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A Novel Maintenance Decision Making Model of Power Transformers Based on Reliability and Economy Assessment

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ABSTRACT The present "condition-based maintenance decision making" of power transformers will cause large financial losses to electric enterprises, because of not having taken reliability and economy into consideration. To solve this problem, a maintenance decision-making model with the consideration of reliability and economy was established to choose the best maintenance strategy for oil-filled transformers. With the corrected parameters of operating environment and maintenance records, a condition assessment model including DGA test, oil test, and the electrical test was proposed to decide the comprehensive health index of transformers. After establishing the relationship between the fault rate and the comprehensive health index, a reliability evaluation model was formed, which can simulate the impact of different maintenance types. Taking the reliability and economy operation of transformers into consideration, a particle swarm optimization method was developed to solve the optimization model and select the best maintenance strategy according to the current condition of transformers. Two cases were studied and the results demonstrate that the proposed model offers an improved maintenance strategy.

INDEX TERMS Power transformers, fault rate, comprehensive health index, risk assessment, maintenance decision making.

I. INTRODUCTION

With grid size and customer demand level increasing, the power transmission equipment operating safely and economically becomes a significant issue to electric enterprises. As one of the keys to electrical equipment, a large power transformer plays an important role in a power system, and its abnormal operating is one of the most general causes of power system blackout accidents. Therefore, the performance of transformers which is more than any other components is the main factor to influence the reliability and economy of power system [1]. By conservative estimation, there are more than 30,000 transformers (more than 66kV) in China. Their condition and operation lives are mostly depended on the practical running environment including load rate, running temperature, family defects, and running time. If in good conditions they could work unceasingly without any maintenance but if they were in poor conditions without proper maintenance they would cause transformer faults or even severe electrical accidents. In that case, conducting traditional transformer maintenance (first major repair in the 10th operation year, and then major repairs in every 5 years; minor repairs in every one year) will cause "over repair" or "lack of repair", which will cause large financial losses. Recently, condition based maintenance decision making is an effective method to solve the "over repair" and "lack of repair" problems. However, only considering the condition of a transformer may result in selecting a transformer maintenance strategy without optimizing the cost impact, which will cause financial losses. Considering the reliability and economy operation of transformers, effective maintenance selection can save 25%-30% of the total transformer life cycle cost based on a survey conducted by the Electric Power Research Institute. Therefore, considering both the reliability

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and economy assessment of a transformer, it is a critical issue for electrical enterprises to select a transformer maintenance program [2].

In recent years, it mainly focused on the reliability based maintenance for the transformer maintenance strategy researches, whose pivotal content is fault diagnosis and condition assessment of transformers. For the fault diagnosis of transformers, some methods were reported to assess the insulation condition of a transformer, such as insulation dielectric spectrum analysis [3], [4], partial discharge method [5]–[8], and dissolve gas analyses [9]–[12]. However, the effectiveness of dielectric spectrum analysis and partial discharge method had not been largely demonstrated in practical transformers; besides, dissolved gas analyses (DGA) was a helpful and practical method to assess transformer condition in the past few years. Some DGA related methods, including genetic programming [9] and support vector machine [10], were applied to diagnose the faults of transformers and assess the condition of the transformers. Furthermore, some methods, including PSO-least squares support vector [11], LSSVM [12], were used to forecast faults of power transformers based on DGA and assess the future condition of the transformers. However, the accomplishments of these DGA methods are often limited in their failure classifications of the fault condition. In fact, the condition of power transformers is often somewhere between normal condition and failure condition [13], [14].

Therefore, for condition assessment of transformers, transformer condition is usually depended on main body condition (determined by DGA, electrical tests, and oil tests), bushing condition, and accessories condition. The aging mechanism of inner transformer is complex, and some attention values of indexes are ambiguous and hard to be defined. Thus, it is hard to obtain the accurate result when assessing the transformer condition. To handle these problems, reference [13]–[15], and [16] proposed a method of condition assessment for transformers using fuzzy theory, evidential reasoning approach, and fuzzy evidential reasoning model. Some researchers Krishnavel *et al.* [17] reported an excellent work on the well-being analysis of generator step-up (GSU) transformer insulation which offers a novel thinking for transformer condition assessment.

The above researches only consider the condition of a transformer without considering the overall operation economics. The drawback of the condition based maintenance is that it may result in selecting a transformer maintenance strategy which does not optimize the cost impact [18]. On the other hand, some models only consider the overall economics of the transformer that was proposed, including asset management techniques for transformers [19], life cycle cost model of power transformers under the new environment [20], and small power transformer selection and specification [21]. However, research on maintenance decision making for power transformers by considering both reliability and economy synthetically is scarce. It is because the impact factors of maintenance decision making, including reliability condition assessment, fault rate charges after different maintenance types, fault risk evaluation, and optimal maintenance selection, are complex and hard to be measured.

Therefore, an ideal maintenance strategy was proposed to address the problem, which was based on the combined considerations of operational reliability, failure risk and associated cost impact. A reliability assessing model of transformers and the impact mechanism of the reliability model under different maintenance types were studied in Section II. The maintenance strategy decision making model based on the operation risk evaluation and optimal function was developed in Sections III. The proposed method was suitable to decide the maintenance strategy of transformers in Sections IV. The conclusions are given in Section V.

II. OPERATION RELIABILITY MODEL OF OIL-FILLED TRANSFORMER

In general, the transformer operation reliability (negatively correlated with fault rate) has a huge influence on maintenance decision making, and the fault rate of a transformer is usually influenced by some factors including insulation health, operation environment, maintenance records, and different maintenance actions. Therefore, indices were selected in section II.A for calculating the insulation health. The operation environment and maintenance records were chosen to be corrected parameters for calculating the comprehensive health index in section II.B. The relationship between the comprehensive health index and fault rate was built in section II.C to obtain the fault rate model. The influence of the maintenance actions towards the fault rate was studied to obtain the maintenance impact mechanism in section II.D.

A. INDICES SELECTION OF INSULATION ASSESSMENT

Indices selection is necessary for insulation health assessment. Some indices which are easily measured and have an important impact on transformer insulation condition are selected to form the insulation assessing index system according to relevant standards [22]–[25].

The assessing index system of transformer insulation condition is shown in Figure 1. Different indices offer somewhat different pictures of transformer insulation condition, therefore how to determine the weights of assessing indices is extremely important. The improved AHP method (an effective method to weights decision) was applied to determine the weights of the assessing index system. In Fig. 1, after using the improved AHP method, the weights of the DGA, oil test, and electrical test are 0.3974, 0.2361, and 0.3665, respectively.

The weights of the subset of the DGA, oil test, and electrical test are {0.3581, 0.1154, 0.2362, 0.1749, 0.1154}, {0.1964, 0.1964, 0.1710, 0.4362} and {0.2305, 0.1402, 0.1402, 0.3041, 0.1850}, respectively.

B. ASSESSING INDEX SYSTEM OF THE CORRECTED PARAMETERS

The comprehensive health condition of a transformer is not only related to the insulation condition of the transformer

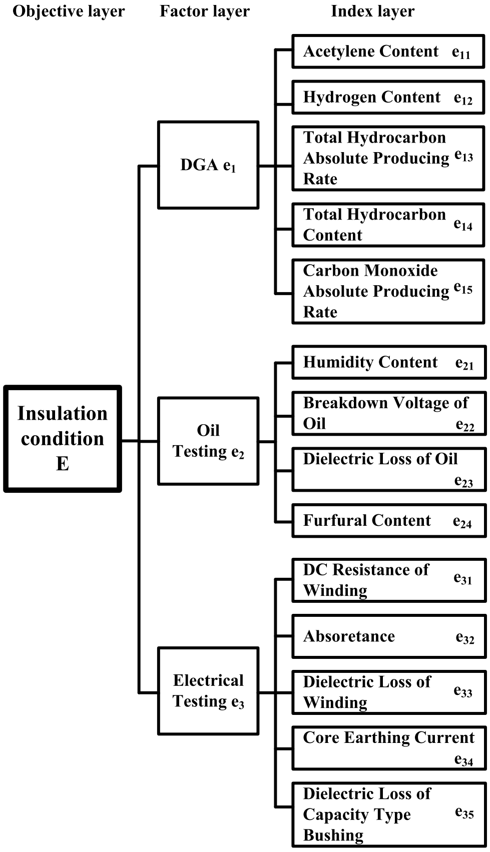

FIGURE 1. Assessing index system of transformer insulation condition.

but also related to its operation environment condition and maintenance records. The operation environment condition contains indices including operation years, average lifetime, operation environment, and load rate. The maintenance records include indices including family defects, short circuit of near zone, cooling system condition, defect records, fault records, and partial discharge. These indices depict or infer an impact on the aging rate of transformer insulation. Therefore, the indices were used to establish the corrected parameter of the operation environment condition a_1 and the corrected parameter of maintenance records a_2. The relationships between the indices and the corrected parameters are built by expert experience and shown in Table 1, and assessing index system of the corrected parameters is shown in Fig. 2. If any of the indices is missed, the corrected parameter of the index is set to 1 in the paper.

C. FAULT RATE CALCULATION OF TRANSFORMERS

The comprehensive health index of a transformer is not only related to the insulation condition of the transformer but also related to the condition corrected parameters. The comprehensive health index is calculated by (1) and (2).

$$a_1 = \prod_{n=1}^{4} X_{1n} a_2 = \prod_{n=1}^{6} X_{2n} \tag{1}$$

$$TH = HI \times a_1 \times a_2 \tag{2}$$

TABLE 1. The relationships between the indices and the corrected parameters.

Indices	Corrected parameters X_{bc}
a_{11}	a_{11} is the operation year. If $0 \leq a_{11} \leq 5$, $X_{11}=1$; if $5<a_{11} \leq 10$, $X_{11}=1.01$; if $10<a_{11} \leq 20$, $X_{11}=1.02$; if $20<a_{11} \leq 30$, $X_{11}=1.05$; if $30<a_{11} \leq 40$, $X_{11}=1.07$; if $40<a_{11}$, $X_{11}=1.09$.
a_{12}	a_{12} is the average lifetime. If $0 \leq a_{12} \leq 25$, $X_{12}=1.02$; if $25<a_{12}<40$, $X_{12}=1.01$; if $40 \leq a_{12}$, $X_{12}=1$.
a_{13}	a_{13} is the installed place. If a_{13}=“work in a room”, $X_{13}=0.96$; if a_{13}=“outside” and “maximum temperature in the year”<39°C, $X_{13}=1.02$; if a_{13}=“outside” and 39°C≤“maximum temperature in the year”, $X_{13}=1.04$.
a_{14}	a_{14} is the average load rate of one year. According to expert experience, the array of load rate is A_{14} = [0.6 0.7 0.8 0.9 1 1.1 1.2], and the related array is X_{14} = [0.82 0.89 0.97 1.06 1.15 1.26 1.37]. By using the curve fitting based on least square method [24], the relations can be obtained: if $a_{14} \leq 0.6$, $X_{14}=0.8153$; if $a_{14}>0.6$, $X_{14}=0.4851 \times e^{a14 \times 0.8653}$.
a_{21}	a_{21} is the family defect history. No defect, $X_{21}=0.96$; little defects, does not hurt the operation, $X_{21}=1$; repeated defects, potential safety hazard, $X_{21}=1.04$.
a_{22}	a_{21} is the condition of the short circuit in the near zone. If the transformer was suffered from short circuit in the near zone, $X_{22}=1.04$; if the transformer was not suffered from short circuit in the near zone, $X_{22}=1$.
a_{23}	a_{23} is the cooling method. If a_{23}=“oil-immersed self-cooled” or a_{23}=“oil-immersed air cooled”, $X_{23}=1$; if a_{23}=“forced oil and air cooled”, $X_{23}=1.04$.
a_{24}	a_{24} is the defect times. If $a_{24}=0$, $X_{24}=0.96$; if $0<a_{24}<2$, $X_{24}=1$; if $2 \leq a_{24}<5$, $X_{24}=1.04$; if $5 \leq a_{24}<10$, $X_{24}=1.1$; if $10 \leq a_{24}$, $X_{24}=1.15$.
a_{25}	a_{25} is the fault times. If $a_{25}=0$, $X_{25}=0.96$; if $0<a_{25}<2$, $X_{25}=1$; if $2 \leq a_{25} \leq 5$, $X_{25}=1.04$; if $5<a_{25} \leq 10$, $X_{25}=1.2$; if $10<a_{25}$, $X_{25}=1.4$.
a_{26}	If normal, $X_{26}=1$; if existing partial discharge, $X_{26}=1.1$.

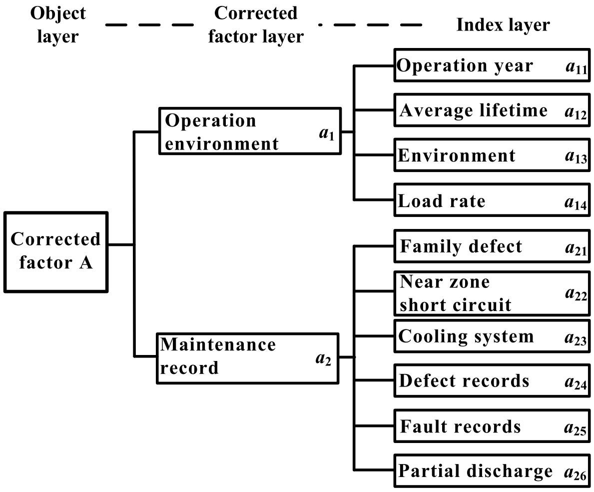

FIGURE 2. Assessing index system of the corrected parameters.

where *TH* is the comprehensive health index of a transformer and its range is within [0,100]; the smaller its value the better its health condition. *HI* is the insulation health index of the transformer; a_1 and a_2 are the corrected factors of operation environment condition and maintenance records, respectively.

In order to establish a model considering health index, fault rate, and practical operation years synthetically, a calculation equation of the comprehensive health index was applied and shown in (3). This equation has been widely used in condition assessment of electrical equipment [26].

$$TH = TH_0 \times e^{B\times(T_2 - T_1)} \tag{3}$$

where TH is the comprehensive health index; TH_0 is the initial value of the comprehensive health index, and it was set to be 5 in the paper; B is the aging parameter; T_1 is the first operation year; T_2 is the current operation year.

If the initial value and life end value of the comprehensive health index can be obtained, the aging parameter B can be calculated by (4) and (5). Assuming that the initial value of the comprehensive health index is set to be 5;T_{exp} is the expected lifetime of the transformer. It is expected that, after T_{exp} years operation, the fault rate of the transformer will rise rapidly and the health index will increase to 100. T_{exp} can be obtained by the relationship among the design lifetime, the corrected factors of operation environment condition, and maintenance records. The relationship among them is shown in (4).

$$T_{\exp} = \frac{T_{des}}{a_{11} \times a_{21}} \tag{4}$$

where T_{exp} is the expected lifetime of the transformer; T_{des} is the design lifetime of the transformer. ($T_{des} = 40$ in this study based on the service life of the actual transformers in China's power companies; a_{11} and a_{21} are the corrected factors of average lifetime and family defect, respectively.)

Therefore, the aging parameter B can be calculated by (5):

$$B = \frac{lnTH_{end} - lnTH_0}{T_{\exp}} \tag{5}$$

After obtaining the value of the aging parameter B, the predicted health index of the transformer can be calculated approximately by (6). Considering the influence of maintenance types, the equation of (3) can be revised to (6).

$$TH = TH_0 \times e^{B\times\Delta T'} \tag{6}$$

where $\Delta T'$ is the equivalent service age of the transformer.

Fuzzy theory is an easy and effective method for solving the insulation condition assessment problem [16]. Therefore, with the assessing index system and weights information in section II.A, fuzzy theory was applied to calculate the insulation health index of the transformer. The calculating steps are show as follows:

1. Normalize the index value, obtain the membership matrix of the indices according to the fuzzy membership function.
2. Using the weights information and membership function information, apply the fuzzy evaluation matrix to calculate the evaluation matrixes of the three factor layers.
3. Use these evaluation matrices to conduct fuzzy calculation to obtain an evaluation matrix of the insulation condition.
4. Establish the relationship between the evaluation matrix and the insulation health index of the transformer. Transform the information of the evaluation matrix to a health index value between 0-100 according to (7).

$$\begin{aligned} HI = m_r(H_1) \times 0 + m_r(H_2) \times 25 + m_r(H_3) \times 50 \\ + m_r(H_4) \times 75 + m_r(H_5) \times 100 \end{aligned} \tag{7}$$

where HI is the insulation health index; its range is within [0, 100]; 0 refers to the insulation condition of the transformer is very good, while 100 refers to the insulation condition is extremely severe.m_r is the final evaluation matrix;$m_r(H_n)$ is the possibility that the evaluation matrix supports the nth grade.

5. According to the historical records and Table 1, the corrected factors of the comprehensive health condition are determined by (1).
6. Calculate the comprehensive health index of the transformer by (2).
7. Establish the reliability model of the transformer by (8).

$$\lambda = K \times e^{C\times TH} \tag{8}$$

where λ is the fault rate of the equipment; K is the proportional factor;C is the curvature coefficient; TH is the comprehensive health index of the transformer.

According to the data of Table 1 in [27], C and K were calculated by method of inversion in (9) and $K = 0.011$, $C = 0.045$. The real data sets of TH and fault rate are obtained, and set $TH = [16.5\ 25.4\ 35.2\ 41.6\ 53.7]$, set *fault rate* = [0.03 0.028 0.048 0.084 0.121]. The parameters estimation coefficients are shown as follows: $K = 0.011$ (95% confidence bounds: [0.0073, 0.0147]), $C = 0.045$ (95% confidence bounds: [0.025, 0.065]); *SSE* (the sum of squares due to error): 0.0002756, *R-square* (coefficient of determination): 0.9565, Adjusted *R-square* (degree-of-freedom adjusted coefficient of determination): 0.942, *RMSE* (root mean squared error): 0.009585.

$$\lambda = \frac{l}{L} \times 100\% = \sum_{n=1}^{10} L_n \times K \times e^{C\times TH_n} \times 100\% \tag{9}$$

where λ is the fault rate of the equipment; l is the fault amount of the transformers; L is the total amount of the transformers, $n = 1, 2, \ldots, 10$; L_n is the amount number of the nth grade transformer; TH_n is the average value of the bound value of the nth grade.

III. MAINTENANCE STRATEGY SELECTION BASED ON RELIABILITY AND COST ANALYSIS OF TRANSFORMERS

A. OPERATION RISK EVALUATION MODEL OF TRANSFORMERS

Operation risk evaluation model of a transformer is usually related to financial losses. Financial losses of transformer failures not only include the repair or replacement cost of the transformer, but also contain the costs caused by the failure including environmental risk, injury risk, and service disruption risk. The operation risk of a transformer can be calculated by (10).

$$Risk = POTF \times LOTF \tag{10}$$

where *Risk* is the risk value of a transformer (unit: RMB); *POTF* is the probability of fault occurrence (fault rate λ), which is determined by II.C; *LOTF* is the financial loss of the transformer after suffering from fault; *LOTF* mainly includes system risk, fault repairing costs, security of the staffs, and environment influence.

$$LOTF = Loss_1 + Loss_2 + Loss_3 + Loss_4 \tag{11}$$

Towards the system risk, different fault types cause different financial losses. In order to calculate the financial loss of the transformer, the faults of the transformers were divided into normal fault, serious fault, and extremely serious fault. The definitions of the faults are shown as follows:

Normal fault-not emergency fault; the fault can be repaired within 24 hours;

Serious fault-emergency fault; the fault can be repaired within 2-10 days;

Extremely serious fault- extremely emergency fault; the fault can be repaired more than 10 days;

The fault probabilities of the three faults r_1,r_2, r_3 are determined by statistic data and they are 64.2%, 32.1%, and 3.7%, respectively [28].

If the transformer fails, the financial loss caused by cutting the load can be calculated by (12).

$$\begin{aligned} Loss_1 &= \sum_{t=1}^{3} S_N \times \cos\varphi \times l \times c_{11} \times t_{year} \times d_{11} \\ &\quad \times \theta \times \beta_1 \times e_{11} \end{aligned} \tag{12}$$

$$\theta = \theta_0 = 10RMB/kWh \tag{13}$$

$$\beta_1 = \beta_{11} \times \beta_{12} \tag{14}$$

where S_N is the capacity of the transformer; $cos\varphi$ is the average power factor, and $cos\varphi = 0.9$ in the paper;l is the transformer load rate; c_{11} is the cost differential between power generating and power supply, and $c_{11} = 0.2$ RMB/MWh in the paper; t_{year} is the hours in a year, and $t_{year} = 8760$h/year; d_{11} is the contribution rate of the transformer in the total power supply chain, and $d_{11} = 0.5$ in the paper; θ is the risk value of per electricity unit, the recommended value is θ_0; 10RMB/MWh in the paper [29]; e_{11} is the blackouts probability caused by transformer failures; β_1 is the corrected factor of system risk. It includes the importance of the substation β_{11}, the importance of the transformer load β_{12}. F_i $(i = 1, 2, 3)$ represents the load cutting probabilities under normal fault, serious fault, and extremely serious fault. They are 1%, 5%, and 10%, respectively; the fault times are set to 24, 120, and 240 hours, respectively. The values of them are determined by Table 2.

Using the Latin hypercube sampling techniques [30], the reliability indexes of a regional power grid are shown as follows:

BPCTF(the blackouts probability caused by transformer failures e11): 0.01, *PLC* (probability of load curtailments): 3.0477×10^{-3}, *EFLC* (expected frequency of load curtailments, unit: frequency/a): 1.9709 (time/a), *EDLC* (expected duration of load curtailments, unit: h/a): 26.6981 (h/a), *ADLC* (average duration of load curtailments, unit: h/frequency): 13.5454 (h/time), *ELC* (expected load curtailments, unit: MW/a): 100.1974 (MW), *EENS* (expected energy not supplied, unit: MWh/a): 679.5012 (MWh/a).

TABLE 2. Corrected parameters of system risk and repair cost.

Objects	Factors	Corrected parameters
The importance of the substation	The importance of the substation	Load-center substation, β_{11}=1.16; Connection substation or default, β_{11}=1; single-ended substation, β_{11}=0.8;
	The importance of the transformer load	Important load, β_{12}=1.16; general load or default, β_{12}=1;
The importance of the transformer load	Place of production	Local transformer (low cost), β_{21}=0.9; the transformers produced in China or default, β_{21}=1; the transformers produced in industrialized countries, β_{21}=1.3;
	Maintenance environment	Outdoor transformer (big tool can be used), β_{22}=1; inside transformer (big tool cannot be used), β_{22}=1.16

Fault repair costs include material costs, labor costs, equipment costs and other expenses. Failure repair costs can be calculated as follows:

$$Loss_2 = \sum_{i=1}^{3} C_i \times r_i \times \beta_2 \tag{15}$$

$$\beta_2 = \beta_{21} \times \beta_{22} \tag{16}$$

Probabilities of different fault types (normal fault, serious fault, and extremely serious fault) r_1, r_2, r_3 are 64.2%, 32.1%, 3.7%, respectively.$C_i(i = 1, 2, 3)$ refers to the repair costs of the transformer in different fault types. Under C_1 condition (normal fault), the fault repair costs of 110kV, 220kV, and 500kV transformers are 10,000 RMB, 20,000 RMB, and 30,000 RMB, respectively; under C_2 condition (serious fault), the fault repair costs of 110kV, 220kV, and 500kV transformers are 100,000 RMB, 200,000 RMB, and 280,000 RMB, respectively; under C_3 condition (extremely serious fault), the fault repair costs of 110kV, 220kV, and 500kV transformers are 1,800,000 RMB, 5,000,000 RMB, and 8,000,000 RMB, respectively. β_2 is the corrected factor of the repair cost. It includes place of production β_{21}, maintenance environment of the transformer β_{22}. Their values are shown in Table 2.

Personnel security risk mainly refers to security risk caused by accidents. It can be divided to three levels: minor injuries, injuries, deaths. They can be calculated by (17).

$$Loss_3 = \sum_{i=1}^{3} S_i \times r_i \tag{17}$$

S_i $(i = 1, 2, 3)$ refers the fault cost under different levels (minor injuries, injuries, and deaths). They are 20,000 RMB, 5,000,000 RMB, and 50,000,000 RMB, respectively. The occurrence probability of minor injuries, injuries, and deaths are set to be 1%, 0.5%, 0.1%, respectively.

Environmental risk refers to the risk of environment pollution after the transformer failure. Since the environment pollution is mainly caused by the oil spills and the release of carbon dioxide, the environmental risk can be calculated by (18).

$$Loss_4 = \sum_{i=1}^{3} E_i \times r_i \tag{18}$$

E_i ($i = 1, 2, 3$) represents the average environment cost under different fault types. They are 10,000 RMB, 100,000 RMB, and 200,000 RMB, respectively.

B. INFLUENCE OF DIFFERENT MAINTENANCE TYPES ON FAULT RATE

The maintenance recover effect always depends on the executing maintenance types of the transformer. According to engineering experience, when the value of the fault rate of a transformer is small, the condition of the transformer is good and the recover effect of the maintenance towards the fault rate is small. With the aging of the transformer insulation, the fault rate becomes bigger than before, the health condition of the transformer becomes worse, and the recover effect of the maintenance towards the fault rate is bigger than that of the small fault rate. If the no maintenance (including routine preventive inspection and condition monitoring) is taken, the recover value of fault rate is 0; If the minor repair is taken, the recover value of the fault rate is 0.2λ; If the major repair is taken, the recover value of the fault rate is 0.5λ; If the replacement maintenance is taken, the fault rate of the transformer is the same as a new one and $\lambda = \lambda_0$.

According to equations (3) to (8), the relationship between the equivalent service age T of the transformer and the fault rate λ can be described by (19).

$$\lambda = K \times e^{C \times TH_0 \times e^{B \times T}} \tag{19}$$

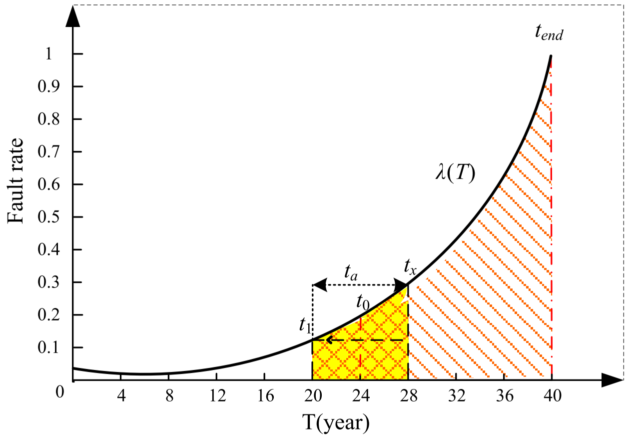

FIGURE 3. The relationship between the equivalent service age and the fault rate.

The relationship between the equivalent service age and the fault rate is shown in Figure 3. As shown in Fig.3, assuming that t_0 is the equivalent service age and λ_{t0} is the fault rate of the transformer at the time; t_x is the best maintenance operation time and λ_{tx} is the fault rate at that time; t_1 is the equivalent service age after the best maintenance operation time and λ_{t1} is the fault rate at that time; t_a ($a = 0, 1, 2, 3, 4$ representing no maintenance, minor repair, major maintenance, and replacement, respectively) is the equivalent rollback service age and its value is determined by executing the maintenance types. In other words, four maintenance types extend the transformer equivalent service age t_a ($a = 0, 1, 2, 3, 4$) years.

With the different maintenance types, the relationship between the equivalent service age and the recover value of the fault rate were built and shown in (20).

$$Recover_a = \begin{cases} 0 & a = 0 \\ 0.2\lambda & a = 1 \\ 0.5\lambda & a = 2 \\ \lambda - \lambda_0 & a = 3 \end{cases} \tag{20}$$

Assuming that the relationship between the maintenance costs and the maintenance types are calculated by (21).

$$\begin{cases} Overhaul_{a110kV} = \begin{cases} 0 & a = 0 \\ C_{a1} \times (1+\lambda) & a = 1 \\ C_{a2} \times (1+\lambda) & a = 2 \\ C_{a3} & a = 3 \end{cases} \\ Overhaul_{a220kV} = \begin{cases} 0 & a = 0 \\ C_{a1} \times (1+\lambda) & a = 1 \\ C_{a2} \times (1+\lambda) & a = 2 \\ C_{a3} & a = 3 \end{cases} \\ Overhaul_{a500kV} = \begin{cases} 0 & a = 0 \\ C_{a1} \times (1+\lambda) & a = 1 \\ C_{a2} \times (1+\lambda) & a = 2 \\ C_{a3} & a = 3 \end{cases} \end{cases} \tag{21}$$

where $Ca1$ of the 110kV, 220kV, and 500kV transformers are 100,000 RMB, 200,000 RMB, and 280,000 RMB, respectively; $Ca2$ of the 110kV, 220kV, and 500kV transformers are 480,000 RMB, 1,000,000 RMB, and 3,600,000 RMB, respectively (the major repair costs of the 110kV, 220kV, and 500kV transformers are 6% of their purchase cost [31]; $Ca3$ of the 110kV, 220kV, and 500kV transformers are 8,000,000 RMB, 17000000 RMB, and 60,000,000 RMB, respectively.

C. MAINTENANCE SELECTION MODEL OF TRANSFORMERS

The aim of the maintenance selection model is to ensure the fault rate of the transformer within an acceptable range and to obtain the maximum power supply benefit under minimum maintenance costs. Some regulations are provided for selecting the best maintenance strategy including the equal cost regulation (the best maintenance strategy is obtaining the maximum benefit under the same cost and the constraint conditions), the equal benefit regulation (the best maintenance strategy is to obtain the minimum cost under the same benefit and the constraint conditions), and the cost-to-income ratio regulation (the best maintenance strategy is to acquire the minimum cost-to-income ratio under the constraint conditions). The equal benefit regulation is selected in the paper because it can simplify the maintenance selection model [32].

The first task of the maintenance selection model is to analyze and determine the benefit function and the cost function of a transformer. The benefit function and the cost function can be analyzed and built by Figure 3. As shown in Figure 3, t_0 is the equivalent service age and λ_{t0} is the fault rate of the transformer at the time; t_x is the best maintenance operation time and λ_{tx} is the fault rate at that time; t_1 is the equivalent service age after the best maintenance operation time and λ_{t1} is the fault rate at that time; t_a ($a = 0, 1, 2, 3, 4$ representing no maintenance, minor repair, major repair, and replacement, respectively) is the equivalent rollback service age and its value is determined by the maintenance types. In other words, four maintenance types extend the transformer equivalent service age t_a ($a = 0, 1, 2, 3, 4$) year. Therefore, the reward function of different maintenance types can be calculated by (22).

$$\begin{aligned} Reward_a = {} & \int_{t1}^{tx} powerearn_a dt - \int_{t1}^{tx} Risk_a dt \\ & - \int_{t1}^{tx} powerloss_a dt - overhaul \cos t_a \\ = {} & \int_{t1}^{tx} \left(S_N \times \cos\varphi \times l \times b_1 \times c_{11} \times t_{year} \times d_{11}\right) dt \\ & - \int_{t1}^{tx} (\lambda_a \times LOTFa) dt \\ & - \int_{t1}^{tx} \left(PK_l \times t_{year} + Pk_0 \times l \times l \times t_\tau\right) dt \\ & - overhaulcost_a \end{aligned} \tag{22}$$

The best maintenance strategy is executing the *ath* ($a = 0, 1, 2, 3, 4$ representing no maintenance, minor repair, major repair, and replacement, respectively) at t_x time. Considering the fault rate should be in an acceptable range, therefore, the maintenance selection problem was transformed to the maximization problem in (23).

$$\begin{cases} F = Max\ (Rewarda) \\ = Max\left(\int_{t1}^{tx} powerearn_a dt - \int_{t1}^{tx} Risk_a dt\right. \\ \left. - \int_{t1}^{tx} powerloss_a dt - overhaulcost_a\right) \\ = Max\left[\int_{t1}^{tx} \left(S_N \times \cos\varphi \times l \times b_1 \times c_{11} \times t_{year} \times d_{11}\right) dt\right. \\ - \int_{t1}^{tx} (\lambda \times LOTF_a)\, dt \\ \left. - \int_{t1}^{tx} \left(Pk_l \times t_{year} + Pk_0 \times l \times l \times t_\tau\right) dt - overhaulcost_a\right] \\ Constraints: 0 \le \lambda \le \lambda_{attention};\ t_1 \le t_x \end{cases} \tag{23}$$

where F is the function expression of the maximization problem; $Reward_a$ is the reward of the *ath* maintenance at t_x time; $\int_{t1}^{tx} powerearnadt$ is the power supply benefit value of the transformer by executing the *ath* maintenance from range t_1 to t_x; $\int_{t1}^{tx} Riskadt$ is the operation risk value of the transformer by executing the ath maintenance from range t_1 to t_x; $\int_{t1}^{tx} powerlossdt$ is the power loss value of the transformer, mainly considering the active power loss, by executing the *ath* maintenance from range t_1 to t_x; $overhaulcost_a$ is the maintenance cost by executing the *ath* maintenance; S_N is the capacity of the transformer; $cos\varphi$ is the average power factor, and $cos\varphi = 0.9$ in the paper;l is the transformer load rate; c_{11} is the cost differential between power generating and power supply, and $c_{11} = 0.2$ RMB/MWh in the paper; t_{year} is the hours in a year, and $t_{year} = 8760$ h/year; d_{11} is the contribution rate of the transformer in the total power supply chain, and $d_{11} = 0.5$ in the paper; λ is the probability of fault occurrence, which is determined by 2.3; $LOTF$ is the financial loss of the transformer after suffering from fault;Pk_l is the no-load active loss of the transformer; Pk_0 is the short circuit active loss of the transformer; t_τ is the average maximum load loss hours in one year, $t_\tau = 5600$h in the paper; $\lambda attention$ is the maximum acceptable transformer fault rate of the transformer, $\lambda attention = 0.3$ in the paper. If Max($Rewarda$) is obtained, the best maintenance type a and best maintenance executing time t_x can be determined.

D. MAINTENANCE OPTIMIZATION MODEL BASED ON PARTICLE SWARM OPTIMIZATION (PSO)

PSO shares some similarities with other evolutionary algorithms (e.g. genetic algorithms), however the classical PSO does not use evolution operators including crossover and mutation. PSO emulates and works on the social behavior of particles in the swarm. During the iterative search in the d-dimensional solution space, each particle in the swarm will adjust its flying velocity and position according to its own flying experience as well as those of the others [33]. The major advantage of PSO is that it uses the physical movements of the individuals in the swarm and has a flexible and well-balanced mechanism to enhance and adapt to the global and local exploration abilities. Another advantage of PSO is its simplicity in coding and consistency in performance. So in this study we use the PSO to optimize the model.

In each iteration, the velocity $v_i^d(t)$ and position $p_i^d(t)$ of particles are updated by the following equations

$$\begin{cases} v_i^d(t+1) = v_i^d(t) + c_1 r(t)\left(p_i^d(t) - x_i^d(t)\right) \\ \qquad\qquad + c_2 r(t)\left(p_g^d(t) - x_i^d(t)\right) \\ x_i^d(t+1) = x_i^d(t) + v_i^d(t) \end{cases} \tag{24}$$

where c_1 and c_2 are two acceleration constants. $r(t)$ is a random variable that is drawn from an uniform distribution in the open interval (0, 1). The velocity $v_i^d(t)$ is restricted to the $[-v_{max}, v_{max}]$ range in which v_{max} is a predefined boundary value. $p_i^d(t)$ is the best solution that particle i has obtained until iteration t, and $p_g^d(t)$ represents the best solution obtained among all particles in the swarm thus far.

As PSO has strong global optimization ability, it has been applied to select the best maintenance method and

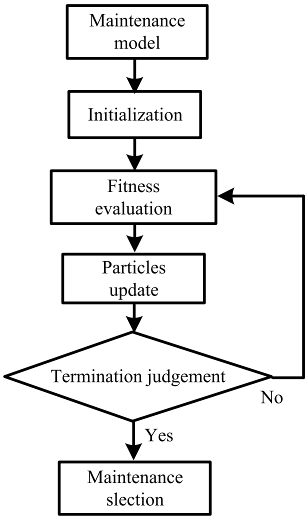

FIGURE 4. Flowchart of maintenance optimization.

maintenance time by solving the function maximization problem in (23) for the power transformer. The flow chart is shown in Figure 4.

The main processes of the model are as follows:

1) INITIAL SELECTION OF THE MAINTENANCE

Establish the maintenance optimization model according to the comprehensive health index of the transformer and the constraints.

2) PSO INITIALIZATION

Initial the PSO method to different maintenance model. Define d (d =2) dimension space; randomly generate initial particle $X_1, \ldots, X_i, \ldots, X_s$ to form population X; set Population to be 24; set the maximum value of the particle speed change to be $v_{max} = 0.2\times$ rang (TH); set acceleration constant value to be $c_1 = 2$, $c_2 = 2$ and set the maximum particle evolution generation to be $T_{max} = 2,000$.

3) FITNESS EVALUATION

Determine the initial fitness values of the particles in the search space; compare the fitness degree of each particle with individual extremum of each particle p_{id}; if current value is better than p_{id}, set p_{id} to be the current value and record the position of the individual extremum; compare the fitness of each particle with global extremum p_{gd}, if current value is better than p_{gd}, set p_{gd} to be the current value and record the position of the global extremum p_{gd}.

4) PARTICLES UPDATE

Update the speed and position of the particles to obtain the best global solution.

5) TERMINATION JUDGMENT OF THE MODEL

If the maximum generation T_{max} is met or the value of errors is smaller than the given accuracy eg = 10-25, terminate the PSO processes. If not, turn to process 3.

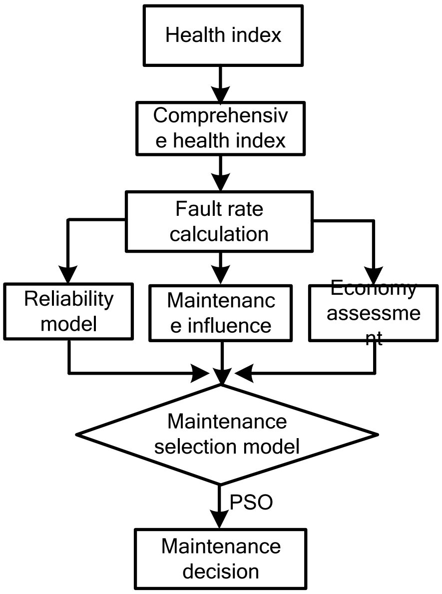

FIGURE 5. Flowchart of maintenance decision making.

6) MAINTENANCE TIME AND MAINTENANCE METHOD SELECTION

Determine the maintenance strategy of the transformer according to the best results under different maintenance types.

E. MAINTENANCE DECISION MAKING FLOWCHART OF OIL-FILLED TRANSFORMERS

Maintenance decision making flowchart of power transformers can be shown in Figure 5 and summarized as following steps.

Step 1: Calculate the insulation health index of the transformer by steps 1-4 in section II.C.

Step 2: Calculate the comprehensive health index of the transformer by steps 5-6 in section II.C.

Step 3: Calculate the fault rate of the transformer by step 7 in section II.C.

Step 4: Obtain the calculation results of operation fault rate, operation risk evaluation, and influence of different maintenance types on fault rate by processes of section II.C, section III.A, and section III.B, respectively.

Step 5: determine the unknown parameters and establish the maintenance selection model (equation (23) in section III.D), according to calculation results of fault rate (section II.C), operation risk evaluation (section III.A), and influence of different maintenance types on fault rate (section III.B).

Step 6: Use the PSO method (section III.D) to solve the maintenance selection model to make an optimal maintenance decision.

IV. CASES STUDY

A. CASE 1- A 150 MVA 220 kV TRANSFORMER

A 220kV, 150MVA outside power transformer works in Yunnan province. Its first operation was in the year of 1998.

TABLE 3. Preventive test data of the transformer.

Testing items	Testing dates		
	Initial values	2012-2	2012-8
Furfural content (mg/L)	0	/	0.013
Humidity content (mg/L)	/	/	6.5
Dielectric loss of oil (%)	/	/	0.031
Breakdown voltage of oil (kV)	63.1	/	58.7
DC resistance of winding* (%)	0.11	/	0.31
Core earthing current (A)	/	/	0.032
Absorption	1.8	/	1.647
Dielectric loss of winding (%)	/	/	0.195
Dielectric loss of capacity type bushing (%)	0.3	/	0.33
H_2 (μL)	3.5	16.3	17.23
CH_4(μL)	3.2	20.64	25.79
C_2H_6(μL)	0	7.01	6.34
C_2H_4(μL)	0	15.23	16.21
C_2H_2(μL)	0	0	0
CO(μL)	232.8	/	637.2
Total hydrocarbon(μL)	3.2	42.88	48.34

* The maximum of interphase unbalance coefficient

TABLE 4. Result of membership degrees.

Membership Degrees	D_1	D_2	D_3	D_4	D_5
11	0	0.8510	0.1490	0	0
12	0.9709	0.0291	0	0	0
13	0.0443	0.9557	0	0	0
14	0	0.9719	0.0281	0	0
15	0	0.977 9	0.0221	0	0
21	0	1.0000	0	0	0
22	0.1597	0.8403	0	0	0
23	0.3084	0.6916	0	0	0
24	1.0000	0	0	0	0
31	0.9156	0.0844	0	0	0
32	0	1.0000	0	0	0
33	0	1.0000	0	0	0
34	0	0.9843	0.0157	0	0
35	0	0	1.0000	0	0
	0.248 9	0.657 4	0.093 7	0	0

Its average load rate is about 80%. The maximum temperature in its operation years was 33.5 °C. The data of preventive tests are shown in Table 3.

The steps of maintenance decision making is shown in Figure 5:

Step 1: the relative degree of degradation of the indices was calculated according to article [16]: $E_1 = \{e_{11}, e_{12}, e_{13}, e_{14}, e_{15}\} = \{0.3465, 0.0937, 0.2100, 0.3242, 0.3223\}$; $E_2 = \{e_{21}, e_{22}, e_{23}, e_{24}\} = \{0.25, 0.1905, 0.1731, 0.065\}$; $E_3 = \{e_{31}, e_{32}, e_{33}, e_{34}, e_{35}\} = \{0.1058, 0.3060, 0.3060, 0.3200, 0.4714\}$. Using the results of fuzzy membership degrees in Table 4 and the weights information in II.A, the calculation method of fuzzy matrix was applied and the health judgment matrix of the transformer was obtained and $E = \{0.2489, 0.6574, 0.0937, 0, 0\}$. The matrix was transformed to health index by (7), and the comprehensive health index of the transformer was obtained (the health index of the transformer is 21.12).

Step 2: according to other related information, the other corrected factors were equal to 1, except $a_{11} = 1.02$, $a_{13} = 1.02$, $a_{14} = 0.9694$. Where, a_{23}, a_{24}, a_{25} were all set to be 1 by using the default value. According to (1), $a_1 = 1.0085$, $a_2 = 1$. Based on (2), $TH = 21.30$.

Step 3: In addition, according to (3) - (6), the aging coefficient $B = 0.0749$, equivalent service age $\Delta T'$ equaled to19.3511 years. according to (8), $POTF = \lambda_0 = 0.0289$.

Step 4: *POTF* can be obtained in step 3. Based on (10) - (12) and Figure 3, influence of different maintenance types on fault rate can be obtained. According to (15) - (21), $loss_1$=1.744×105 RMB, $loss_2$= 2.250×105 RMB, $loss_3$= 1.000×104 RMB, $loss_4$= 4.592×104 RMB. Based on (14), the financial loss after the failure of the transformer was *LOTF*=2.0254×106 RMB.

Step 5: use the results of step 4 to determine the unknown parameters of the equation (23) in section III.D.

Step 6: Based on (10) - (12) and (22) - (23), according to the flowchart of maintenance optimization (Figure 4) in III.C, the optimization results under different maintenance types were established in Fig.6. As shown in Figure 6, four subgraphs were named optimization results under no maintenance, optimization results under minor repair, optimization results under major repair, optimization results under replacement and represented by Figure 6 (a), Figure 6 (b), Figure 6 (c), and Figure 6 (d), respectively. As shown in Figure 6 (a), horizontal axis (epoch) represents the particle evolution generation of PSO; vertical coordinates represent the optimal value of function F; for partial dynamics, dimension 1 represents the maintenance type of a transformer; dimension 2 represents the optimal *TH* value under this maintenance type; Some parameters of PSO model were set in section III.D and displayed in Figure 6 (a). Figure 6 (b), Figure 6 (c), and Figure 6 (d) shows the similar information as Figure 6 (a). The maximum value of the function F under different maintenance types (including no maintenance, minor repair, major repair, and replacement) were 2.5273×108, 2.0759×108, 5.1786×108 and 5.0681×108, respectively. The best maintenance strategy is executing the major repair after 16.4288 years (35.7799 - 19.3511). According to the equivalent service age $\Delta T'$=19.3511, the actual operation time was roughly the same as the equivalent service age. Therefore, it can be deduced that the transformer is aging in the normal rate. In addition, the health index of the transformer was 21.30, which represents the transformer was still in a normal condition. Only routine preventive inspection and condition monitoring are recommended to act to the transformer and there was no need to arrange maintenance for the near term. Therefore, to get the maximum benefit, major repair will be taken after 16.4288 years is reasonable.

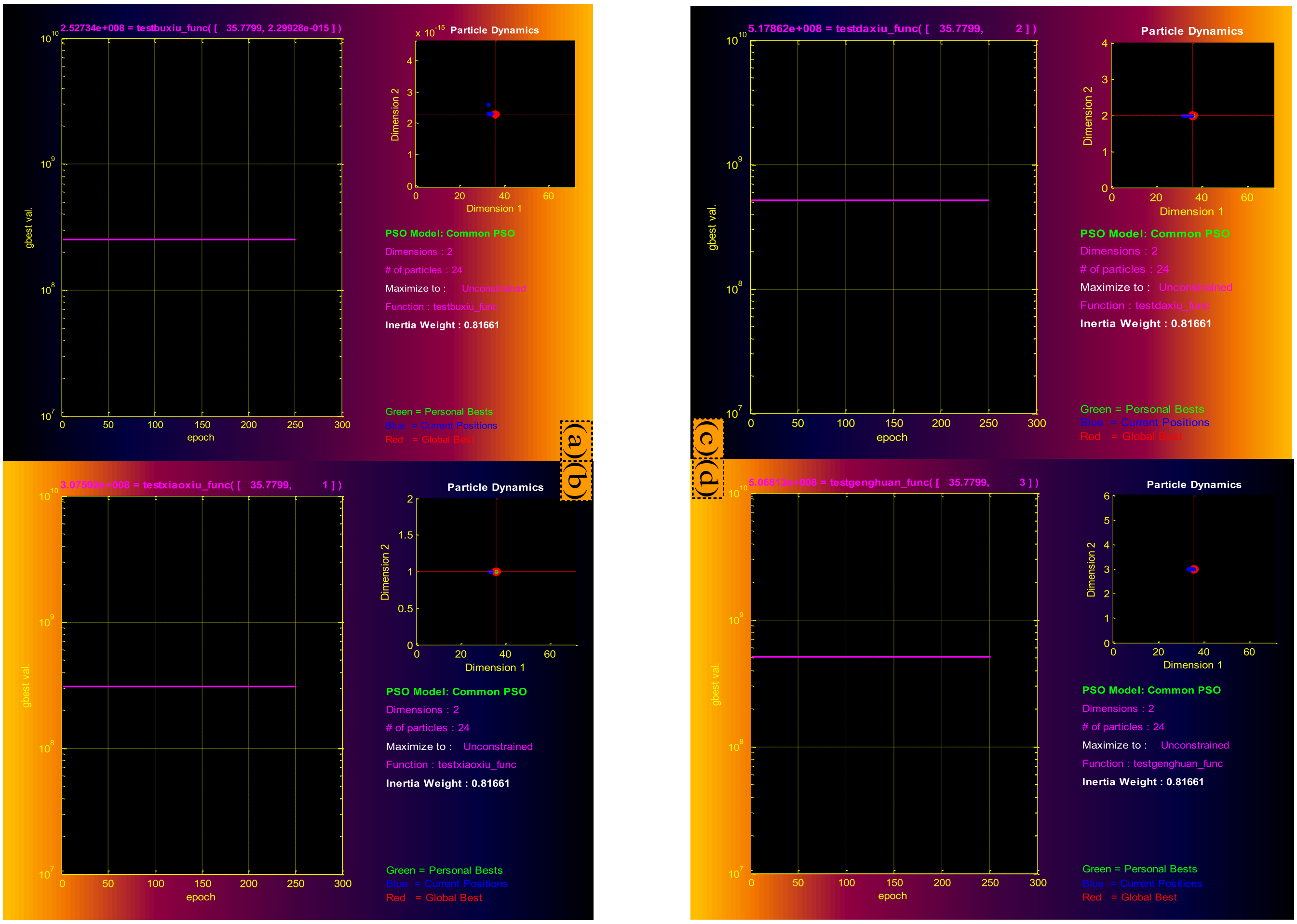

FIGURE 6. Optimization results under different maintenance types (a)–(d) (case 1).

By applying the condition assessment methods of fuzzy evidential and cloud evidential in [16] and [34] respectively, the results of the condition assessment the transformer are shown in(25)and (26), respectively. The results demonstrate that the transformer is still in a good condition and the suggested maintenance action is prolonging maintenance cycle, which is consistent with the recommended maintenance type of the proposed method.

Comparing with the other two methods, the results of the three methods for maintenance decision making is no maintenance in the short team, however the proposed method provide a quantitative maintenance time which is better than the other two methods [35]. Actual situation was that, until August 2015, the transformer was in a normal condition, there was no fault in the transformer.It demonstrates that the proposed model is an effective method.

$$T1 = \{0.12600.85810.00240.006800.0067\} \tag{25}$$

$$T2 = \{0.07690.91250.0021000.0042\} \tag{26}$$

B. CASE 2-A 240 MVA 220 kV TRANSFORMER

A 220kV, 240MVA, SFPSZ1-240000/220, outside power transformer works in China. The body data, the operational history, and the maintenance records of the transformer in [16] were selected to demonstrate the efficiency of the proposed model.

Following the steps of maintenance decision making in Figure 5:

Step 1: the relative degree of degradation of the indices was calculated according to article [16]: $E_1 = \{e_{11}, e_{12}, e_{13}, e_{14}, e_{15}\} = \{0.0042, 0.1112, 0.3942, 0.4904, 0\}$; $E_2 = \{e_{21}, e_{22}, e_{23}, e_{24}\} = \{0, 0.4152, 0.2513, 0.1452, 0.1883\}$; $E_3 = \{e_{31}, e_{32}, e_{33}, e_{34}, e_{35}\} = \{0\, 0.4293, 0.1867, 0.2981, 0.0859\}$. Using the weights information in II.A, the calculation method of fuzzy matrix was applied and the health judgment matrix of the transformer was obtained and $E = \{0.0017, 0.2977, 0.2928, 0.3185, 0.0893\}$. The matrix was transformed to health index by (7), and the comprehensive health index of the transformer was obtained (the health index of the transformer is 54.9).

Step 2: according to other related information, the other corrected factors were equal to 1, except $a_{11} = 1.05$, $a_{13} = 1.02$, $a_{14} = 0.97$, $a_{21} = 1.04$, and $a_{23} = 1.04$. Where, a_{23}, a_{24}, a_{25} were all set to be 1 by using the default value. According to (1), $a_1 = 1.0382$, $a_2 = 1.0816$. Based on (2), $TH = 61.6498$.

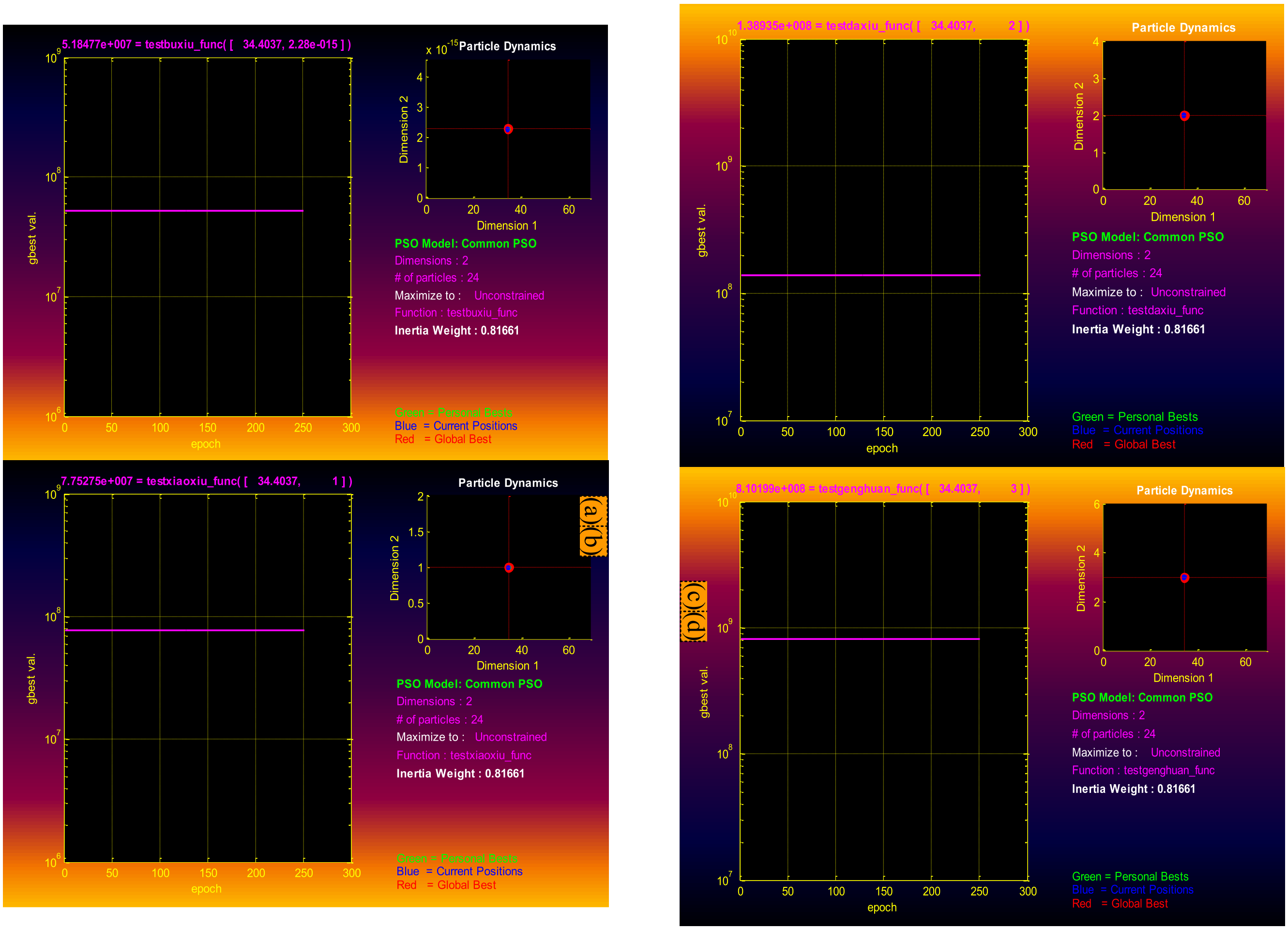

FIGURE 7. **Optimization results under different maintenance types (a)–(d) (case 2).**

Step 3: In addition, according to (3) - (6), the aging coefficient $B = 0.0779$, equivalent service age $\Delta T'$ equaled to 32.2514 years. according to (8), $POTF = \lambda_0 = 0.18$.

Step 4: *POTF* can be obtained in step 3. Based on (10) - (12) and Figure 3, influence of different maintenance types on fault rate can be obtained. According to (15) - (21), $loss_1$ =1.744×105 RMB, $loss_2$ = 2.250×105 RMB, $loss_3$ = 1.000×104 RMB, $loss_4$ = 4.592×104 RMB. Based on (14), the financial loss after the failure of the transformer was $LOTF$ = 2.0254×106 RMB.

Step 5: use the results of step 4 to determine the unknown parameters of the equation (23) in section III.D.

Step 6: Based on (10) - (12) and (22) - (23), according to the flowchart of maintenance optimization (Figure 4) in III.C, the optimization results under different maintenance types were established in Fig.7. As shown in Figure 7, four subgraphs were named optimization results under no maintenance, optimization results under minor repair, optimization results under major repair, optimization results under replacement and represented by Figure 7 (a), Figure 7 (b), Figure 7 (c), and Figure 7 (d), respectively. As shown in Figure 7 (a), horizontal axis (epoch) represents the particle evolution generation of PSO; vertical coordinates represent the optimal value of function F; for partial dynamics, dimension 1 represents the maintenance type of a transformer; dimension 2 represents the optimal *TH* value under this maintenance type; Some parameters of PSO model were set in section III.D and displayed in Figure 7 (a). Figure 7 (b), Figure 7 (c), and Figure 7 (d) shows the similar information as Figure 7 (a). The maximum value of the function F under different maintenance types (including no maintenance, minor repair, major repair, and replacement) were 5.1848×107, 7.7528×107, 1.3894×108 and 8.1020×108, respectively. The best maintenance strategy is executing the replacement after 2.1523 years (34.4037 - 32.2514). According to the equivalent service age $\Delta T' = 32.2514$, the actual operation time was much smaller than the equivalent service age [36].Therefore, it can be deduced that the transformer was aging in the accelerated rate. In addition, the health index of the transformer was 61.6498, which represents the transformer was still in a serious condition. Therefore, to get the maximum benefit, replacement will be taken after 2.1523 years is reasonable.

By applying the condition assessment methods of fuzzy evidential and cloud evidential respectively in [16] and [34], the results of the condition assessment the transformer are shown in (27) and (28), respectively. The results demonstrate that the transformer is in a serious condition and the suggested maintenance action is executing major repair as soon as possible. However, as shown in Figure 7, executing replacement is more economic than executing major repair, which means the proposed method is an effective method.

Comparing with the other two methods, the results of the three methods for maintenance decision making is replacement after 2.1523 years, however the proposed method provide a quantitative maintenance time which is better than the other two methods. The actual situation was that, the transformer was executed major repair after 1 month; however, the loss and the fault rate of the transformer were too high to obtain a well benefit [37]. The transformer was recommended to replace in the end, which demonstrated that the proposed model is an effective method to solve maintenance decision making problem.

$$T1 = \{0.00010.00460.03600.94400.00010.0152\} \quad (27)$$

$$T2 = \{0.00110.24450.34320.34720.03360.0042\} \quad (28)$$

V. CONCLUSIONS

According to some relevant standards and expert experience, based on the establishment of an insulation evaluation system, a maintenance decision making optimization model of power transformers considering both reliability and economy was proposed in the paper. The achievements are shown as the follows:

A reliability evaluation model of power transformers was established in the paper. DGA tests, oil tests and electrical tests were selected to assess the insulation condition of transformers. With the insulation condition assessing result, the operation environment and maintenance records were chosen to be corrected parameters for calculating the comprehensive health index of transformers. Based on the relationship between the comprehensive health index and fault rate and the influence of the maintenance actions towards the fault rate, a reliability evaluation model of the transformer was presented in the paper. Reliability assessing results of transformers shows that the reliability evaluation model is an effective method because it not only includes the insulation of transformers but also considers the operation environment and maintenance records of transformers.

Based on the PSO method, a maintenance optimization method considering reliability and economy assessment was proposed in the paper, which can be used to determine the best time and the best maintenance type for the transformer maintenance. Two cases were studied and the results demonstrated that the proposed model is effective. The proposed model can offer a new thinking to transformer maintenance selection.

However, the research of the condition based maintenance and maintenance decision making is still in its infant stage. It is hard to collect plentiful practical economic data and test data before and after maintenance actions. Therefore, it is hard to get the precise value of some parameters and the practical influence of different maintenance actions under different comprehensive health index values [38]. In addition, some parameters are obtained by some subject experience in the risk evaluation of the transformer. Therefore, the future study is to improve the precision of the maintenance decision making model.

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M.D., H.Z. and Y.Z. designed the algorithms and performed the writing. K.S., S.Y., X.K., G.D., and L.G. analyzed the data; all authors have approved the submitted manuscript. The authors also thank the anonymous reviewers and the editor for their valuable comments. *(Hanbo Zheng and Yiyi Zhang contributed equally to this work.)*

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Authors' photographs and biographies not available at the time of publication.

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