Risk-Cost Integrated Assessment Based Overhaul Strategies for Transformers

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***Abstract*—Reliable operation of transformers is of significant importance to the entire power system concerned. Therefore, it is necessary to reduce the failure rate of transformers through timely overhaul. Given this background, the optimal overhaul planning problem for transformers is addressed in this work based on risk-cost integrated assessment. First, a linear aging regression model is established employing the Weibull distribution based failure rate model of transformers. The investment and operation costs of transformers are next classified and calculated according to the theory of Life Cycle Cost (LCC). Subsequently, from the perspective of managing risk, the optimal overhaul time under different overhaul frequencies is formulated as an optimization problem and solved by the Particle Swarm Optimization (PSO) algorithm, and economic analysis based on the annual average LCC is carried out. Finally, a case study is conducted to demonstrate the proposed approach.**

Keywords—transformer, failure rate, life cycle cost, overhaul strategies

I. INTRODUCTION

As a kind of core devices in power systems, transformers need to be carried out regular overhaul so as to maintain a low-risk operating state. Some overhaul strategies have been developed such periodic overhaul and post-failure overhaul. These existing overhaul strategies cannot well meet the ever-increasing security and reliability requirements in modern power system operation. Consequently, it is necessary to develop more sophisticated overhaul strategies for transformers [1].

When developing optimal overhaul strategies for transformers, the frequency of overhaul actions should be appropriate. An appropriate frequency of overhaul actions can effectively reduce the failure rate as well as the costs of operation and maintenance. Therefore, reasonable overhaul strategies of transformers must consider both operational reliability and cost-effectiveness. Ref [2] proposed a power system condition-based overhaul technique based on transformer outage models, aiming to formulate overhaul strategies for power systems with minimal system risk. However, it did not consider the economic factors of overhaul. Ref [3] presented a method for calculating the Life Cycle Cost (LCC) of transformers, which did consider economic aspects but did not delve into the analysis of transformer failure mechanisms or establish corresponding overhaul decision models.

Given the above mentioned background, a comprehensive decision-making approach for determining overhaul schedule of transformers is presented with both operational reliability and cost-effectiveness taken into account. First, a failure rate model is presented for transformers under given overhaul strategies. Then, the LCC theory is employed to determine the cost variations for transformers. Afterward, the optimal overhaul strategies under different overhaul frequencies are addressed. Finally, comparisons and analyses are conducted using the equivalent annual average risk cost to derive the ultimate overhaul strategy.

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II. TRANSFORMER FAILURE RATE MODEL FOR GIVEN OVERHAUL STRATEGIES

A. *Failure Rate Model Based on Weibull Distribution*

The failure rate is fundamental to the study of transformer reliability and refers to the proportion of devices experiencing failures within a time interval Δt among a large number of identical devices. Based on extensive historical data [4], the distribution of typical failure rates for transformers is illustrated in Fig. 1.

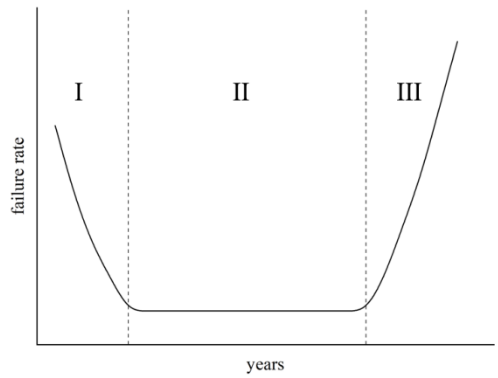

Fig. 1. Typical Distribution of Failure Rates for Electrical Transformer

Area I in the figure represents the early operational phase of transformers, during which failures may occur due to design or installation and commissioning processes. Area II represents the normal operating phase of transformers, during which the failure rate remains consistently low. Area III represents the wear and aging phase of transformers, where the failure rate increases rapidly with time.

Currently, the prevailing mathematical models for describing transformers failure rates include the exponential distribution, normal distribution, and Weibull distribution. Among these, the Weibull distribution is the most widely applicable because it can simulate various phases of transformer operation by adjusting its parameters [5]. The expression for the Weibull distribution is as follows:

$$\lambda(t)=\frac{m}{\eta}\cdot(\frac{t}{\eta})^{m-1}+\gamma \quad (1)$$

Where $\boldsymbol{m}$ is the shape parameter, $\boldsymbol{\eta}$ is the scale parameter, and $\boldsymbol{\gamma}$ is the initial location parameter. By varying the value of parameter $\boldsymbol{m}$, different stages of the bathtub curve can be simulated. Specifically: When $\boldsymbol{m}$<1, the failure rate follows a decreasing trend, indicating that the transformer is in its initial break-in phase. When $\boldsymbol{m}$=1, the failure rate remains constant, signifying stable transformer operation with a low failure rate. When $\boldsymbol{m}$>1, the failure rate exhibits an increasing trend, indicating that the transformer is experiencing significant aging and wear, leading to a rapid increase in the failure rate over time.

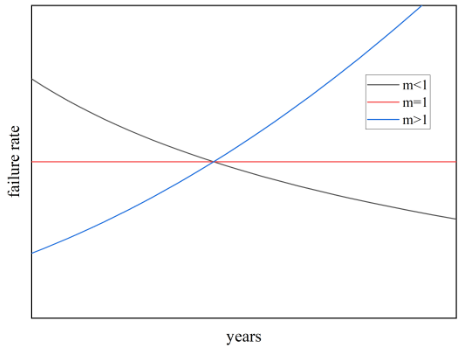

Fig. 2. Influence of Shape Parameter on the Weibull Distribution

B. The Linear Decrement Model of Age Regression

To quantitatively characterize the effectiveness of overhaul actions, this paper employs an age-regression model to represent the impact of overhaul strategies on the failure rate of transformers. Age regression refers to the significant increase in reliability of transformer after an overhaul, which is equivalent to reducing the operational time on the transformer's failure rate-time curve. Simultaneously, the maintenance costs for the transformer decrease, indicating that the transformer's equivalent age regresses.

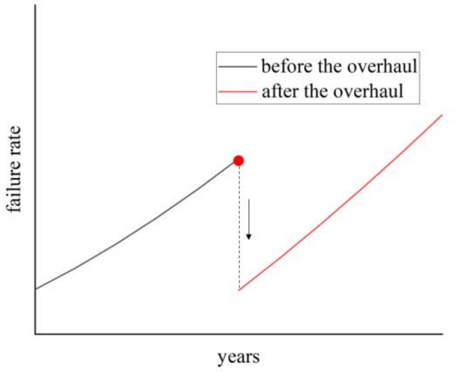

Fig. 3. Changes in Failure Rate Caused by Overhaul

After the regression, the equivalent service life of the transformer will decrease compared to the actual service life. However, in real-life situations, this reduction is not fixed but rather represents a long-term phenomenon of repair fatigue. In other words, as the number of overhaul actions increases, the effectiveness of overhaul gradually decreases, and the amount of age regression also decreases [6]. In this work, a linear decrement transformer age regression model is employed to address the limitations of traditional models that cannot account for repair fatigue phenomena. The age regression quantity $\boldsymbol{\tau_i}$ for a transformer after the $\boldsymbol{i}$-th repair is defined as:

$$\tau_i=\eta_1\cdot T_{1,0}+...+\eta_i\cdot T_{i,i-1}+\frac{i(i-1)}{2}k \quad (2)$$

Therefore, the equivalent service life $\boldsymbol{e_i}$ of the transformer after the $\boldsymbol{i}$-th repair can be expressed as:

$$e_i=t_n-\tau_i=t_n-[\eta_1\cdot T_{1,0}+...+\eta_i\cdot T_{i,i-1}+\frac{i(i-1)}{2}k] \quad (3)$$

Where $\boldsymbol{t_n}$ represents the actual service life of the transformer, $\boldsymbol{\eta_i}$ is the age regression factor at the $\boldsymbol{i}$-th repair, which indicates the extent of the repair. The value range of $\boldsymbol{\eta_i}$ is (0,1), and it decreases with the increase of overhaul action times. $\boldsymbol{T_{i,i-1}}$ represents the time interval between the $\boldsymbol{i}$-th and ($\boldsymbol{i}$-**1**)-th overhaul actions, and $\boldsymbol{k}$ is the decay factor.

Assuming that the transformer undergoes overhaul actions at three different times, $\boldsymbol{t_1}$, $\boldsymbol{t_2}$, and $\boldsymbol{t_3}$, it can be observed from the figure below that the new model used in this paper better fits the depiction of overhaul fatigue phenomena compared to the original model. As the number of overhaul actions increases, the age regression gradually decreases, aligning with real-world scenarios.

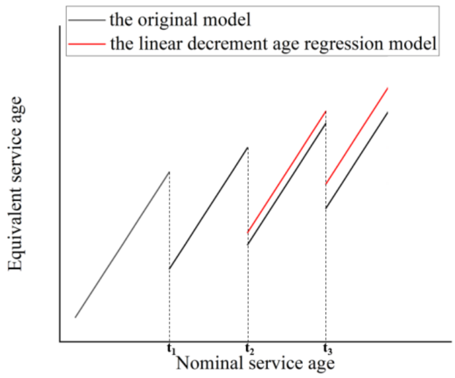

Fig. 4. Linear Decrement Age Regression Model

By utilizing the Weibull distribution-based transformer failure rate model and the linear decrement age regression model, it becomes possible to quantitatively depict the changes in the transformer's failure rate during its service life, as well as the reduction in the failure rate due to overhauls. Therefore, this model plays a crucial role in assessing the risk associated with overhaul strategies.

III. The LCC Model of Transformers

A. Classification of transformer costs

Considering the cost-effectiveness of overhaul strategies requires aggregating the costs of transformers based on the theory of LCC. The LCC refers to the sum of all expenses incurred over the lifespan of a transformer, including design, development, production, transformer operation, overhaul, accident losses, and even disposal. The LCC model for transformers can be represented using the following equation:

$$LCC=C_1+C_2+C_3+C_4+C_5 \quad (4)$$

Where $\boldsymbol{C_1}$ represents the initial investment cost of the transformer, $\boldsymbol{C_2}$ represents the operational costs, $\boldsymbol{C_3}$ represents the maintenance costs, $\boldsymbol{C_4}$ represents the outage or downtime cost, $\boldsymbol{C_5}$ represents the decommissioning or retirement cost.

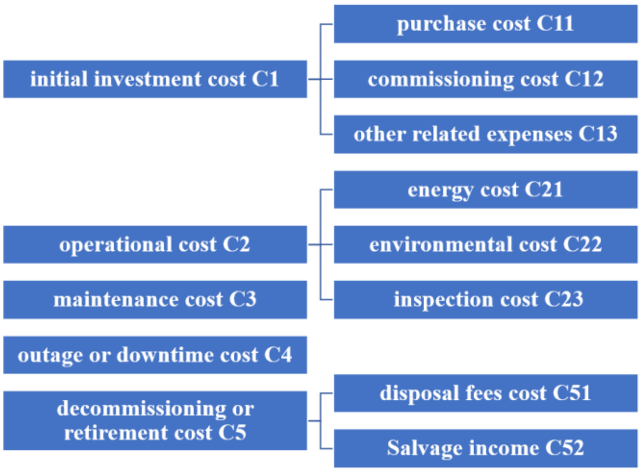

Fig. 5. Distribution of Transformer Costs

B. *Calculation of transformer costs*

Due to variations in transformer models, the methods for cost calculation can differ significantly. This paper provides a cost calculation example based on a 220kV transformer from a specific power grid company [7]. The transformer model and parameters are as follows in the table below:

TABLE I. TRANSFORMER MODEL AND PARAMETERS

Parameter Names	***Parameter Values***
Transformer Model	SFPSZ8-120000/220
Rated Voltage Ratio	220/115/38.5kV
Rated No-Load Loss	70kW
Rated Load Loss"	327kW
Initial Cost	￥10,000,000

The following is an itemized calculation of the costs for this transformer. The transformer's C_1 refers to the comprehensive costs incurred before its official operation, primarily including the purchase cost C_{11}, commissioning cost C_{12}, and other related expenses C_{13}. C_{11} is obtained from relevant information provided by the power grid company, while C_{12} and C_{13} can be calculated as a certain percentage of the purchase cost.

$$C_1 = C_{11} + C_{12} + C_{13} \tag{5}$$

$$C_{12} = 6\% \cdot C_{11} \tag{6}$$

$$C_{13} = 11.8\% \cdot C_{11} \tag{7}$$

The transformer's C_2 refers to the costs incurred after operation, including the energy consumption cost generated by the transformer itself, the environmental cost arising from electromagnetic interference and ecological damage during transformer operation, and the inspection cost incurred for better transformer management. It can be divided into energy cost C_{21}, environmental cost C_{22}, and inspection cost C_{23}, with their respective calculation equations as follows:

$$C_2 = C_{21} + C_{22} + C_{23} \tag{8}$$

$$C_{21} = P_s \cdot T \cdot P_0 + P_s \cdot \left(0.15\eta + 0.85\eta^2\right) \cdot P_k \cdot T \tag{9}$$

$$C_{22} = \left(L_r - L_0\right) \cdot C_u + Comp \tag{10}$$

$$C_{23} = \sum_{\{s\}} \sum_{n=1}^{N} d_{ns} \cdot c_S \tag{11}$$

Where $\boldsymbol{P_s}$ represents the average selling price of electricity, typically taken as 0.5 *yuan*/kWh. $\boldsymbol{T}$ represents the annual average operating time, typically taken as 8760 hours. $\boldsymbol{\eta}$ represents the annual average load factor. $\boldsymbol{P_0}$ is the no-load loss. $\boldsymbol{P_k}$ is the load loss. $\boldsymbol{L_r}$ is the annual actual losses, usually taken as 1.2 times the standard losses. $\boldsymbol{L_0}$ is the annual standard losses, calculated using the equation $L_0 = P_0 \cdot T + P_k \cdot \eta^2 \cdot T$. $\boldsymbol{C_u}$ is the emission cost per unit loss. ***Comp*** represents the cost of mitigating or compensating for the impact of transformer electromagnetic radiation and noise on residents. $\boldsymbol{d_{ns}}$ represents the frequency of routine inspection activity $\boldsymbol{s}$ conducted on the transformer after it has been in operation for $\boldsymbol{n}$ years, and $\boldsymbol{c_s}$ is the cost of routine activities.

The transformer's C_3 refers to the maintenance costs incurred due to transformer failures after formal operation. In this paper, a transformer state overhaul model based on the bathtub curve is established concerning the Weibull distribution.

$$C_3 = M \cdot \left(1 - e^{-\left(\frac{T_t}{\eta}\right)^m}\right) \tag{12}$$

Where $\boldsymbol{M}$ represents the overhaul cost for the transformer in its initial operational period. $\boldsymbol{T_t}$ represents the number of years the transformer has been in operation. $\boldsymbol{m}$ is the shape parameter in the Weibull distribution, and $\boldsymbol{\eta}$ is the scale parameter in the Weibull distribution, fitted based on historical data [8], with values taken as 2.4606 and 16.5805 in this paper.

The transformer's C_4 refers to the outage cost caused by power transformer failures, leading to power loss. Due to the lack of relevant data for this specific transformer, this cost is estimated and fitted based on historical statistical data for similar transformer [7].

The transformer's C_5 refers to the cost incurred for the disposal of the transformer after retirement, and the calculation method is as follows:

$$C_5 = MA - \rho \cdot C_{11} \tag{13}$$

Where ***MA*** represents the cost of disposing of the power transformer, typically calculated as 1% of the purchase cost. $\boldsymbol{\rho}$ represents the residual value rate of the power transformer, generally taken as 5%.

C. *Cost discounting for the time value of money*

Because money has a time value, the net present value (NPV) method is used to discount costs. The NPV method calculates the present value algebraically by discounting the income, expenses, or net cash flows generated each year over the entire life cycle at a specific discount rate. According to the NPV method, actual costs can be calculated using the following equation:

$$C_1' = C_1 \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{14}$$

$$C_2' = \left(\sum C_2 \cdot \frac{(1+r)^n}{(1+i)^n}\right) \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{15}$$

$$C_3' = (\sum C_3 \cdot \frac{(1+r)^n}{(1+i)^n}) \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{16}$$

$$C_4' = (\sum C_4 \cdot \frac{(1+r)^n}{(1+i)^n}) \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{17}$$

$$C_5' = C_5 \cdot \frac{(1+r)^n}{(1+i)^n} \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{18}$$

$$LCC' = C_1' + C_2' + C_3' + C_4' + C_5' \tag{19}$$

Where n represents the number of years the transformer operates. i is the discount rate for the entire society, taken as 8% here. r is the inflation rate, taken as 1.5% here. LCC' represents the discounted annual average cost considering the time value of money.

After calculating the transformer's annual average LCC, it can be plotted as a line graph over the years. The lowest point on the graph represents the moment when the annual average LCC is minimized. At this moment, the corresponding LCC value is the lowest annual average cost for the transformer. By comparing the size of this lowest value, we can determine the most cost-effective overhaul strategy.

IV. Overhaul Strategies Considering both Risk and Cost-effectiveness

From a risk perspective, performing overhaul work on a transformer can reduce its equivalent service life, thereby lowering the failure rate of the transformer. However, overhaul also incurs additional costs. Therefore, an economic analysis is necessary to determine whether overhaul is justified. If the overhaul cycle is too long or even omitted, the failure rate of the transformer in its later years of operation may become excessively high, leading to increased safety risks and downtime costs. On the other hand, if the overhaul cycle is too short, it can result in suboptimal overhaul outcomes, leading to both time and cost inefficiencies. To strike a balance between these factors, this paper proposes a overhaul strategy that considers both risk and cost-effectiveness.

A. Determining overhaul timing based on Particle Swarm Optimization

To minimize the maximum value of the transformer failure rate under a certain number of overhaul actions, Particle Swarm Optimization (PSO) is used to determine the optimal timing for performing overhaul. PSO is an evolutionary computation technique inspired by the behavior of birds in foraging. Due to its simplicity and efficiency, it is widely applied in fields such as function optimization and neural network training. In the PSO algorithm, the equations for particles to determine their own velocity and position are as follows:

$$v_i = w \cdot v_i + c_1 \cdot rand \cdot (pbest - x_i) + c_2 \cdot rand \cdot (gbest - x_i) \tag{20}$$

$$x_i = x_i + v_i \tag{21}$$

Where v_i is the velocity of the i-th particle. x_i is the position of the i-th particle. w is the inertia weight, used to balance global exploration and local exploitation capabilities. c_1 and c_2 are the learning factors, representing the strength of a particle's learning ability from itself and the global best solution. ***pbest*** represents the individual best solution. ***gbest*** represents the global best solution. The flowchart of the PSO algorithm is shown in Fig. 6.

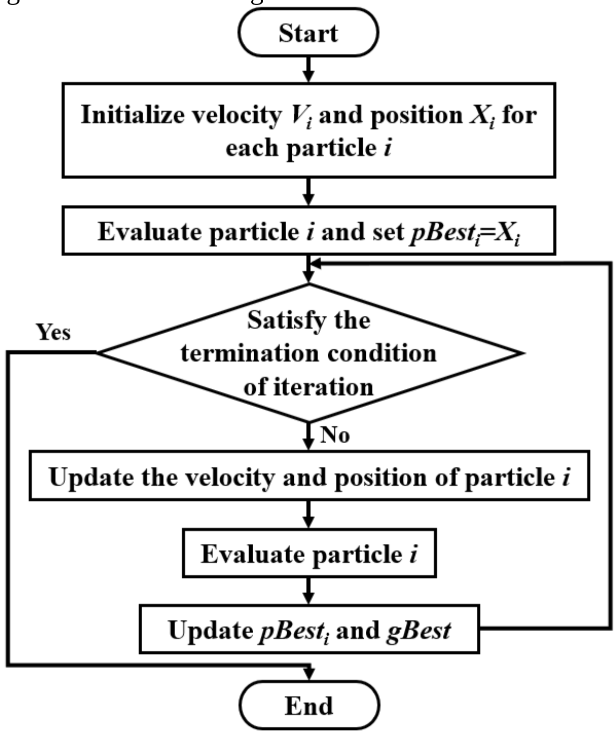

Fig. 6. Flowchart of the Particle Swarm Optimization

Using the aforementioned transformer as an example for overhaul timing determination, a curve fitting and parameter estimation method based on the Levenberg-Marquardt (LM) algorithm is employed to fit the curve and estimate parameters for the transformer's loss-failure period. The aging phase failure rate follows a Weibull distribution with parameters m=2.4606 and n=16.5805 [8]. The failure rate distribution graph is shown in Fig. 7:

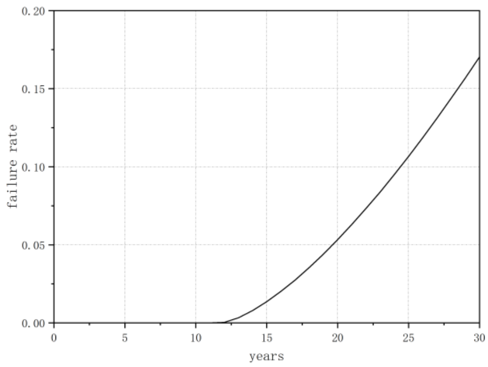

Fig. 7. Transformer Failure Rate Distribution

Assuming that the transformer undergoes a total of N overhaul actions during its service life, the particles will move within an N-dimensional space, with coordinates x_i (t_1, t_2,…, t_i,…, t_N) representing the timings of the i-th overhaul action. It is assumed that each overhaul action results in a linearly declining service life regression, following a model with n=0.4 and k=0.2. The objective function is to minimize the maximum failure rate during the transformer's service life. In other words, the objective function can be expressed as:

$$F = \max\{\lambda(t_1), \lambda(t_2 - \tau_1), ..., \lambda(T - \tau_{n-1})\} \tag{22}$$

Where t_i represents the timing of the i-th overhaul action, $\lambda(t_i)$ is the failure rate at that time, τ_i is the service life regression generated by the i-th overhaul action, and T is the design life of the transformer, taken as 30 years in this case.

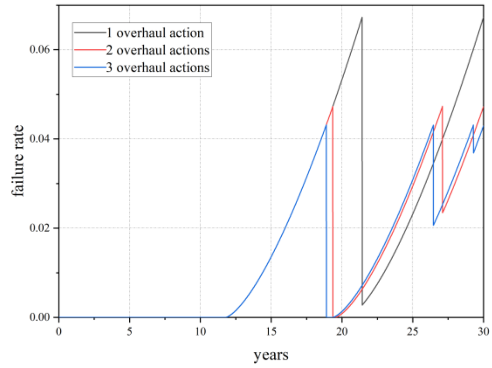

Fig. 8. Transformer Failure Rate Distribution

With overhaul actions set at 1, 2, and 3 times, according to the results obtained using the PSO algorithm, the optimal timing for overhaul can be calculated as follows: For one overhaul action, the timing should be 21.4 years, resulting in a maximum failure rate of 0.067. For two overhaul actions, the timings should be 19.3 and 27.1 years, resulting in a maximum failure rate of 0.047. For three overhaul actions, the timings should be 18.9, 26.4, and 29.3 years, resulting in a maximum failure rate of 0.043. By adopting this overhaul strategy, it ensures that the transformer's failure rate remains at a consistently low level throughout its entire service life.

B. *Economic evaluation of overhaul based on the minimization of annual average LCC*

Based on the analysis from the previous section, the optimal timing for overhaul can be determined for different overhaul actions. However, from an economic perspective, a too-short overhaul cycle may lead to resource wastage. Therefore, the focus is on finding the most reasonable overhaul strategy for the transformer based on annual average LCC.

According to the cost calculation in Chapter III for the transformer, the annual average LCC can be calculated. The results are shown in Fig. 9:

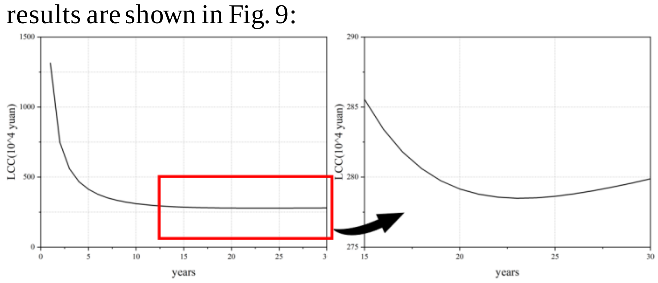

Fig. 9. Transformer's Annual Average LCC Curve

The annual average LCC curve shows a trend of initially decreasing and then increasing. The minimum annual average LCC is achieved at 23 years, amounting to 278.5*10^4 *yuan*. Taking into account the impact of the overhaul strategy discussed in the previous section, with overhaul costs representing 5% of the transformer's original asset value, the annual average LCC curve, considering overhaul costs and service life regression, can be obtained as shown in Fig. 10.

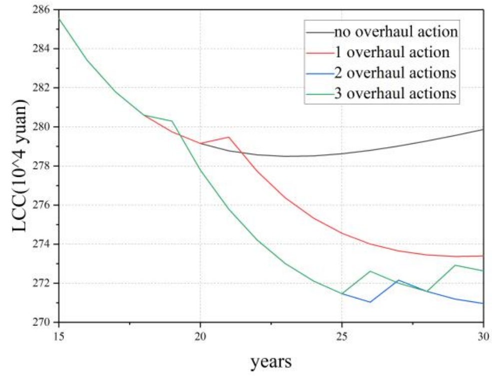

Fig. 10. Annual Average LCC Curves for Different Numbers of Overhaul Actions

It can be observed that when performing only one overhaul action, the lowest annual average LCC is 273.4*10^4 *yuan*, occurring at 30 years. For two overhaul actions, the lowest annual average LCC is 271.0*10^4 *yuan*, also at 30 years. With three overhaul actions, the lowest annual average LCC is 271.5*10^4 *yuan*, occurring at 25 years. However, at 30 years, the annual average LCC increases to 272.6*10^4 *yuan*.

To incorporate the factor of reliability into the economic evaluation, the concept of equivalent annual average risk cost is introduced, which translates the failure rate into the equivalent cost increment caused by failures. The calculation method for equivalent annual average risk cost is as follows:

$$C_r = LCC' + \frac{0.06 \cdot C_{11}}{N} \sum_{i=1}^{N} \lambda_i \quad (23)$$

Where LCC' represents the annual average LCC, C_{11} represents the transformer's procurement cost, N represents the operational lifespan of the transformer, and λ_i represents the failure rate in the i-th year. After calculations, the equivalent annual average risk costs for 1, 2, and 3 overhaul actions are as shown in Table II:

TABLE II. EQUIVALENT ANNUAL AVERAGE RISK COSTS FOR DIFFERENT NUMBERS OF OVERHAUL ACTIONS

Number of Overhaul Actions	*Equivalent Annual Average Risk Cost(yuan)*
1	283.9*10^4
2	278.8*10^4
3	280.0*10^4

It can be seen that when performing 2 overhaul actions, the equivalent annual average risk cost is the lowest. Therefore, in this case, conducting 2 overhaul actions at 19 years and 27 years is the optimal decision in terms of both reliability and economy.

V. CONCLUDING REMARKS

This study presents an approach to formulate overhaul strategies for transformer during their service life by comprehensively considering both transformer failure rates and economic costs. It provides a basis for enterprises to develop overhaul schedules. In fact, the applicability of this method is not limited to transformers. it can be applied to other repairable systems as well. Furthermore, if information about the health of the transformer can be obtained, it can be incorporated as a factor in the failure rate, further enhancing the accuracy of the analysis.

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