase of network scale. Therefore, it is not necessary to deploy a large number of relay nodes in pursuit of high network reliability.

Figure 5 shows the relationship between network reliability and network transmission delay. With the increase of reliability, the transmission delay of the network decreases obviously. This is because the reliability is affected by the distribution of relay stations. The more the number of relay stations, the stronger the network reliability and the lower the network transmission delay. When the network reliability increases above 0.98, the change of transmission delay is no longer obvious, which is more obvious with the increase of network size.

Figure 6 shows the change curve of transmission delay with network transmission energy under the condition that the maximum threshold of network average transmission energy is 39 mJ and the network reliability requirement is 0.95, 0.96 and 0.97, respectively. As can be seen from Fig. 6, with the increase of transmission energy threshold, in order to reduce the average transmission delay of the network, the links

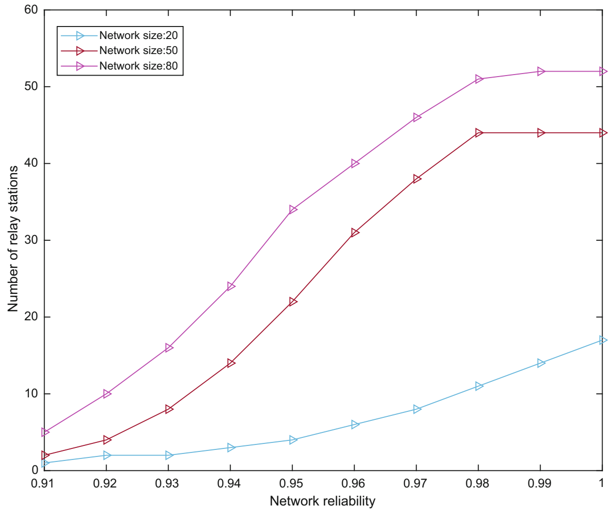

Fig. 4. Relay station numbers change.

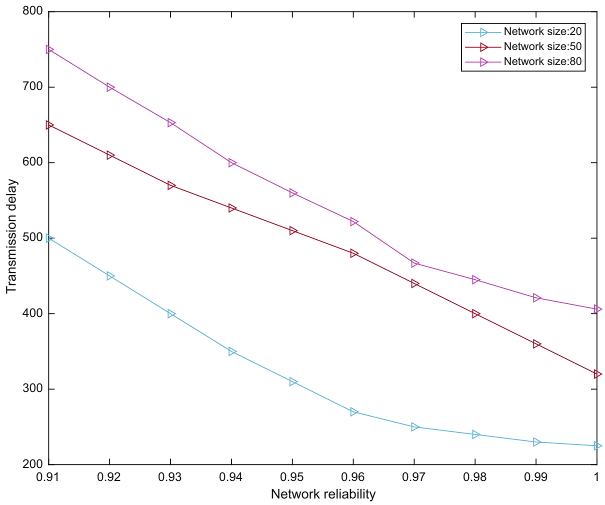

Fig. 5. Transmission delay change.

corresponding to the stations with high transmission power are more selected, and the link uplink node is selected as the relay station with a greater probability, thus significantly reducing the transmission delay of the network. The greater the reliability, the smaller the influence of transmission energy on the average network delay. When the transmission energy threshold is large, the improvement effect of the increase of transmission energy on the transmission delay decreases gradually. This is because when the reliability is improved to a certain extent, the quality of the relaying route

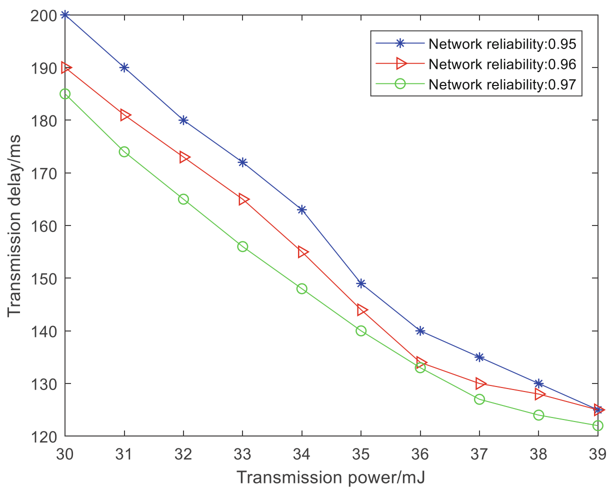

Fig. 6. Transmission power change.

corresponding to the link in the network is generally higher with the limitation of energy threshold, and the influence of the relay station selection result on the delay will be weakened.

Above all, simulation results show that the proposed relay station deployment results under different network environments can be obtained effectively. By deploying the relay station in a reasonable location, the network can meet the limitation of reliability and improve the network transmission delay.

4 Conclusion

The construction of smart grid needs to develop and optimize the deployment and scheduling methods of communication network. In this paper, the deployment and optimization methods of PLC network in smart grid are studied, and a relay station deployment algorithm based on delay optimization is proposed. Simulation results show that our algorithm can well guide the deployment of PLC network relay points and help develop a reliable, efficient, safe and friendly smart grid and its communication network.

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