Study on the optimization of maintenance strategy based on life cycle cost estimate of transformer

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Abstract

As the key equipment of power system the status of power transformer impacts the security and stability of the grid. Make appropriate maintenance strategies for life cycle according to its operating status is important for the safe operation of the power grid. The power transformer life cycle cost (LCC) is analyzed through the establishment of the power transformer LCC decomposition model from the perspective of the life-cycle management. The cost – effectiveness of maintenance strategy is studied based on the analysis of maintenance costs and military age change under different maintenance level. Then a power transformer maintenance cost-performance optimization model and introduce genetic algorithm to solve the model. The maintenance optimization model operational, scientific and effective through case studies.

Keywords: Life Cycle Cost; Condition-based Maintenance; Power Transformer; Genetic Algorithms

1 Introduction

As the key equipment of power system the status of power transformer impacts the security and stability of the grid. However, blindly overhaul to improve the reliability of the transformer will significantly increases the cost of operation and maintenance. Life cycle management, considering reliability and economy, based on transformer risk assessment and life cycle cost analysis, can select the best maintenance strategy of a transformer to reduce optimize equipment operation and maintenance costs[1].

In recent years, many research institutions have done a lot of research on the state maintenance theory[2-12]. Transformer operation and maintenance costs account for a large proportion of the total life cycle stages, respectively, accounted for roughly 35% to 70%[13-14]. Although the current overhaul analyzes the economy of condition-based Maintenance, but did not consider the time value of money, its maintenance cost is static. It has theoretical significance and practical value to make a cost- effecttiveness ratio transformer optimal maintenance decisions on the basis of ensuring the reliability of the device.

In this paper, the power transformer LCC is analyzed through the establishment of the power transformer LCC decomposition model from the perspective of the life-cycle management. The cost – effectiveness of maintenance strategy is studied based on the analysis of maintenance costs and military age change under different maintenance level. Then a power transformer maintenance cost-performance optimization model and introduce genetic algorithm to solve the model.

2 The power transformer LCC decomposition model

According to the article, the values of LCC was calculated by the LCC calculation processes[15,16]. Generally, LCC can be calculated by equation:

$$LCC = CI + CO + CF + CD, \quad (1)$$

where LCC is life cycle cost of a transformer; CI is the initial investment costs of the transformer, CO is the operating and maintenance costs of the transformer, CF is the fault costs of the transformer, CD is the decommissioning costs of the transformer.

$$CI = CI_E + CI_I + CI_O, \quad (2)$$

where CI_E is original equipment costs which consists of the cost of equipment, tools and spare parts transportation, CI_I is installation costs which consists of the cost of delivery and installation, CI_O is other costs, such as some monitoring devices.

$$CO = CO_1 + CO_2, \quad (3)$$

where CO_1 is wastage cost, CO_2 is maintenance cost which consists of labor costs, environmental costs and maintenance costs[19].

$$\Delta W = (P_0 + \beta^2 P_k) \times 8760, \quad (4)$$

$$CO_1 = \Delta W \times a, \quad (5)$$

$$CO_2 = \lambda_P CO_P + \lambda_E CO_E + \lambda_M CO_M, \quad (6)$$

where ΔW is annual energy loss, β is average load(kW), P_k is loss of load(kW), P_0 is no-load loss(kW), a is electricity

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price, CO_P is labor costs, CO_E is environmental costs, CO_M is maintenance costs, λ_P, λ_E, λ_M are coefficients of different part.

The fault costs of the transformer mainly points outage costs and repair costs[20].

$$CF = b \times S_N \times \beta \times \cos\varphi \times T + \lambda \times RC \times MTTR \,, \tag{7}$$

where b is profit of electricity, S_N is rated capacity, $\cos\varphi$ is average power factor, T is stop working hours, λ is average fault time, RC is repair costs per hour, $MTTR$ is repair time.

$$CD = CD_T - CD_R \,, \tag{8}$$

where CD_T is total decommissioning costs, CD_R is residual value. Normally, CD_R is a certain percentage of CI_E.

3 Cost analysis based on discount rate

With the development of economy, the value of the finance will change over time, the actual value of the finance are different in two different moments of time. Transforms have a long service life, so the time value of finance must be consider. In this article, the time value of finance means discount rate.

If discount rate i is a constant value, then value P became F after n year later.

$$F = P \times (1+i)^n \,, \tag{9}$$

$$P = F \times \frac{1}{(1+i)^n} \,, \tag{10}$$

If value P is equally recover in n years, the annual amount is annuity A.

$$A = P \times i \frac{(1+i)^n}{(1+i)^n - 1} \,, \tag{11}$$

$$P = A \times \frac{(1+i)^n - 1}{i(1+i)^n} \,, \tag{12}$$

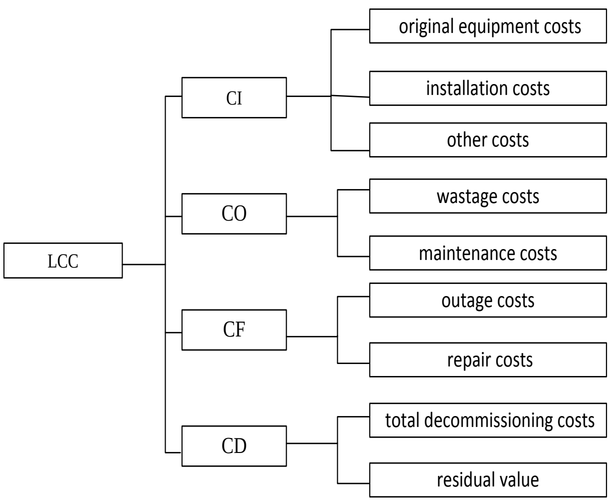

FIGURE 1 Transformers LCC decomposition model

4 Transformer optimal maintenance model

This paper presents the idea of optimizing maintenance time. Select the time for the maintenance to get the lowest total cost of maintenance on condition that the performance of transform is not less than the minimum limit.

4.1 MAINTENANCE COST ANALYSIS

Usually, transformers need overhaul two or three times during the life cycle. In this article, the overhaul is two, and the cost Mm are same. The fault costs of the transformer are ignore for the percent of it in LCC is too low.

According to the actual situation, transformers need minor overhaul at least once a year. And the cost is increased with age. In this article, the cost of minor overhaul is defined as a linear function (13).

$$M_s = \beta \times W_1 \times t \,, \tag{13}$$

where M_S is the cost of minor overhaul, β is a coefficient, W_1 is initial investment costs, t is the age of transformer.

4.2 THE COST – EFFECTIVENESS OF MAINTENANCE

In the life cycle, maintenance after a fault and minor overhaul do not change the failure rate, the reduction factor of age α=0. Overhaul is the overall repair and maintenance of equipment, reduction factor of age α_3= 0.8.

If the time of overhaul are t_1 and t_2, then equivalent age of transformer can be described in general formula (14) below.

$$t_a = \begin{cases} t_n & t_n \le t_1 \\ t_n - \alpha_3 t_1 & t_1 < t_n \le t_2 \\ t_n + (\alpha_3^2 - \alpha_3)t_1 - \alpha_3 t_2 & t_n > t_2 \end{cases} \,, \tag{14}$$

And the cost of minor overhaul can be described in general formula (15) below.

$$\begin{aligned} M_s(t_a) &= \beta \times W_1 \times t_a = M_s'(t_n) \\ &= \begin{cases} \beta \times W_1 \times t_n & t_n \le t_1 \\ \beta \times W_1 \times (t_n - \alpha_3 t_1) & t_1 < t_n \le t_2 \\ \beta \times W_1 \times [t_n + (\alpha_3^2 - \alpha_3)t_1 - \alpha_3 t_2] & t_n > t_2 \end{cases} \,, \end{aligned} \tag{15}$$

To ensure the reliability of the transformer, the failure rate need to be control in a low level. So the time of overhaul must ensure the failure rate will not exceeded its threshold value.

Maintenance costs consisting almost entirely of minor overhaul cost and overhaul cost. The minor overhaul cost is increase with years. Then, two overhaul time is the optimization variables in this model. The objective is a fewest cost.

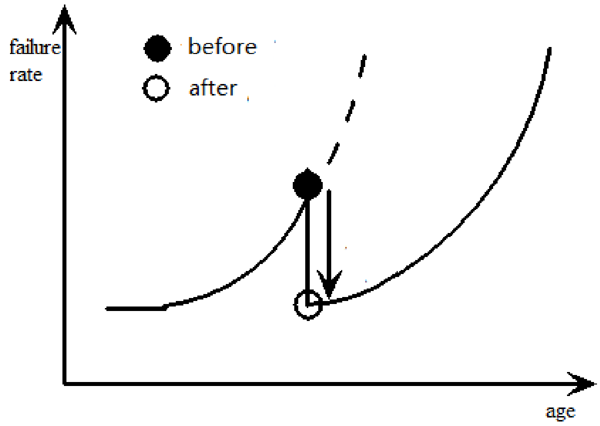

FIGURE 2 Influence of overhaul on failure rate of the transformer

Then the object function and restrictive condition can be described in general formula (16) below.

$$\begin{cases} \min f = \sum_{t_n=1}^{T_{age}} C_s(t_n) + C_m(t_1) + C_m(t_2) \\ \text{s.t.} \quad \lambda(t_a) = \lambda'(t_n) \le \lambda_0 \end{cases}, \tag{16}$$

where T_{age} is the life of a transformer, λ_0 is the threshold value of the failure rate. $\lambda(t_a)$ is the failure rate, $C_s(t_n)$ is annual maintenance costs based on discount rate, $C_m(t_1)$ and $C_m(t_2)$ are overhaul costs based on discount rate.

$C_s(t)$, $C_m(t_1)$ and $C_m(t_2)$ can be described in general formula below.

$$C_s(t_n) = \frac{M_s'(t_n)}{(1+i)^{t_n}}, \tag{17}$$

$$C_m(t_1) = \frac{M_m}{(1+i)^{t_1}}, \tag{18}$$

$$C_m(t_2) = \frac{M_m}{(1+i)^{t_2}}, \tag{19}$$

4.3 BASED ON GENETIC ALGORITHM TRANSFORMER OPTIMAL MAINTENANCE MODEL SOLUTION

Transformer repair process can be seen as a model solution for the minimum objective function optimization problems, mathematical programming model can be described in general formula (20) below.

$$\begin{aligned} &\min \quad f(x) \\ &s.t. \quad \begin{cases} x \in R \\ R \in U \end{cases}, \end{aligned} \tag{20}$$

In the formula, function *f(x)* as decision variables, $x \in R$ and $R \in U$ as constraints, *U* is the basic space; *R* is a subset of *U*. To meet the constraints of the solution of *X* is called the feasible solution; set *R* said the feasible solution set.

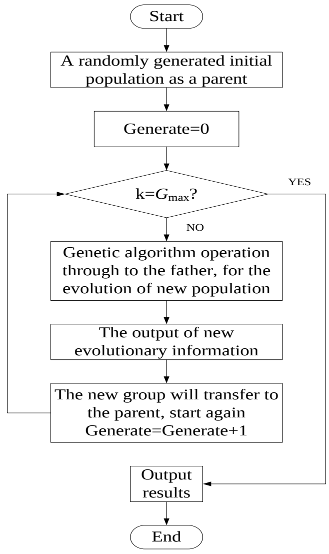

FIGURE 5 Calculation procedure of Genetic Algorithm

The optimization problem is solved using genetic algorithm [23], the flow chart of genetic algorithm as shown in Fig. 5, the specific steps are as follows:

① The initialization: setting the evolution algebra counter k=0, set the maximum number of Gmax, using binary encoding, randomly generated n individuals as the initial population of *P(0)*.

② Individual evaluation: Calculation individual fitness of group *P(k)*, fitness function to be optimized by the objective function, namely *f(x)*.

③ For genetic manipulation, including selection, crossover and mutation:

1) Selection operations: selection operator acting on the group. The purpose is to direct genetic individual optimization to the next generation or by paired crossover generates new individual genetic to the next generation. Selection is based on individual fitness evaluation.
2) Crossover: the crossover operator acting on the group. The so-called cross refers to the part of the structure of two parent individuals to replace the restructuring and generate new individual operation. The crossover operator plays a core role in genetic algorithm.
3) Mutation operation: the mutation operator acting on the group, is to change values for some loci of individuals in the population on the gene. Group *P(k)* followed by selection, crossover and mutation, to calculate next generation $P(K_1)$.

④ Termination condition: if k = G_{max}, the evolution of the obtained with the minimum fitness individuals as the optimal solution output, terminate the computation.

In order to solve the time and precision of solution equilibrium of GA operation, The value range of group size *n* is [30,160]; the crossover probability Pc value range is [0.25,0.75]; for the balance of population diversity and search randomness, mutation probability P_m values range is [0.01,0.2].

5 The example analysis

Maintenance optimization of a 500kV transformer, considering the value of time and money, transformer general repairs during the life cycle cost as shown in formula (21).

$$\sum_{t_n=1}^{T_{age}} C_s(t_n) = \frac{M_s'(t_n)}{(1+i)^{t_n}} = \begin{cases} \dfrac{\beta \times W_1 \times t_n}{(1+i)^{t_n}} & t_n \le t_1 \\ \dfrac{\beta \times W_1 \times (t_n - \alpha_3 t_1)}{(1+i)^{t_n}} & t_1 < t_n \le t_2 \\ \dfrac{\beta \times W_1 \times [t_n + (\alpha_3{}^2 - \alpha_3)t_1 - \alpha_3 t_2]}{(1+i)^{t_n}} & t_n > t_2 \end{cases},$$
$$= \beta \times W_1 \times \left(\sum_{k=1}^{t_1} \frac{k}{(1+i)^k} + \sum_{j=t_1+1}^{t_2} \frac{j - \alpha_3 t_1}{(1+i)^j} + \sum_{r=t_2}^{T_{age}} \frac{r + (\alpha_3{}^2 - \alpha_3)t_1 - \alpha_3 t_2}{(1+i)^r}\right) \quad (21)$$

Substitute it into formula (16) to get the objective function to be optimized for:

$$f = \sum_{t_n=1}^{T_{age}} C_s(t_n) + C_m(t_1) + C_m(t_2)$$
$$= \beta \times W_1 \times \left(\sum_{k=1}^{t_1} \frac{k}{(1+i)^k} + \sum_{j=t_1+1}^{t_2} \frac{j - \alpha_3 t_1}{(1+i)^j} + \sum_{r=t_2}^{T_{age}} \frac{r + (\alpha_3{}^2 - \alpha_3)t_1 - \alpha_3 t_2}{(1+i)^r}\right) + \frac{M_m}{(1+i)^{t_1}} + \frac{M_m}{(1+i)^{t_2}}, \quad (22)$$

Formula (22) optimization model is given as the constraints:

$$\text{s.t.} \quad \lambda(t_a) = \lambda'(t_n) \le \lambda_0, \quad (23)$$

The function of transformer failure rate λ is the equivalent of age ta, the failure rate is the function $\lambda(t_a)$ as the formula (24):

$$\lambda(t_a) = 0.00294 + 0.01 \times (e^{0.05 t_a} - 1), \quad (24)$$

Substitution formula (14) to get function $\lambda'(t_n)$ of failure rate on nominal age for t_n:

$$\lambda'(t_n) = \begin{cases} 0.00294 + 0.01 \times (e^{0.05 t_n} - 1) & t_n \le t_1 \\ 0.00294 + 0.01 \times (e^{0.05(t_n - \alpha_3 t_1)} - 1) & t_1 < t_n \le t_2 \\ 0.00294 + 0.01 \times (e^{0.05(t_n + (\alpha_3{}^2 - \alpha_3)t_1 - \alpha_3 t_2)} - 1) & t_n > t_2 \end{cases}, \quad (25)$$

The β =0.002, W_1=4500 million; transformer overhaul costs M_m=200 million; transformer fault rate threshold for λ_0 =0.01; the life of the transformer is T_{age}=30. Assuming that the transformer operation within 5 years will not be overhauled, will set the range of t_1 and t_2 were [5, 30] and [10, 30].

Parameters of genetic algorithm were set as follows: the population size is set to 25, the crossover probability is 0.85, and mutation probability is 0.15, the other parameter is set to the default value. Using Matlab genetic toolbox GADS to solve formula (10) and (12) limiting conditions are given. After the 50 generation genetic iterative calculation, get the minimum maintenance cost f= $5479700, two times of overhaul are t_1 =7.3333, t_2 =16.3538. Overhaul time unit solution for years, the fractional transform for overhaul time months were approximately put into operation after 7 years and 4 months and 16 years 4 months.

5 Conclusion

In this paper, an optimization model of maintenance of transformer based on life cycle cost, we obtain the following conclusions:

1. With the previous point of repair scheme research on static repair cost based on different, from the point of view of life asset management point of view, considering the time value of money, set up a maintenance optimization model based on the dynamic cost of repair.
2. The age reduction factor calculated equivalent age, the equivalent age as the link among the repair scheme, the repair cost and reliable performance, and the repair effect on the repair cost and reliability are quantified.

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