A Decision Model for Substation Equipment Maintenance Based on Correlation Set Decomposition

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Abstract. Substation equipment status maintenance background. Solve the problem of high cost in equipment maintenance. A decision model for substation equipment maintenance based on association set decomposition is proposed. Under the premise that the state of the device state is known. Analysis of the basic structure of substation equipment. And predict the operating status of the device. Starting from the functional association between devices, the association set is the basic unit. Realize the time-varying maintenance decision of the equipment. The conclusion is obtained by the model verification experiment: Compared with traditional equipment overhaul models. The method of substation equipment maintenance decision model based on association set decomposition can save 16.5% maintenance cost.

Keywords: Associative set decomposition · Transformer substation · Equipment overhaul · Maintenance decision

1 Introduction

As an important part of the power system, the substation refers to the place where the voltage is changed. The function of the equipment is to transmit the electric energy from the power plant to a distant place. The voltage must be raised into a high voltage, to the user's vicinity and then as needed to reduce the voltage, the work of this voltage rise and fall depends on the substation to complete. The main equipment in substations are switches and transformers. According to the size of the different, small called substation. Substations are larger than substations. A substation is an electric power facility in a power system that changes voltage, receives and distributes electric energy, controls the flow of electric power and adjusts voltage. It connects all levels of voltage to the grid through its transformers [1]. Substation has ac-dc-ac conversion process in specific environment. For example, undersea power transmission cables and long-distance transmission, some of which are in the form of high-voltage dc transmission and transformation, Dc transmission overcomes the capacitive and reactance loss of ac transmission and has the effect of energy saving. The main equipment and connection of substations vary according to their functions. Generally, the life cycle of a substation is as long as 30–50 years. Therefore, in the total life cycle cost of a substation, Operation cost, maintenance cost and failure cost often account for a large proportion.

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It can be seen that good maintenance of various equipment in the substation is not only the basis for normal operation of the substation, but also can reduce the safety risks of the substation. An important way to achieve a balance between utility and cost. Under the guidance of the concept of network state maintenance, for the equipment maintenance decision problem topologically only associated with the substation, if the incoming and outgoing line state of the substation is assumed to be certain, the decision model of substation state maintenance is established. According to the concept of power grid state maintenance, the equipment under maintenance is all related to the substation. In terms of topological association, a type of equipment is associated with more than two substations, such as transmission lines. The other type is associated with only one substation, such as transformers, circuit breakers, disconnecting switches, etc. For substation, when the incoming and outgoing lines are given and the equipment only associated with the substation is in state maintenance, it is in line with the concept of network state maintenance. The timing of substation equipment maintenance is full of correlation and contradiction, so it is necessary to compromise between maintenance risk and fault risk. The research on the decision model of substation equipment maintenance is one of the important links in the process of adopting decomposition and coordination idea in the implementation of complex network state maintenance.

In reference [2], an early warning decision model of equipment preventive maintenance based on mean control chart is designed. Based on the economic design model of mean control chart, the economic model of mean control chart considering single system factor is constructed by combining the equipment preventive maintenance with mean control chart. Two thirds of the control boundary is set as warning area, Carry out preventive maintenance activities when the sample falls in the warning area. Through the parameter analysis of the model, it is found that the expected cost per unit time of preventive maintenance is lower than that of preventive maintenance when the alarm in the early warning area of control chart is given, which shows that the early warning decision model of equipment preventive maintenance based on mean control chart is of great value to reduce the cost and improve the quality control level of products. But the maintenance cost of the model is high and the maintenance time is long. Therefore, this paper proposes a decision-making model of substation equipment maintenance based on Association set decomposition.

2 Design of Substation Equipment Maintenance Decision Model

In order to minimize the maintenance cost of substation equipment, the maintenance strategy optimization of electrical equipment is realized by means of associative set decomposition in order to determine the optimal maintenance cycle and the upper limit of the optimal failure rate under the condition of maintenance.

2.1 Analyze the Basic Structure of Substation Equipment

Figure 1 shows the basic structure of substation equipment.

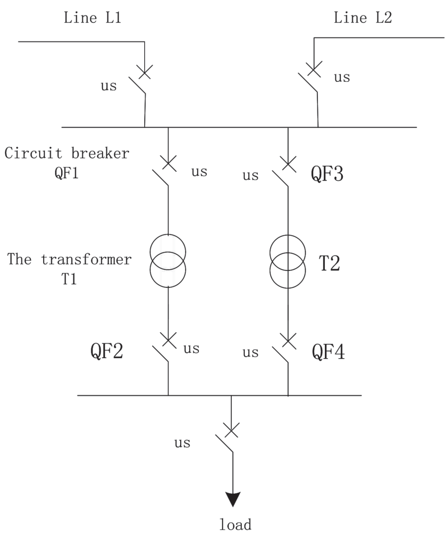


Fig. 1. Basic structure of substation equipment

In the basic structure $\{QF1, T1, QF2\}$, QF1 represents circuit breaker and T1 represents transformer. When transformer T1 is out of service due to maintenance or fault, all the air pressure associated with the equipment will also be out of service [3]. In this way, if the maintenance of other equipment is carried out after the shutdown of equipment T1, the maintenance cost and system outage loss caused by repeated shutdown of the system can be reduced.

2.2 Predict the Running State of the Equipment

The prediction of the running state of substation equipment is to judge whether the current running state of substation is a fault state. Generally speaking, the running state of substation equipment can be divided into normal running state, abnormal state, state transition state, fault state and failure-related transition state. The prediction of equipment running state is divided into two steps. Firstly, the state transition process of substation equipment is analyzed, and the probability of equipment in different states is calculated respectively, so as to get the prediction result of equipment running state.

(1) Device state transfer process

Transformers, circuits, circuit breakers and other equipment will be aging in use, maintenance is an important means to delay equipment aging and improve its reliability [4]. The aging process of the equipment is relatively long, and the state transition process of the equipment in a short time can be described by a two-state model. Figure 2 shows the state transition process of substation equipment.

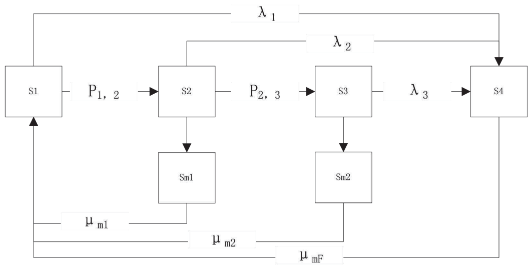


Fig. 2. Device state transition process

It can be seen from the figure that the substation equipment can be divided into six states, including S1 for good state, S2 indicates mild deterioration, S3 indicates severe deterioration status, S4 indicates functional failure status, S_{m1} indicates inspection m1 status, and S_{m2} indicates maintenance m2 status. When the equipment is in state S1, maintenance is not required. When the equipment is in state S2, S3, S4, maintenance can be carried out, expressed as m1 m2 and mF respectively, and all three maintenance methods make the equipment repaired to state S1 [5]. In addition, with the improvement of substation automation, the duration of switching state caused by active failure of equipment is short, which is negligible compared with the duration of equipment maintenance.

(2) Solve the equipment state probability

In the research cycle, the starting time of the next maintenance plan is set as M, and the substation equipment may be repaired or opportunity repaired after the failure occurs before the start of the maintenance plan, so as to change the failure rate of the equipment, thus affecting the subsequent risk level and decision-making level. The device state transition matrix is expressed as:

$$P_T = \begin{pmatrix} 1 - P_{1,2} - \lambda_1 & P_{1,2} & 0 & \lambda_1 & 0 & 0 \\ 0 & 1 - P_{2,3} - \lambda_2 & P_{2,3} & \lambda_2 & 0 & 0 \\ \mu_{m_F} & 0 & 0 & 1 - \mu_{m_F} & 0 & 0 \\ \mu_{m_1} & 0 & 0 & 0 & 1 - \mu_{m_1} & 0 \\ \mu_{m_2} & 0 & 0 & 0 & 0 & 1 - \mu_{m_2} \end{pmatrix} \quad (1)$$

Where, parameter μ_{m_F} represents the transfer rate of equipment failure state S4 to state S1; similarly, parameters μ_{m_1} and μ_{m_2} respectively represent the transfer rate of maintenance state Sm1 Sm2 to state S1 [6]. According to the nature of preventive maintenance, the equipment can be transferred to S1 state 100% after completion of m1 m2 maintenance. So the probability of state of device I in time period t can be calculated by formula 2.

$$\begin{cases} p_{i,S}(t) = p_{i,S}(0)P_{i,T},\ t = 1 \\ p_{i,S}(t) = p_{i,S}(t-1)P_{i,T},\ 1 < t \leq N_T \end{cases} \tag{2}$$

Where $p_{i,S}(t_0)$ is the state probability vector of equipment I in the current period,$P_{i,T}$ and $P_{i,M}$ are the state transition matrix and preventive maintenance transition matrix of substation equipment I, respectively.

2.3 Diagnose Substation Equipment Faults

Based on the prediction results of the running state of the equipment, the aging faults and sudden faults of the equipment are considered to diagnose whether the substation equipment has a fault state.

(1) Collect the operation signal of substation equipment

The signal sensor is installed on the equipment to be tested in the substation, and the collected signal is mainly the frequency signal generated during the operation of the equipment, so as to prove the failure of the equipment. The continuous working time of the sensor of substation equipment is set as 24 h, and the collection interval of sensor signals is set as 0.5 s [7]. In order to ensure the accuracy of the signal collection results, the selected sensor was modified. On the basis of the traditional sensor, a filter circuit was added to the sensor circuit to realize the signal filtering processing. As the equipment in the substation is interrelated, when a fault is found in the substation equipment, the equipment is the center to continue to detect the surrounding.

(2) Build the associated set risk assessment unit

The correlation between devices can be divided into three categories: functional correlation, economic correlation and random correlation. Function correlation means that when a device is out of service due to failure or maintenance, the related equipment will also be out of service. Economic correlation means that the maintenance cost will be reduced or increased if the related equipment is not in service at the same time. Random association refers to the random occurrence of external factors may make a certain device correlation. After the switching operation after the failure, the equipment that has a total outage belongs to an association set. Through analysis, it can be seen that the equipment set between two topological nodes can form an association set, which generally includes circuit or winding circuit breaker isolator, grounding switch arrester and high reactance. For substation lines, the constructed association set risk assessment unit, or association set, is shown in Fig. 3.

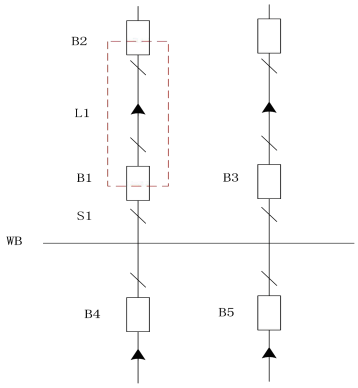


Fig. 3. Schematic diagram of association set

The association set contains three devices: circuit breaker B1 and B2 circuit L1. Under the premise of proper operation of the protection device, if there is a fault in line L1, the circuit breaker B1 and B2 will automatically jump to isolate the fault line, and the three devices will stop running at the same time until the fault is removed. If circuit breaker B1 fails, the circuit breaker B2 on the opposite side and the circuit breaker B3 B4 B5 on the bus WB will skip and all circuits will be out of service. Then, the disconnecting switch S1 will be disconnected to isolate the fault equipment and close the circuit breaker B3 B4 B5. Finally = only circuit breaker B1 and B2 line L1 will be out of service [8]. It can be seen that devices in the same association set are out of service. After switching operation, the association set will be out of service as a whole.

(3) The associative set can be solved by degree

The change of equipment performance is described as a time-varying shutdown model. Under the influence of correlation set, the state transition of substation equipment in the correlation set is shown in Fig. 4.

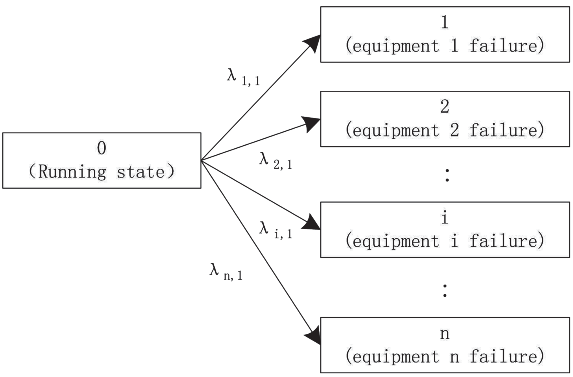


Fig. 4. Correlation set state transition process

Define the correlation set state transition rate as the matrix in formula 3.

$$v = \begin{bmatrix} -\mu_m & \mu_m & 0 & 0 & 0 \\ 0 & -\lambda_{12} & \lambda_{12} & 0 & 0 \\ 0 & 0 & -\lambda_{23} & \lambda_{23} & 0 \\ 0 & 0 & 0 & -\lambda_{34} & \lambda_{34} \\ 0 & \mu_f & 0 & 0 & -\mu_f \end{bmatrix} \quad (3)$$

If p represents the probability that the association set is in state I, then the instantaneous state probability of solving the association set can be expressed as:

$$\mathrm{U_A} = \frac{\mathrm{dp(t)}}{\mathrm{dt}} \quad (4)$$

If the initial state of the association set is a, the instantaneous availability at time t can be expressed as:

$$A_a(t) = p_1(t) + p_2(t) + p_3(t) \quad (5)$$

According to the setting of initial state and different state transition rate, the instantaneous solution of state probability distribution in different state transition process can be solved by this block diagram.

(4) Correlation set decomposition analysis

When the association set is determined to be available, the substation equipment in the association set is decomposed, and the specific processing process is shown in Fig. 5.

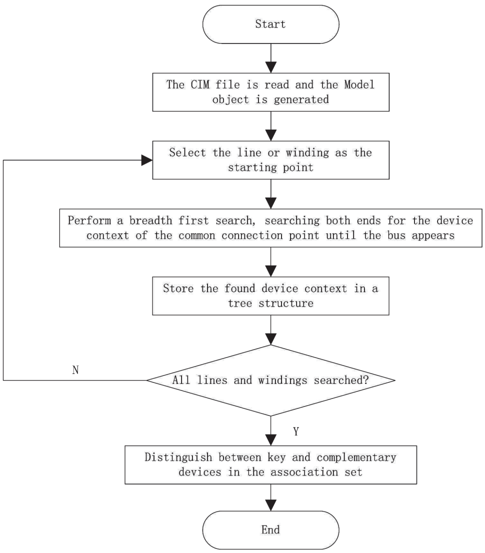


Fig. 5. Association set decomposition flow chart

The connection set and the branches in the network topology are one to one correspondence, and there is only one set of components in the circuit or winding. Taking the connection set as the basic unit can improve the efficiency of risk assessment.

(5) Calculate the associated set outage probability

Using the method of equipment risk assessment to calculate the outage probability of the correlation set completed by decomposition processing, and judging whether the substation equipment in the correlation set needs maintenance treatment based on the calculation result of probability [9]. The specific associated set device risk assessment technical architecture is shown in Fig. 6.

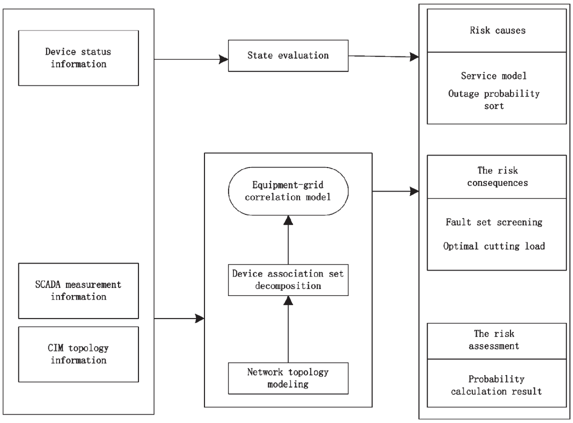


Fig. 6. Technical architecture diagram of equipment risk assessment

This technical architecture can realize the complete process from data acquisition to risk analysis to application decision. By collecting and analyzing the information of the data layer, the basic layer obtains the evaluation result of equipment state and the equipment-power network association model with topology modeling as the core and association set as the basic unit. The core layer obtains the real-time fault probability of the equipment by establishing the equipment outage model, and selects the correlation set with high outage probability to conduct the power grid operation risk assessment under the predicted fault set. Assuming that the correlation set is in the running state $P'(0)$ at the initial moment and its value is 1, the probability distribution of the state before the first failure in the corresponding period can be obtained through the decomposition of the correlation set, and the probability expression of the working state of the correlation set under different conditions is analyzed. If no equipment in the associated set fails before the maintenance plan, that is:

$$P_{case,0} = P_0(M) \tag{6}$$

When this situation occurs, the equipment in the associated set can run reliably until the time of maintenance. If the solution result of $P_{case,0}$ does not meet the conditions in formula 6, it can be determined that the substation equipment in the correlation set needs maintenance treatment.

2.4 Realize the Maintenance Decision of Equipment in Time - Varying Shutdown

According to the fault diagnosis results of the equipment in the associated centralized substation, the maintenance treatment of the equipment with faults is carried out. Before the maintenance work, the maintenance decision scheme is formulated for the purpose of reducing the maintenance cost.

(1) State dependent decision

For unexpected changes in equipment performance, when the equipment state transition process is known, the state correlation decision is the specific implementation of the equipment performance correlation decision. All the states of the equipment that change with time are related to the possible changes of the scheduled maintenance decision. Obviously, the same state at different times should be viewed as different states, with a cluster of states associated with the same decision change.

(2) Select maintenance mode

In general, basic maintenance methods of substation equipment include complete maintenance, incomplete maintenance, minimal maintenance, post-maintenance and deterministic preventive maintenance, etc., among which some maintenance principles are shown in Fig. 7.

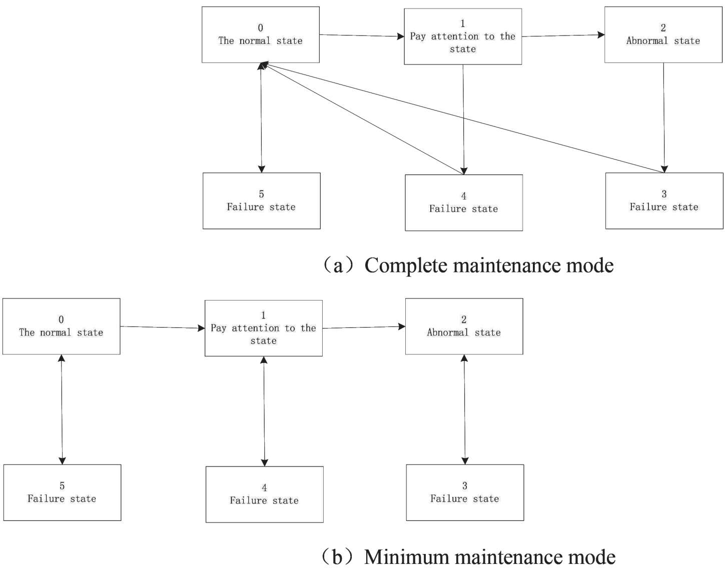


Fig. 7. Maintenance schematic diagram

Take the minimal maintenance method as an example, the maintenance method is mainly to clear the equipment fault and make it in the running state after the equipment is repaired, but it will not improve the performance of the equipment or eliminate any influence of the aging of the equipment. In the working principle diagram of minimum maintenance, each failure state is transferred to the operating state before the equipment failure after the post-maintenance. Therefore, corresponding maintenance decisions can be selected according to the status diagnosis results of equipment and associated sets [10]. In addition to this state maintenance decision strategy, in order to ensure the safety of the use of substation equipment, it is also necessary to set a regular maintenance decision, and the corresponding maintenance decision expression is:

$$\begin{cases} \min C = f(T) \\ s.t. \quad 10\,years \leq T_1 \leq T_{st} \\ \quad 5\,years \leq T_2 \leq 10\,years \\ \quad T_1 - T_2 \geq 5 years \end{cases} \tag{7}$$

Where T is T_1 two-dimensional decision vector, a represents the major repair period, and T_2 represents the minor repair period. T_{st} represents the upper bound of the overhaul cycle, and the value of this parameter is determined by the service life of the transformer equipment.

(3) Maintenance decision objective function and constraint condition

In order to minimize the total risk of the system, the functional expression of the state maintenance decision model of time-varying performance of related sets of substation equipment is obtained:

$$g = \min\left[\sum_{k=1}^{N} R_{1,k} + R_S\right] \tag{8}$$

In formula 8, is the operation risk of the k th device of $R_{1,k}$. The constraint conditions are set from three aspects of maintenance time simultaneous maintenance constraint and substation system safety constraint. The maintenance time constraint condition is:

$$\beta_i(t) = \begin{cases} 0,\ t < b_i \,or\, t > e_i \\ 0 \,or\, 1,\ b_i \leq t \leq e_i \end{cases} \tag{9}$$

Where, $\beta_i(t)$ is the state variable of equipment i in time period t. If the value is 1, it means the equipment is being repaired; if it is 0, it means the equipment is not being repaired. In addition, parameters b_i and e_i respectively represent the earliest and the latest time periods for the maintenance of equipment i. For the equipment in the same correlation set, it should be arranged together for maintenance to avoid repeated power failure of the system, that is:

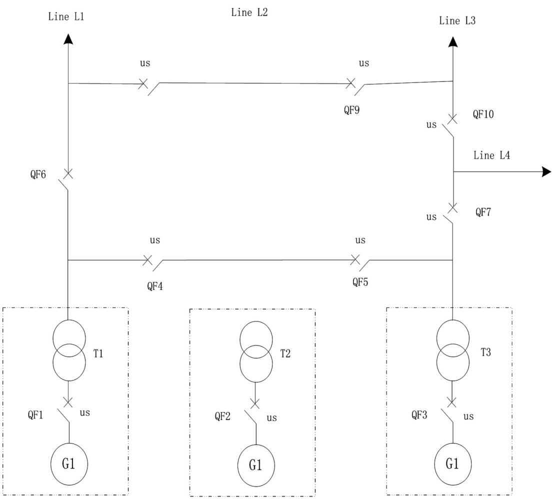
$$x_i(t) = x_j(t) \tag{10}$$

The two variables in the above equation respectively represent the substation equipment in the same correlation set. In addition, the purpose of safety constraint is to control the maintenance power and control the actual power of power transmission and transformation equipment in the maintenance process within the maximum allowable transmission limit power.

3 Model Validation Analysis

In order to verify the feasibility and effectiveness of the proposed transformer substation equipment maintenance decision model based on association-set decomposition, the paper compares the different maintenance decision strategies of different equipment in the substation environment as shown in Fig. 8, and compares the maintenance costs consumed by different decision-making methods.

（a）Actual scene of substation environment



（b）Main wiring of substation equipment

Fig. 8. Substation environment

The study period was 60 days, divided into 60 periods in days. According to the monitoring results of equipment status, the relevant data of substation equipment scheduled for maintenance and repair in the cycle are shown in Table 1.

Table 1. Device-associated set initial state

Device name		Breaker kV211 220-3	Ming west line 211 switch	Ming west line	220 kV. #2 main transformer
Device type		Isolating switch	The circuit breaker	Line	Winding
The association set		Ming west	Ming west	The main direction of	The main direction of
The initial state	S1	0.90	0.10	0.0	0
	S2	0.10	0.90	0.0	0
	S3	0.00	0.80	0.2	0
	S4	0.00	0.70	0.3	0

Three different substations were selected as a, b and c respectively, and T1 and B2 were set as the equipment to be repaired in this experiment. Set and record the initial state of the equipment as shown in Table 1, and adjust the failover speed and state of the substation equipment through manual control. In order to highlight the decision performance of the proposed transformer substation equipment maintenance decision model based on correlation set decomposition, the literature [2] model was set as the control group in this verification experiment. The two decision models obtained two different maintenance methods, respectively recording the maintenance time and total risk cost of substation equipment, and the verification results obtained through statistics and calculation were shown in Table 2.

Table 2. Verify experimental data results

Maintenance decision method	Substation	Start time		Maintenance decision risk cost/ten thousand yuan
		T1	B2	
Literature [2] model	a	45	34	1554.9
	b			356.8
	c			165.7
A decision model for substation equipment maintenance based on correlation set decomposition	a	33	20	1303.4
	b			287.5
	c			142.6

After calculation, the average maintenance cost of the literature [2] model is 6.924 million yuan, and the average maintenance cost of the designed maintenance decision model is 5.778 million yuan, saving 1.46 million yuan. By comparing the two maintenance strategies, the corresponding results of substation a, b and c can be seen: the maintenance costs of the corresponding maintenance strategies of the substation equipment maintenance decision model based on the correlation set decomposition are the minimum, which can effectively make maintenance decisions on the substation equipment under the condition monitoring background.

4 Conclusion

On the basis of the existing research results, aiming at the functional correlation between equipment, the mathematical model of substation equipment state maintenance is constructed based on the idea of associative set decomposition, and the significance of model maintenance decision to improve the reliability and economy of maintenance cost is verified through experiments. Limited by time and space, it is necessary to conduct in-depth research on equipment condition maintenance of complex systems in the future research work around the correlation between multiple devices and the correlation with the system.

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