Research into Power Distribution Network Condition Evaluation Method Based on Equipment Health Index

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Abstract. To evaluate the health status of the power distribution network is of vital importance to condition-based maintenance of the power distribution network. By studying the power distribution network health condition using the theory of health index (HI), this paper proposes a method to evaluate the power distribution network health condition based on the equipment health index. To start with, the power distribution network health index model is built so as to ensure reliable and sustainable power supply for users. Meanwhile, the network equivalent method and the goal-oriented (GO) method in reliability analysis are employed to analyze and solve the model. Second, the existing equipment health index is used to work out the network health index, and examine the weak link of the power distribution network. Finally, the model is verified in the IEEE RBTS-Bus 2 Feeder Line 4 structure through simulation, and results suggest that this method is highly logical and convenient to realize computer programming, thus it can provide a viable plan for quantitative evaluation of the power distribution network health condition.

Introduction

Previously, indexes of reliability analysis were usually used to evaluate the power distribution network. Nevertheless, reliability analysis excessively relies on historical fault statistics of components. The lagging fault data and the basis provided by overall statistics of equipment of the same kind can hardly reflect performance attenuation within the valid service life of single equipment. Inspired by the health evaluation of the human body, the health diagnosis theory with power grid equipment's real-time performance condition as the evaluation basis has been gradually introduced to the electric system, gradually demonstrating its advantages in electric maintenance and planning. In 2003, Hughes first developed the concept of "health index", which represents the equipment's real-time health condition by quantitatively evaluating the object's health degree via the specific number [1]. Compared with the traditional reliability analysis, the theory of health diagnosis outperforms in accuracy and instantaneity.

So far, the concept of electric system health diagnosis has been widely discussed. According to flow fingerprint characteristics, Literature [2] puts forward the preliminary diagnosis method for the power distribution system. In Literature [3], the electric transformer remaining service life evaluation method based on the health index heavily relies on the duration of operation, thus ignoring, to some extent, the practical operation condition. On the whole, researchers mostly concentrate on studying the health condition diagnosis of primary equipment with a higher voltage grade, but little research attention is paid to health diagnosis of the low-voltage equipment and network of the power distribution system.

Because of the extensive existence and low cost of power distribution equipment, the equipment detection and evaluation, condition-based maintenance standards and decision-making methods adopted by the power transmission network might not be applicable to the power distribution network. Therefore, it has become an imperative to build the health diagnosis model specifically for the power distribution network, which makes full use of various equipment indexes to objectively reflect the power grid health condition and provide valid theoretical basis for formulation of power distribution

condition-based maintenance strategies. Literature [4] screens out a series of indexes from the perspective of power grid integrated operation to measure the health condition of the complex power distribution network. Since the evaluation indexes cannot directly reflect the health condition of the power grid's equipment group, these indexes cannot yet provide reliable theoretical basis for the power grid condition-based maintenance.

Comprehensively taking into account characteristics and condition of the power distribution network, this paper focuses on connectivity analysis and divides the network into feeder line elements for layer-by-layer processing. The network equivalent method is used to realize equivalent processing upward from the bottom layer, and the equipment health index is mapped as the successful operation probability to facilitate computing of the network health index. Finally, simulation analysis is conducted of the IEEE RBTS-Bus 2 Feeder Line 4 structure to verify the feasibility and accurateness of this method. In addition, the existing equipment health index is used to work out the network health index to find out weak links of the power distribution network, and ensure a better combination with the condition-based maintenance of the power distribution network.

Health Index Theory

The electric equipment health index is not a simple substitution for professional engineering knowledge and judgment but a numerical value, which is obtained through complex logic and mathematical operations based on the object's characteristic parameters to measure and represent the health condition of a research object (single equipment), and the electric equipment health index quantitatively evaluates every equipment's health degree using numbers from 0 to 10 [5]. The electric equipment health index proposed by the British EA company is written as below:

$$\text{HI} = HI_0 \times e^{B(T-T_0)}.$$

(1)

Where, HI denotes health index; HI_0 denotes the initial health index; B denotes the aging rate; T denotes the year in which the HI is computed; T_0 is the year of the HI_0, which generally refers to the launch year of the equipment; HI denotes a single value ranging from 0 to 10. The lower the value of HI is, the better the equipment condition is.

HI of Power Distribution Network

The HI theory and reliability analysis are similar to each other in some aspects. Both of them obtain the final system indexes through point-to-surface network structural analysis on the basis of component indexes. Therefore, this paper applies the network equivalent method and the successful flow method to the power distribution network HI analysis.

Modeling Based on Network Equivalent Method

The network equivalent method computes the reliability indexes through hierarchy analysis of the network. In the equivalent process, the influence of the branch feeder line on the upper feeder line is represented by the equivalent node component on the upper feeder line. In this paper, IEEE RBTS-Bus 2 Feeder Line 4 system shown in Fig. 1 is used to build the HI model.

First, the network is searched layer by layer from the main feeder line on. The branch feeder line searched from the main feeder line and the components connected with the branch feeder line are divided into the same layer. At the same time, whether there is the lower branch feeder line is searched to finally obtain the system hierarchy chart [6]. See Fig. 2 below.

Then the health index model of distribution network is established according to the hierarchical graph as shown in Figure 3.
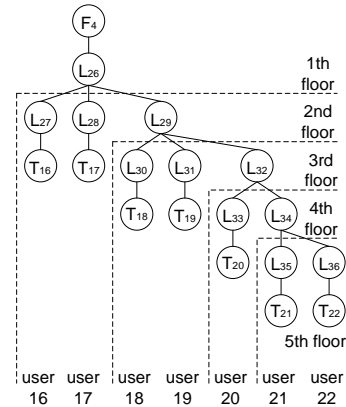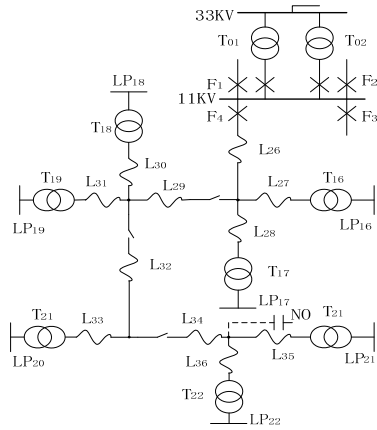
Figure 1. IEEE RBTS-Bus 2 feeder 4 system structural diagram

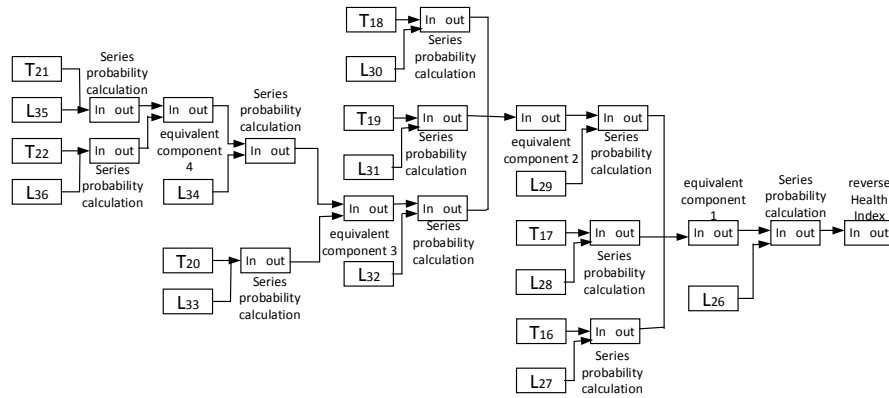Figure 2. IEEE RBTS-Bus2 feeder 4 hierarchy diagram

Figure 3. Distribution Grid Health Index model diagram

Model Solving Based on GO Method

This paper computes the network HI using the GO method and based on the equipment HI. Therefore, it is assumed that the HI (ranging from 0 to 10 or the hundred-mark system) of all equipment in the power distribution system is already known. At the same time, the power distribution network is mostly in an open-loop operation status. The load transfer upon fault cannot recover the lost load, so the influence of load transfer among feeder lines is not taken into consideration.

According to the successful dependence relationship of components, the reliability indexes of components can be obtained. The components' successful operating probability, P, can be converted as below through the GO method:

$$P = 1 - \frac{\lambda}{N}$$

$$\text{(2)}$$

Where, λ denotes the equipment fault rate; N denotes a period of time, which is set to be 8760h;

The health index (HI) and the fault rate constitute the index relationship, so the fault probability P1 can be written as below:

$$P_1 = \exp\left[-\left(\frac{HI - 10}{HI} \right)^2 \right]$$

$$\text{(3)}$$

Since the fault rate and the successful operation probability are complementary, so the successful operation probability P can be written as below:

$$P = 1 - P_1$$

$$\text{(4)}$$

Conduct GO conversion of the component's HI to obtain the successful operation probability of the component k, namely:

$$P_{ij.k} = f(\text{HI}_{ij.k}).$$

(5)

Where denotes the health index of the component k in the j branch feeder line at the i layer of the system.

According to the system hierarchy chart, the upward equivalent is conducted in turn from the bottom layer. Every branch feeder line undergoes the series analysis, and the successful operation probability of all components in the same circuit is equivalent to the successful operation probability of one branch feeder line, namely:

$$P_{ij} = \prod_{k \in ij} P_{ij.k}.$$

(6)

If some important users adopt the double-circuit power supply, the parallel computing should be adopted, namely:

$$P_{ij}^{'} = 1 - (1 - p_{ij1}) \times (1 - p_{ij2}).$$

(7)

Where $P_{ij.1}$ and $P_{ij.2}$ denote the successful operation probability of No. 1 circuit and No. 2 circuit in the double-circuit power supply, respectively.

Substitute the computing outcome of the i layer into the (i-1) layer as an equivalent component Mi to obtain the following computing outcome:

$$P_{M_i} = \sum_{j=1}^{n} (a_{ij} \times p_{ij}).$$

(8)

Where aij denotes the percentage of the j branch feeder line in the total load of the i layer. Repeat the above steps until the equivalent process reaches the highest layer of the network. The successful operation probability, PM1, can be obtained, and converted into the health index:

$$\text{HI}_{\text{总}} = 10/(1 + \sqrt{-\ln(1 - P_{M_i})}).$$

(9)

Computing Example Analysis

The typical radial power distribution system structure, IEEE RBTS Bus 2 Feeder Line 4 system [7] is shown in Fig. 1. The power distribution network contains 19 components (including seven transformers, 11 power distribution lines, and one breaker), and seven terminal load points. The disconnector fault rate is around 0.002 times/a; the power distribution transformer fault rate is 0.015 times/(a.km). The fault rate of various load points, load data, and length of various circuits are shown in Table 1, Table 2, and Table 3 below, respectively.

Table 1. Reference value of various load points' fault rate

Fault rate of the circuit load point	16	17	18	19	20	21	22	Average
Aerial style	0.253	0.243	0.243	0.256	0.256	0.253	0.256	0.251
Cable layout	0.161	0.155	0.155	0.163	0.163	0.161	0.163	0.160

Table 2. Circuit length

Circuit number	Length/km
28, 30, 34	0.6
27, 29, 32, 35	0.75
26, 31, 33,36	0.8

Table 3. Load of various load points

Load point	Load type	Average load/MW	Load importance grade
16, 22	Commerce	0.454	Grade-3
17-19	Resident	0.450	Grade-3
20, 21	Government,	0.566	Grade-2 (Multiply by 1.2)

The system hierarchy chart can be obtained through layer-by-layer searching of the IEEE RBTS-Bus 2 Feeder Line 4. (As shown in Fig. 2.) Following that, a simulation model is built according to the hierarchy chart under the MATLAB environment. The simulation analysis is conducted from the following three aspects:

Influence of Equipment Deterioration on Network Health Index

Choose the equipment, either of the same layer or of the different layers, to simulate the deterioration process of the equipment HI at different layers. (The corresponding health index changes from 2 to 8.) The health index of the remaining equipment is good, and the overall health index of the network is observed. The simulation results are shown in Fig. 4 below. Fig. 4 (a) shows the influence of equipment deterioration at the same layer on the network health index, while Fig. 4 (b) shows the influence of equipment deterioration at different layers on the network health index.

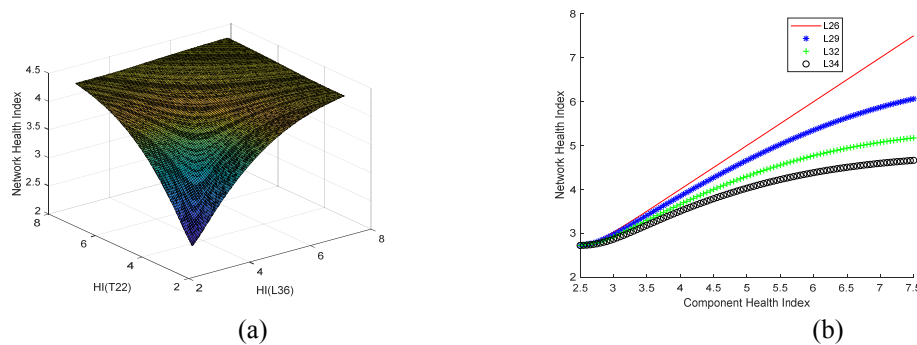(a)   (b)

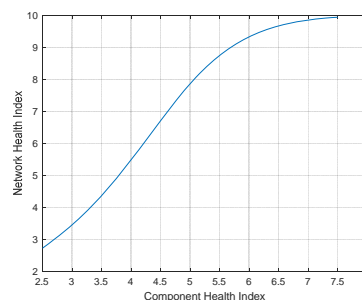Figure 4. Influence of equipment aging on the network health index

Figure 5. Influence of all equipment deterioration on network health index

As shown in Fig. 4, the equipment with the same health index at different layers of the system can exert a different influence on the power distribution network's overall health index. The higher the hierarchy of the equipment is, the larger the contribution of the equipment's health status is to the power distribution network health index. This is because the higher the hierarchy of the equipment is in the system, the more severe the losses will be caused by its fault.

Relationship between Equipment Health Index and Network Health Index

Fig. 5 shows the changing process of the network health index of all equipment deterioration. From Fig. 5, it can be seen that, when all equipment in the network is deteriorating, the overall network health index increases and is always higher than the equipment health index.

As one notices in Fig. 1, when the health index of all equipment averages at 2.5, and when 21 load points do not adopt the double-circuit power supply, the network health index is 2.7256. On the contrary, when the double-circuit power supply is adopted, the network health index is 2.7170. It can be seen that, though the number of components increase, the health index of the network decreases, suggesting that the double-circuit power supply can effectively improve the network health index.

Comparison of Computing Results by Different Methods

The network health index obtained by the GO method in this paper is compared with the computing outcome given by substituting the average reference fault rate of load points in Equations (2), (3), (4) and (9) according to Literature [8]. The comparison results are shown in Table 5 below:

From Table 4, it can be seen that the network health index adopting cable-circuit power supply is lower than that adopting the aerial circuit power supply. This is mainly because the cable circuit is less subject to the external influence, and the fault rate is thus at a lower level.

Table 4. Comparison of network health index computing results

Circuit type	Computing outcome by GO method	Reference value	Relative error (%)
Aerial	2.3890	2.3617	1.16
Cable	2.3501	2.3239	1.13

Since health diagnosis of equipment in the power distribution network is insufficient, this paper conducts indirect verification of the fault rate data via simulation. The computing outcome obtained by the GO method is compared with the reference value directly obtained the equations, and the results provide solid evidence for accurateness of the method proposed in this paper.

Exploration of Weak Links in Power Distribution Network

According to the health index of the current equipment, the network health index computed by the model built in this paper is presented in Table 5 below:

Table 5. Computing outcome of network health index

Equipment	Equipment HI (%)	Network HI	Equipment	Equipment HI(%)	Network HI
LP20	69	3.9608	L32	80	3.7087
LP18	74	3.9400	L36	78	3.6355
LP22	75	3.8880	L35	76	2.7172

From Table 5, it can be seen when the equipment HI of LP20 is 69%, the corresponding network HI reaches the maximum, indicating that LP20 is a weak point of the network. The network HI can be ranked in a descending order to examine the weak links of the power distribution network.

Conclusions

Aiming at ensuring sustainable and reliable power supply for the user end, this paper introduces the GO method and combines the network topological structure and wiring method to put forward a power distribution network condition evaluation method based on the equipment health index. Meanwhile, the IEEE RBTS-Bus 2 Feeder Line 4 is taken as an example for simulation verification. Results suggest that this method is feasible. Finally, the already known equipment health index is combined with the model built in this paper to obtain the network health index and to find out weak links of the network. These weak links can be organically combined with the power distribution network maintenance plan to realize rational use of the maintenance resources.

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