Reliability tracking method of power system equipment based on Embedded Internet of things technology

Zikuo Dai¹*, Guohu Xu², Yan Xu³, Shiyang Zhang⁴ and Zhengzhi Yu⁵

¹State Grid Liaoning Electric Power Company, ShenYang, Liaoning, 110000, China
²AnShan Power Supply Company of State Grid Liaoning Electric Power Co. LTD., AnShan, Liaoning, 114000, China
³Tieling Power Supply Company of State Grid Liaoning Electric Power Co. LTD., Tieling, Liaoning, 112000, China
⁴Liaoyang Power Supply Company of State Grid Liaoning Electric Power Co. LTD., Liaoyang, Liaoning, 111000, China
⁵Fushun Power Supply Company of State Grid Liaoning Electric Power Co. LTD., Fushun, Liaoning, 113008, China

*E-mail: caoguoqiang@sgepri.sgcc.com.cn

Abstract. Power equipment is one of the most important transmission and transformation equipment in power system. Improving the reliability of power equipment is of great significance to the safe and reliable operation of the whole power grid. A reliability tracking method of power system equipment based on Embedded Internet of things technology is proposed. The minimum cut set algorithm of reliability index based on Embedded Internet of things technology is given. In this paper, a fault tree analysis method for power system equipment unreliability index is proposed. According to the analysis of equipment structure, component function and failure mode, the fault tree model of power system equipment is established, and the reliability tracking calculation example is analyzed. Experiments show that the method can track the order stably, determine the key components that affect the reliability of the equipment, and identify the weak links of the equipment.

1. Introduction

Transmission system is an important part of power system, and the reliability management of transmission and transformation facilities is an important part of power system reliability management[1]. At the same time, power equipment failures caused by manufacturing, transportation, installation and maintenance quality not only affect the transmission capacity of power system, but also may cause large-scale blackout of power system, bringing huge losses to power system and national economy[2]. Therefore, improving the reliability of power equipment is of great significance to the safe and reliable operation of the whole power grid. At present, the research on power equipment reliability can be divided into qualitative analysis and quantitative evaluation. In the aspect of qualitative analysis, according to the statistical data over the years, China power reliability management center analyzes the equipment operation reliability index and the influencing factors of equipment reliability, analyzes the unplanned outage of equipment by components, and points out that the equipment faults are mainly concentrated in the equipment winding, bushing, insulating medium, cooling device, iron core, tap
changer, regulating device, conservator and other components\textsuperscript{[3]}. According to the statistical data of equipment reliability index, the equipment reliability evaluation model is established by using frequency and duration method. To study the reliability of equipment, it is not only necessary to evaluate some reliability indexes, such as failure probability and failure frequency, but also to find out the factors that have great influence on the reliability, identify the weak links, and determine the countermeasures to improve the reliability of the equipment, including the measures that should be taken in design, manufacture and operation maintenance.

2. Reliability tracking method of power system equipment

2.1. Collection of reliability characteristic quantity of power transmission and transformation facilities

With the continuous improvement of power distribution automation and power consumption information collection level, equipment operation data and alarm information are more and more abundant, which are transmitted to various application systems through various monitoring equipment\textsuperscript{[4-5]}. Therefore, aiming at the characteristics of low efficiency and narrow application range of traditional single source fault location methods, this paper studies the reliability tracking method of power system equipment based on Embedded Internet of things technology, which can effectively repair the fault and reduce the outage time, and provides technical support\textsuperscript{[6-7]}. When the equipment can be processed into two states of "working" and "shutdown", the main reliability characteristic quantities of tracking and evaluating repairable products are availability $A$ and unavailability $U$. The calculation formulas of availability $A$ and unavailability $U$ are as follows:

\begin{equation}
A = \frac{\sum_{i=1}^{n} x_i}{\sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i} = \frac{\sum_{i=1}^{n} x_i \left( \sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i \right)}{1} \quad (1)
\end{equation}

\begin{equation}
U = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i} = \frac{\sum_{i=1}^{n} y_i \left( \sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i \right)}{1} \quad (2)
\end{equation}

Where, $X_1, X_2, \ldots, X_n$ represents the time when the power equipment is in "working" state; $Y_1, Y_2, \ldots, Y_n$ indicates the time when the power equipment is in the "shutdown" state. When the service status of power transmission and transformation facilities can be treated as "available" and "unavailable", referring to the following formula, the calculation formulas of availability factor $A_F$, unavailability factor $U_F$ and stability tracking factor $\rho$ of power transmission and transformation facilities are as follows:

\begin{equation}
A_F = \frac{\sum_{i=1}^{n} x_i \left( \sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i \right)}{1} = \frac{t_{AH}}{t_{AH} + t_{UH}} = \frac{1}{1+\rho} \quad (3)
\end{equation}

\begin{equation}
U_F = \frac{\sum_{i=1}^{n} y_i \left( \sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i \right)}{1} = \frac{t_{UH}}{t_{AH} + t_{UH}} = \frac{\rho}{1+\rho} \quad (4)
\end{equation}

\begin{equation}
\rho = \sum_{i=1}^{n} y_i \left( \sum_{i=1}^{n} x_i \right) = \frac{t_{UH}}{t_{AH}} \quad (5)
\end{equation}

\begin{equation}
n_u = n_{u0} + n_p \quad (6)
\end{equation}
If $X_1, X_2, \ldots, X_i$ is the time when the transmission and transformation facilities are in the "available" state; $Y_1, Y_2, \ldots, Y_i$ is the time when the transmission and transformation facilities are in the "unavailable" state; $n_u$ is the number of unavailable, $n_i$ is the number of unplanned outage, $n_{po}$ is the number of planned outage, $t_{AH}$ is the number of available hours, and $t_{UH}$ is the number of unavailable hours, and:

$$t_{AH} = \rho \sum_{i=1}^{n_i} x_i + n_{po} / n_u$$  
$$t_{UH} = \sum_{i=1}^{n_i} y_i + n_{uo}$$

According to the power industry standard, the calculation formula of the availability factor $A_p$ of power transmission and transformation facilities is:

$$A_p = \frac{t_{AH}}{t_{AH} + t_{UH}}$$  

Then the calculation formula of stability tracking coefficient of power transmission and transformation facilities can be expressed as follows:

$$\rho = \frac{1}{A_p} = \frac{t_{PH}}{t_{AH}} - \frac{t_{AH}}{t_{AH}} = \frac{t_{UH}}{t_{AH}}$$

The stability tracking coefficient $\rho$ is defined as the ratio of unavailable hours $t_{UH}$ to available hours $t_{AH}$, which has a clear physical meaning. In the reliability research of power transmission and transformation facilities, the stability tracking coefficient is an important reliability characteristic quantity, which is used to study the reliability change law of power transmission and transformation facilities. It has a good application prospect in the reliability prediction of power transmission and transformation facilities.

### 2.2. Reliability state tracking evaluation of power system equipment

In order to meet the requirements of power supply reliability and improve the fault detection ability of equipment, the widely distributed information acquisition technology is adopted in the Internet of things environment, and the storage layer and access layer are designed. The deduction value of each state quantity is determined by the deterioration degree and weight of the state quantity, that is, the deduction value of the state quantity is equal to the basic deduction value of the state quantity multiplied by the weight coefficient, as shown in the table below:

| State deterioration | Basic deduction value | Weight coefficient | R1  | R2  | R3  |
|---------------------|----------------------|--------------------|-----|-----|-----|
| 1                   | 2                    | 2                  | 4   | 6   | 8   |
| 2                   | 4                    | 4                  | 8   | 12  | 16  |
| 3                   | 6                    | 8                  | 16  | 24  | 32  |
| 4                   | 8                    | 10                 | 20  | 30  | 40  |

Usually, a certain fault or defect of the equipment will cause the deterioration of multiple state quantities. At this time, it is necessary to carry out fault diagnosis, judge the cause of the deterioration of state quantities, and then determine the components that should be deducted and the deducted value. Finally, the current health status score of electronic transformer is calculated by bottom-up synthesis. Considering that the function of current voltage hybrid electronic transformer covers pure current or voltage electronic transformer, and it is widely used, the hierarchical model of status tracking evaluation of electronic transformer is shown in the figure.
2.3. Realization of power system equipment reliability tracking
Furthermore, the fault tree model is constructed. It is assumed that the states of root node, intermediate node and leaf node of power system equipment structure are represented by $R_s^i$, $M_j^i$ and $L_q$, where $s$, $i$, $j$, $q$ denotes the number of fault states of corresponding nodes. If the fault rate of each root node in each state is known to be 12K, if the root node $\left[ R_s^i \right]$, $\left[ R_s^i \right]$, $\left[ R_s^i \right]$ is in fault state $\left[ R_s^i \right]$, the conditional probability of leaf node $L$ in fault state $L$ is

$$P(L = L_q | R_s = R_s^i) = \frac{P(R_s = R_s^i, L = L_q)}{P(R_s = R_s^i)} \quad (11)$$

Where, $P(R_s = R_s^i, L = L_q)$ is the joint probability of root node $R_s$ in fault state $R_s^i$ and leaf node $L$ in fault state $L_q$. The above formula describes the influence degree of root node fault on system fault, that is, the result is derived from the cause. Under the condition that leaf node $L$ is in fault state $L_q$, the posterior probability of root node $X_i$ in fault state is

$$P(R_s = R_s^i | L = L_q) = \frac{P(R_s = R_s^i, L = L_q)}{P(L = L_q)} \quad (12)$$

Based on the above algorithm for reliability tracking, the power equipment system is divided into body and accessories according to the function and location characteristics of equipment components. The body includes current carrying system, iron core, insulating oil and oil tank, and accessories include cooling system, bushing, on load tap changer and protection test device. Furthermore, the proportional allocation criterion of unreliability index for power system reliability tracking is proposed, which is also suitable for reliability tracking of fault tree model. According to the proportional allocation criterion, the contribution of the bottom event $x_i$ to the top event probability index is as follows:

$$P_{S \rightarrow S_i} = \frac{P(x_i)}{P(x_H) + P(x_J) + \cdots + P(x)} P(x_1, x_2, \ldots, x_n) \quad (13)$$

Based on the above algorithm, the reliability tracking criteria are standardized, and the process of reliability tracking algorithm is optimized.

3. Analysis of experimental results
In order to verify the feasibility of the tracking method, the following experiments are designed. In the experiment, the special programmable DC analog power supply is used to simulate the weak disturbance signal of power system, which can set different photovoltaic array curves (such as different open circuit voltage, short circuit current, etc.). Using the experimental test platform based on TI DSP chip...
(TMS320F2808), by calculating the conditional probability of leaf node failure in the case of root node failure, the influence of component failure on equipment failure can be analyzed according to the conditional probability. According to the conditional probability in the table, for equipment failure, R1 has the greatest impact on equipment failure among all abnormal failure components; R2 has the greatest impact on equipment failure among all serious failure components; R3 has the greatest impact on equipment failure among all failure components. For other equipment faults, the analysis methods are in turn and so on. By using the equipment reliability parameters and applying the reliability tracking algorithm mentioned above, the allocation data of each equipment component to the equipment probability index is calculated, and the reliability tracking of power system equipment is listed in the table below. The reliability tracking results of power system equipment are shown in Table 2.

| Parts        | Number | Failure probability allocation | Reliability |
|--------------|--------|--------------------------------|-------------|
| Winding      | R1     | 0.000648                       | 83.45       |
| Iron core    | R2     | 0.000235                       | 87.21       |
| Bushing      | R3     | 0.000644                       | 90.14       |
| Cooling system | R4     | 0.000531                       | 86.94       |
| Tap changer  | R5     | 0.000584                       | 91.26       |
| Insulating medium | R6     | 0.000450                       | 93.45       |
| Conservator  | R7     | 0.000320                       | 87.35       |
| Other        |        | 0.000219                       | 92.46       |
| Total        |        | 0.000488                       | 94.39       |

It is found that in the process of reliability tracking, the winding bears the most "responsibility" for the failure probability index of the equipment, which is due to the improper design of the winding, weak insulation, atmospheric overvoltage, switching overvoltage and other factors, which are prone to short circuit fault, and the maintenance process is complex, which takes a long time to repair; the second is the bushing, and the proportion of other components is relatively small From the above analysis, it can be seen that the equipment fault is mainly caused by the winding and bushing, and the winding and bushing are the weakest link of the converter equipment. Therefore, the design and development of equipment winding and bushing should be strengthened to improve the reliability of equipment. Furthermore, the traditional method is compared to detect the accuracy of reliability tracking.

![Fig. 2 Reliability tracking effect comparison test](image)

It can be seen that the weak link of the equipment is mainly concentrated in the various parts of the equipment body, especially the equipment winding. Therefore, in the process of equipment design, material selection, manufacturing and operation and maintenance, we should focus on all parts of the equipment body, constantly improve its reliability, reduce the occurrence of equipment failure as far as possible, so as to improve the reliability of the equipment. From the above analysis, it can be seen that using embedded network to realize equipment reliability tracking can determine the stability tracking order of equipment components according to the severity of equipment failure, determine the key components affecting equipment reliability, and identify the weak links of equipment. This method
provides data support for equipment life cycle management. The method is applied to condition based maintenance and life cycle management of equipment, so as to achieve the optimal economy on the premise of ensuring reliable power supply of equipment.

4. Conclusions
A reliability tracking method of power system equipment based on embedded network technology is proposed. This method gives the direct allocation relationship between the system unreliability index and each component, so as to effectively identify the weak link of the system. According to the analysis of power system equipment structure, component function and fault mode, the fault tree model is established to improve the tracking accuracy and ensure the operation effect of power system equipment.

References
[1] Burger A, Cichiwskyj C, Schmeier S, et al. (2020) The Elastic Internet of Things - A platform for self-integrating and self-adaptive IoT-systems with support for embedded adaptive hardware[J]. Future Generation Computer Systems, 113(11):607-619.
[2] Li C Z E, Deng Z W. (2020) The Embedded Modules Solution of Household Internet of Things System and The Future Development[J]. Procedia Computer Science, 166(10):350-356.
[3] Lin Y H. (2019) Novel smart home system architecture facilitated with distributed and embedded flexible edge analytics in demand - side management[J]. International Transactions on Electrical Energy Systems, 29(6):e12014.1-e12014.21.
[4] Liao M, Chakrabortty A. (2019) Optimization Algorithms for Catching Data Manipulators in Power System Estimation Loops[J]. IEEE Transactions on Control Systems Technology, 27(3):1203-1218.
[5] Pappachen A, Fathima A P, Morris S. (2020) ANFIS controller based frequency linked availability based tariff mechanism for a restructured power system[J]. Journal of Physics: Conference Series, 1716(1):012009 (16pp).
[6] Kumar R, Sharma V K. (2020) Whale Optimization Controller for Load Frequency Control of a Two-Area Multi-source Deregulated Power System[J]. International Journal of Fuzzy Systems, 22(1):122-137.
[7] Rajiv, Kumar, V, et al. (2020) Whale Optimization Controller for Load Frequency Control of a Two-Area Multi-source Deregulated Power System[J]. International Journal of Fuzzy Systems, 22(1):122-137.
[8] Kerdphol T, Matsukawa Y, Watanabe M, et al. (2020) Application of PMUs to monitor large-scale PV penetration infeed on frequency of 60 Hz Japan power system: A case study from Kyushu Island[J]. Electric Power Systems Research, 185(10):106393.
[9] Habib M, Ladjici A A, Bollin E, et al. (2019) One-day ahead predictive management of building hybrid power system improving energy cost and batteries lifetime[J]. IET Renewable Power Generation, 13(3):482-490.
[10] Shao Y, Chen B, Xiao H, et al. (2019) Discussion on Performance Evaluation Method of Distributed Combined Cooling, Heating, and Power System[J]. Journal of Thermal Science, 28(6):1212-1220.