Research of the Inspection Optimization Strategy for Distribution Network Based on Comprehensive Information Model

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Abstract. To improve the quality and efficiency of inspection tasks, this paper studies the path planning optimization strategy for distribution equipment inspection of distribution networks. The comprehensive information model of each type of distribution equipment to be inspected is established by integrating the real-time monitoring information, geographic information and historic information effectively. The inspection path optimization model with an admissible cost function is established and solved by using the heuristic search A* algorithm. Comparison of the results of several inspection path planning strategies are provided to verify the effectiveness of the proposed strategy.

1. Introduction
The inspection of distribution devices plays an important role in detecting equipment defects and failures in time, evaluating the status of a distribution network and improving the reliability and quality of power supply [1, 2]. Traditionally, the inspection path of several distribution devices involved in an inspection task is planned by the inspection crew based on their familiarity with the status and geographical locations of feeder lines and distribution equipment, which may be rewarded by inadequate and low efficient inspection for great randomness and subjectivity [3-5].

In order to tackle out this difficult task, many researchers have begun to study the inspection planning strategy for distribution devices by exploring recent theoretical and technical achievements in the field of Internet of Things (IoT) and big data [6, 7]. Reference [8] has proposed an intelligent inspection strategy for 10-kV power lines by introducing fuzzy clustering analysis method. Starting from the actual situation and daily inspection issues of distribution networks, reference [9] developed an intelligent inspection system by effectively integrating several information systems including GIS (Geographical Information System), GPS (Global Positioning System), SCADA (Supervisory Control and Data Acquisition) and GPRS (General Packet Radio Service). However, the optimization of the inspection path has not been fully considered in current researches.

Currently, path planning technology has emerged to be a promising research issue in the field of logistics [10, 11]. The development of optimal operation and maintenance strategy for unattended...
substation has been modeled as vehicle routing problem (VRP) in [12]. Reference [13] analyzed the laws of several factors in governing the performance of inspection schemes. The problem of inspection planning of a medium voltage distribution network has been formulated as an inspection path optimization model that was solved by genetic algorithm. Unfortunately, the practicalities of these strategies are not satisfying since that information on the current status of distribution equipment are usually not incorporated in their model formulation.

This paper presents a novel inspection path optimization strategy with the aim to improve the quality and efficiency of inspection tasks of distribution networks. The major innovation of this paper is as follows: 1) the established comprehensive information model can effectively integrate the real-time monitoring information, geographic information and historic information of the devices to be inspected, thereby overwhelming current path planning methods that only consider the geographic information of the inspection task; 2) a cost function that satisfies the acceptable condition of A* algorithm is formulated elaborately, thus facilitating the searching of the optimal path when employing the A* algorithm.

The remainder of this paper is structured as follow: Section 2 presents the comprehensive information models of several types of distribution devices. The path optimization model for distribution equipment inspection is formulated in Section 3, and the solution based on heuristic search A* algorithm is also presented in this section. Simulation results verifying the effectiveness of the proposed method are provided in Section 4. Finally in Section 5, the main findings of the paper are summarized.

2. Comprehensive information model of distribution devices

The wide application and rapid development of cross-discipline technology including IoT, GPS and GIS system, mobile communication and intelligent terminal devices provide us a better opportunity to access to more accurate and timely information of distribution devices. Accordingly, we utilize the real-time monitoring information and geographic information along with the historic information to construct a comprehensive information model of a distribution device, which is the foundation in developing our inspection path optimization strategy.

2.1. Historical Information Model

Historical Information reflect the historical operation status of a distribution device including service time, historical defect and failure, maintenance and test result and so on.

In this paper, we use an index \( H_b \) called equipment historical health to represent the historical status of a distribution device. The value of \( H_b \) ranges from 0 to 100 and has a positive correlation with the historical status of the equipment, i.e., a lower value of \( H_b \) means a poorer operation status of an equipment, and in turn a greater probability of failure. \( H_b \) is calculated by:

\[
\begin{align*}
H_b & \leq 90, \text{ high failure rate} \\
85 \leq H_b < 90, \text{ middle failure rate} \\
H_b < 85, \text{ low failure rate}
\end{align*}
\]

Normally, the failure rate of a distribution device over its lifetime can be expressed in a form of Weibull distribution as:

\[
\lambda(t) = \begin{cases} 
\lambda_c t^{(\beta-1)} & t < t_1 \\
\lambda_c t^{(1-\beta)} & t_1 \leq t \leq t_2 \\
\lambda_c t^{(1-\beta)} & t > t_2 
\end{cases}
\]  \hspace{1cm} (1)

where \( \beta \) is the exponential coefficients and \( \beta=0.5 \) is preferred in this paper; \( t_1 \) and \( t_2 \) is respectively the commissioning and retire time of the distribution device, which can be obtained from the statistic
results of devices with the same type; \( \lambda_c \) is the commonly used equipment failure rate (times/year) and the values of \( \lambda_c \) of several types of main circuit equipment of a distribution network are summarized in Table 1 [14].

| Device type          | \( \lambda_c \) (times/year) |
|----------------------|-------------------------------|
| Distribution transformer | 0.042                        |
| Switch cabinet        | 0.030                         |
| Power supply cable    | 0.015                         |
| Overhead line         | 0.025                         |

In addition to the factors related to the equipment itself, meteorology factors such as wind and thunderstorm, and the environment in which the equipment locates also have a great influence on the failure rate. Considering this fact, the \( H_b \) of a distribution equipment can be theoretically calculated by:

\[
H_b = K_D \left( 100(1 - \lambda(t)) - K_E \right)
\]  

Where \( K_D \) is a coefficient reflecting the influence of a historic defect on the health condition of the equipment, and for an equipment without defect, \( K_D = 1 \), otherwise \( K_D = 0.95 \). Coefficient \( K_E \) is used to represent the comprehensive impacts of multiple external factors on the operation status of the equipment. In this paper, \( K_E \) is the average failure number of the equipment during the same period of time as the inspection to be performed over the past five years.

2.2. Real-Time State Model

The real-time operation state of a distribution equipment is also closely related to the probability of failure occurrence [15, 16]. We use an index \( H_c \) called real-time health to reflect the real-time status of a distribution device, and similarly, the value of \( H_c \) is in the range of 0-100 and it is positively correlated with the current status of the equipment. \( H_c \) is calculated by:

\[
\begin{align*}
85 \leq H_c & \leq 100, \text{ normal state} \\
75 \leq H_c & < 85, \text{ state to be pay attention to} \\
65 \leq H_c & < 75, \text{ abnormal state} \\
H_c & < 65, \text{ serious state}
\end{align*}
\]  

The specific scoring method can refer to relevant specifications, e.g. Q/GDW 645-2011 "Distribution network equipment status evaluation guidelines" promulgated by the State Grid of China. The state information of each component of a distribution equipment can be obtained by means of on-line monitoring and mobile inspection, and the health index of an element can be determined by:

\[
\begin{align*}
M_p &= m_p \cdot K_F \cdot K_T \\
K_T &= \frac{100 - T_p \cdot \alpha}{100}
\end{align*}
\]  

Where \( M_p \) and \( m_p \) is respectively the health index and base score of component \( p \) of an equipment; \( K_F \) is the component defect coefficient, and for defect-free component, \( K_F = 1 \), otherwise \( K_F = 0.95 \); \( K_T \) is
the life coefficient and $T_p$ is the in-service time of component $p$; $\alpha \in [0, 1]$ is the service age reduction factor.

Therefore, the health index $H_c$ of a distribution equipment is the weighted sum of the health indexes of its components, that is:

$$H_c = \begin{cases} \min M_p, & \exists M_p \leq 85 \\ \sum_{p=1}^{n} K_p M_p, & \forall M_p > 85 \end{cases}$$  \hfill (5)

Where $M_p$ and $K_p$ is respectively the health index and the weight coefficient of component $p$, and $n$ is the total number of the components.

2.3. Geographic Information Model

The geographic information of a distribution network is mainly composed of the spatial positioning data of its equipment, specifically, the geographical location information of substations, transformers, circuit breakers, isolation switches, poles, feeder lines, electricity consumers and so on, represented by geographical coordinates in a geographical map [17]. Combined with real-time traffic map, the geographic relation between the starting point of an inspection task and all the devices to be inspected can be expressed by a geographical distance matrix $D_{n+1}$ as:

$$D_{n+1} = \begin{bmatrix}
0 & d_{12} & \cdots & d_{1(n+1)} \\
d_{21} & \ddots & \vdots & \vdots \\
\vdots & \ddots & \ddots & d_{n(n+1)} \\
d_{(n+1)1} & \cdots & d_{(n+1)n} & 0
\end{bmatrix}$$  \hfill (6)

Where $d_{ij}$ represents the shortest vehicle travel distance between device $i$ and $j$, and $d_{ij}=\infty$ if there is no inspection pathway between these two devices. We use subscript ‘1’ to represent the inspection starting point.

3. Inspection path optimization based on A* algorithm

3.1. Optimization goal and basic assumptions

Taking the distribution network shown in Figure 1. As an example, the optimization of the inspection strategy of this distribution network is to find a path that starts from the operation and maintenance base ▭ and can traverse all the equipment including distribution transformer ♂, ring cabinet/switchgear ◇, cable ○ and overhead line ◊ and at the same time minimizes the cost involved in the inspection task.
Traditional inspection path planning is highly dependent on the experience of inspection staff. Obviously, this way is of great randomness and subjectivity since that real time status of the equipment and real time traffic condition are not fully considered. To overcome this shortcoming, we propose a path optimization strategy for distribution network inspection, and the principle of the method is shown in Figure 2.

The task analysis module determines the set of equipment and area of distribution network to be inspected by parsing the assigned inspection task. While the path optimization strategy indicates the optimal path for inspection according to the comprehensive information models of the equipment involved in the task.

We take the following basic assumptions in formally formulate our inspection path optimization model:

1) There is only one operation and maintenance base, and it should be both the starting and ending point of an inspection path;
2) The inspection task is assigned by a superior such as the distribution network operator, and the information of the equipment to be inspected are known ahead;
3) Cable and overhead line segment to be inspected is also treated as a point in a path, and its distance to other equipment is determined on the basis of the segment ending point;
4) For two (or more) connected devices, for example a switch cabinet and the line segment it connects to, they are treated as one equivalent device of which the health index is the smaller one of the connected devices;
5) Abnormal traffic conditions such as congestions and roadwork are not considered.
3.2. Path optimization strategy

We employ the heuristic search A* algorithm to solve the path optimization model. This algorithm, after several years of development and improvement, is recognized as the most effective algorithm in solving the problem of optimal path searching [18-20]. The core idea of A* algorithm is to evaluate the costs of the routes from nodes to be expanded to the target node, and then give preference to route with the lowest cost to decrease the number of the nodes to expand, thereby reducing the complexity of the algorithm. For a node \( v_m \), its cost function \( f(m) \) is usually defined as:

\[
f(m) = g(m) + h(m)
\]

(7)

Where \( g(m) \) is the cost associated with the travelling from source node to node \( v_m \), and \( h(m) \) is the cost associated with the travelling from node \( v_m \) to the target node.

The admissible condition for A* algorithm is:

\[
h(m) \leq h'(m)
\]

(8)

Where \( h'(m) \) is the actual cost spent in travelling form node \( v_m \) to the destination node.

It has been proven mathematically [18] that if the admissible condition (8) are satisfied for all the evaluated costs \( h(m) \), then the searching result of the A* algorithm is admissible, namely, the obtained path is the optimal solution that has the lowest cost.

Considering the historic information, real time status and geographic information of a distribution equipment, we propose a concept of “inspection cost” to design the cost function of the path optimization model. The inspection cost associated with the path between the maintenance base and \( n \) equipment to be inspected can be expressed as:

\[
C(n+1) = \begin{bmatrix}
0 & c_{12} & \cdots & c_{1(n+1)} \\
c_{21} & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & c_{n(n+1)} \\
c_{(n+1)1} & \cdots & c_{(n+1)n} & 0
\end{bmatrix}
\]

\[
c_{ij} = \frac{\omega_b H_{bij} + \omega_c H_{cij}}{100} d_{ij}
\]

(9)

Where: \( c_{ij} \) is inspection cost associated with the path from equipment \( i \) to \( j \). \( H_{bij} \) and \( H_{cij} \) is respectively the historical health index and real-time health index of equipment \( j \). \( \omega_b \) and \( \omega_c \) is the weighting the historical information and real-time status, where \( \omega_b + \omega_c = 1 \).

We can learn from formula (10) that, a device with smaller values of \( H_{bij} \) and \( H_{cij} \) (i.e. worse historical and real-time status) and shorter geographic distances to the devices that have been inspected is more likely to be expanded in the inspection path.

In order to satisfy the acceptable condition of A* algorithm, we construct a cost function for a certain inspection path as:
\[
\begin{align*}
    f(m) &= g(m) + h(m) \\
    g(m) &= C(1, m) \\
    h(m) &= (n+1-m) \cdot \min c
\end{align*}
\]

(10)

Where \( m \) is index of the last inspected device; \( C(1,m) \) is the total inspection cost associated with the route from the inspection base to equipment \( m \) along the examined path; \((n+1-m)\) indicates the number of remaining routes; \( \min c \) is the minimum value of all inspection costs with non-zero values. Obviously, \( h(m) \) in formula (10) satisfies the admissible condition formula (8).

Figure 3. Illustrates the implementation of our inspection path optimization strategy based on A* algorithm. Table Open is used to store the path to be extended, while the current optimal path is stored in table CLOSED.

**Figure 3.** Flow chart of the path optimization algorithm.
4. Simulation verification

4.1. Simulation model

We consider the inspection task of a distribution network shown in Figure 4. This task involves the inspection of eight distribution devices dispersedly located in the network. The distance between two adjacent devices is marked beside the corresponding route. The proposed path optimization strategy is coded in MATLAB software.

![Figure 4. Locations of distribution equipment to be inspected.](image)

Table 2 lists the health indices of each device, and we can learn that equipment 5 is the one with the highest operation risk since that its $H_c$ is only 60.

| Devices | $H_b$ | $H_c$ |
|---------|-------|-------|
| 2       | 90    | 90    |
| 3       | 98    | 95    |
| 4       | 90    | 95    |
| 5       | 95    | 60    |
| 6       | 86    | 80    |
| 7       | 90    | 85    |
| 8       | 95    | 90    |
| 9       | 99    | 98    |

4.2. Path planning result comparison

The path planning result of our strategy (strategy 3) is compared with those of two traditional methods (strategy 1 and 2).

Strategy 1: Path planning based on human experience. In this method, the inspection staff tend to choose the device that has the shortest distance from their current position as the next one to be inspected. Thus for the inspection task shown in Fig. 4, the final inspection path is $[1-9-8-7-6-5-4-3-2-1]$, and the total inspection distance is 32.8km.

Strategy 2: Path planning based on device real time status. The principle of this method is to give higher inspection priority to devices with a lower value of health index $H_c$. According to Table 2, the final result of this strategy is the path $[1-9-8-7-6-5-4-3-2-1]$, and the total inspection distance is 35.4km.

Strategy 3: Path planning based on comprehensive information model. Figure 5. Shows the inspection cost of two adjacent devices for $\omega_b=0.2$ and $\omega_c=0.8$. 
By using our proposed inspection path optimization strategy, the optimal path is [1-5-6-4-3-2-9-8-7-1], and the total inspection distance is 30km.

Table 3 summarizes the results of the three path planning methods.

We can learn from Table 3 that the inspection path for our strategy is of the shortest total distance of 30km, which saves 9.33% and 18% of the inspection cost, as compared with strategy 1 and 2. Meanwhile, distribution device 5, which is of the worst health condition, is the first equipment to be inspected for our strategy and strategy 2, thus effectively tackling out the problems of randomness and subjectivity of strategy 1 in planning the inspection path.

These simulation results prove that our strategy can effectively incorporate different types of information of the devices into the inspection path planning, and it has better comprehensive performances in term of inspection quality and efficiency.

**Table 3.** Comparison of three path planning strategies.

| Strategy | Total inspection distance (km) | Inspection sequence of device 5 |
|----------|--------------------------------|---------------------------------|
| 1        | 32.8                           | 5                               |
| 2        | 35.4                           | 1                               |
| 3        | 30                             | 1                               |

5. Conclusion

This paper presents a novel strategy to optimize the inspection path in fulfilling inspection tasks of distribution networks. Comprehensive information models of different kinds of distribution equipment are developed to incorporate the real-time monitoring information, geographic information and historic information of the devices to be inspected into the inspection path optimization. The path optimization model with a special designed cost function is solved by using the heuristic search A* algorithm. Simulation results prove that the proposed strategy can tackling out the problems of randomness and subjectivity of current inspection strategy and at the same time improve the inspection efficiency.

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