

## The Maintenance Strategy for Optimizing Distribution Transformer Life Cycle Cost

Bo Ye<sup>1\*</sup>, Lei Xuan<sup>2</sup>, Bo Xu<sup>2</sup>, Gefei Qiu<sup>1</sup>, Zhangzhou He<sup>1</sup>, Ming Li<sup>1</sup>

<sup>1</sup>Engineering Research Center of Smart Grid, Yunnan Province, Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming, China

<sup>2</sup>Yunnan Power Grid Corporation, Kunming, China

\*Corresponding author, e-mail: yeripple@yahoo.com.cn

### Abstract

*During the operation, the distribution transformer performance will deteriorate. The maintenance is an essential task in enhancing the safety of distribution transformer. Based on equal deterioration theory, the relationship among distribution transformer failure rate in each period of maintenance was deduced. After analyzing the maintenance costs and the failure costs in detail, the model of optimal life cycle costs for distribution transformer was established. Then the genetic algorithm was used to solve the model for obtaining the optimal maintenance strategy. Finally, the optimization results and the influence factors were analyzed. The results demonstrate the feasibility and validity of the proposed method.*

**Keywords:** *distribution transformer, maintenance strategy, life cycle cost, genetic algorithm, equal deterioration theory*

**Copyright © 2013 Universitas Ahmad Dahlan. All rights reserved.**

### 1. Introduction

In recent years, power enterprises not only concern initial investment cost but also consider late operating cost, maintenance cost, failure cost, and retirement cost. That is taking overall cost and benefits into account from the respective of life cycle cost of distribution transformer. As to a defined distribution transformer, its initial investment cost (including acquisition expenses, installation and debugging cost, etc), operation cost (including daily inspection expenses, energy consumption expenses, environmental protection expenses, etc), retirement cost are basically fixed. In other words, the cost be optimized mainly contain planned maintenance cost and failure cost. Therefore the optimization of life cycle cost primarily aim at the two kinds of cost [1-3].

The maintenance strategy of distribution transformer on one hand can affect the kind and times of maintenance and then decide maintenance cost (when the equipment is decided, single expenses of all kinds of planned maintenance is certain), and on the other hand can influence both reliability and failure rate during operating. Then the failure cost are decided (when the equipment is decided, the loss cost of single failure can also be regarded as certain) [2-5]. Consequently, making a reasonable maintenance strategy is the key to optimize maintenance cost and failure cost. And in this way the problem will transform into how to determine the optimal maintenance strategy. There are a few literatures on the study of optimal maintenance strategy of distribution transformer, while they have some inadequate more or less. Literature [6] is based on operating reliability function which follows the same distribution function all along and deduces the relationship among the failure maintenance times, preventive maintenance times, and maintenance intervals, then obtains the optimal interval by taking a derivative of the function. However, it ignored the influence from maintenance to equipment's reliability. The literature [7] is in case of the interval between maintenances have been given, then uses integer discrete optimization method to optimize the maintenance types in each interval and classifies them as no need of maintenance, in need of maintenance and in need of replacement, and represents them with 0, 1 and 2, respectively. While due to the interval between maintenances is given, actually a natural limitation comes along with the optimization problem and it's hard to get the optimal maintenance strategy of true sense. The literature [8] is under the condition of assuming that the equipment recovers exactly to the same state of new equipment after each time of maintenance to optimize the maintenance strategy, while it ignored

the trend of constant deterioration of equipment's reliability during its operating. This paper overcomes the disadvantages aforementioned and discusses the optimal maintenance strategy of distribution transformer, and introduces the equal deterioration theory in the field of mechanical engineering into the analysis of distribution transformer. Then, on that basis, deduce the relationship among failure rate during each interval between maintenances, and establishes the solving models of optimization problem. Get the optimized solution with specific numerical examples and briefly analyzed the results and influence factors in the end.

## 2. Distribution Transformer Failure Rate Based on Equal Deterioration Theory

In the field of mechanical engineering, the equipment's equal deterioration theory is put forward. The equal deterioration theory deems that reliability and operating performance of equipment are constantly deteriorated as a whole with time lapse. The either two mean time between failures (*MTBF*) in two adjacent expected maintenances period are equal. Express in mathematical formula as  $MTBF_{i+1} = MTBF_i \times (1-r)$ , where  $r$  is deterioration rate and has the range of (0, 1), and gets a fixed value depending on historical operating situation for the specific equipment. The equal deterioration theory reflects the varying pattern of the indicator of reliability and operating performance of complicated equipments under actual operation. It has been used widely [9].

The authors think the aforementioned theory can be extended to the situation of major and minor maintenance. In the same period of major maintenance, the either two *MTBF* in random adjacent periods of minor maintenance are equal. The *MTBF* in the period of minor maintenance corresponding to two random adjacent periods of major maintenance meets the equal deteriorating theory. Express in mathematical formula:

$$MTBF_{i(j+1)} = MTBF_{ij} \times (1-r_1) \quad (1)$$

$$MTBF_{(i+1)j} = MTBF_{ij} \times (1-r_2) \quad (2)$$

Where,  $i$  and  $j$  represent sequence number of the period of major and minor maintenance, respectively, and  $r_1$  represents the deterioration rate between two adjacent periods of minor maintenance in same period of major maintenance, and  $r_2$  represents the deterioration rate between two adjacent periods of major maintenance. In order to analyze simply, this paper make the value of  $r_1$  equal to  $r_2$  and represent both with  $r$ . Figure 1 reflects this rule.

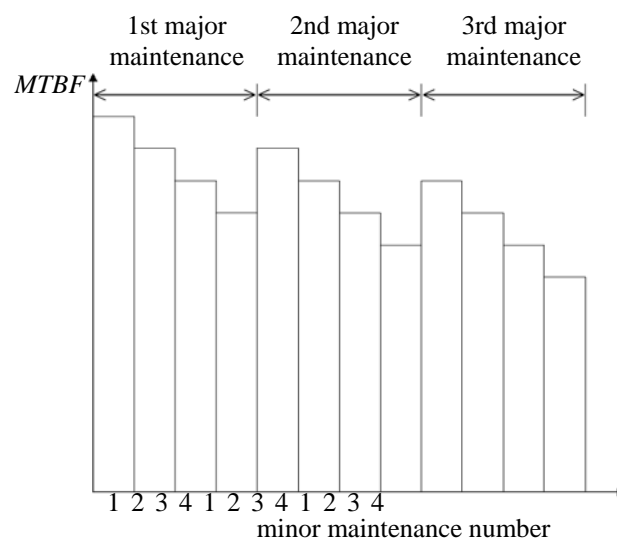


Figure 1. The evolution of MTBF

For the sake of convenience, some assumptions are put forward:

(1) Due to the Weibull distribution can well describe the lifetime model of equipment and in order to analyze simply, this paper adopt two parameters Weibull distribution model. (2) In each maintenance period, failure interval of distribution transformer is independent identically distributed, while with different distribution parameters. Especially to Weibull distribution, it has same shape parameters but different location parameters and scale parameters. (3) Ignoring the maintenance time, it is much shorter than operation time of distribution transformer.

From the two parameters Weibull distribution model, we can obtain the failure density function of equipment can be expressed as:

$$f(t) = \frac{m}{\eta^m} t^{m-1} \times e^{-\left(\frac{t}{\eta}\right)^m} \quad (3)$$

Where,  $m$  is shape parameters and  $\eta$  is scale parameter. Using mean values of Weibull distribution to express  $MTBF$ :

$$MTBF = \int_0^{+\infty} f(t) dt = \int_0^{+\infty} \frac{m}{\eta^m} t^{m-1} \times e^{-\left(\frac{t}{\eta}\right)^m} dt \quad (4)$$

Supposing  $u = e^{-\left(\frac{t}{\eta}\right)^m}$ , after alternative transformation we get:

$$MTBF = \eta \int_0^{+\infty} \frac{1}{u^{\frac{1}{m}}} \times e^{-u} du = \eta \times \Gamma\left(1 + \frac{1}{m}\right) \quad (5)$$

For the No.  $j$  minor maintenance period of the No.  $i$  major maintenance period,  $MTBF = \eta_{ij} \times \Gamma\left(1 + \frac{1}{m_{ij}}\right)$ , then combining the aforementioned formula of equal deterioration theory we can easily get:

$$MTBF_{ij} = MTBF_{i1} \times (1-r)^{i+j-2} \quad (6)$$

According to the assumed formula (2), the shape parameters in each maintenance period are all equal to  $m$ . As a result, there is the relationship among location parameters as below:

$$\eta_{ij} = \eta_{i1} \times (1-r)^{i+j-2} \quad (7)$$

Besides, the distribution transformer failure rate which follows Weibull distribution can be expressed as  $\lambda = m \times t^{m-1} / \eta^m$ . So, the relation formula of failure rate of each maintenance period is shown in Eq. (8).

$$\lambda_{ij} = \frac{m \times t^{m-1}}{\eta_{ij}^m} = \frac{1}{(1-r)^{(i+j-2)m}} \times \lambda_{i1} \quad (8)$$

### 3. Optimization of Maintenance Cost and Failure Cost of Distribution Transformer

#### 3.1. Optimized Model

The traditional maintenance methods of distribution transformer include planned maintenance and accident maintenance. The planned maintenance includes regular major maintenance and minor maintenance. This paper put forward a general maintenance mode based on the traditional maintenance methods. In the general mode, the intervals between random two adjacent maintenances are equal, but the type of maintenance (minor or major) is flexibly chosen according to need. Figure 2 reflects the general maintenance mode (the length

lines represent the major maintenance and the short lines represent the minor maintenance).

Assuming cost of major maintenance of distribution transformer is  $C_d$ , cost of minor maintenance is  $C_x$ , cost of accident maintenance is  $C_f$ , the loss of accident is  $C_{\text{loss}}$ , and times of major maintenance is  $n_d$ , and a time of minor maintenance is  $n_x$ . The planned life time of distribution transformer is  $T$  years and the service time start from  $t=0$  after each maintenance. The difference after the maintenance is embodied in failure rate. The target of the optimization is to minimize the sum of planned maintenance cost and failure cost of distribution transformer within  $T$  years. That is:

$$\min w_1 = C_d \times n_d + C_x \times n_x + (C_f + C_{\text{loss}}) \times n_f \quad (9)$$

Where  $n_f$  is times of failure, and

$$n_f = \int_0^{t_1} \lambda_1(t) dt + \dots + \int_0^{t_k} \lambda_k(t) dt + \dots + \int_0^{t_n} \lambda_n(t) dt \quad (10)$$

Put in Eq. (9) and result in

$$\min w_1 = C_d \times n_d + C_x \times n_x + (C_f + C_{\text{loss}}) \times \left( \int_0^{t_1} \lambda_1(t) dt + \dots + \int_0^{t_n} \lambda_n(t) dt \right) \quad (11)$$

Where  $t_k$  is operating time of No.  $k$  maintenance interval,  $\lambda_k(t)$  is failure rate of No.  $k$  maintenance interval, and  $n = n_d + n_x + 1$  is total number of maintenance interval. Time of distribution transformer planned maintenance and failure maintenance is ignored. That is

$$t_1 = \dots = t_n = \Delta t = T / N \quad (12)$$

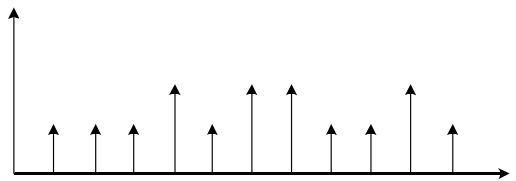


Figure 2. Schematic diagram of maintenance mode

### 3.2. Solution of Optimization Problem

Due to the intervals of maintenance period are equal, the undetermined variables are the times of major maintenance, the times of minor maintenance, and the type of maintenance. Genetic algorithm has been successfully applied to solve several complex optimization problems [10-12]. Genetic algorithm is a general-purpose stochastic search technique based on natural genetic and evolution mechanisms. Genetic algorithm has been widely adopted for the optimization of the maintenance strategy of distribution transformer, mainly due to its ability to avoid being trapped in a local optimum of the objective function. It combines the survival of the fittest law with a structured, yet randomized information exchanges among a population of artificial creatures, resembling samples of the search space of the problem. This paper adapts the genetic algorithm to obtain the optimization problem. The specific operating process can be divided into three levels. The first level is to enumerate the number of times within the permitted range according to the limitation of times of maintenance. The second level is to optimize the maintenance strategy with genetic algorithm under the condition of specific maintenance times. The third level is to find the best solution from the optimal solutions obtained from each maintenance.

The specific operating flowchart is shown in Figure 3. When optimizing with genetic algorithm, the maintenance strategy of distribution transformer is expressed using a string 0 and 1. The length of a string represents maintenance times, and 0 and 1 represent minor

maintenance and major maintenance, respectively. For instance, a string {0101010110} means 10 times maintenance in total including 5 times major maintenance, and 5 times minor maintenance.

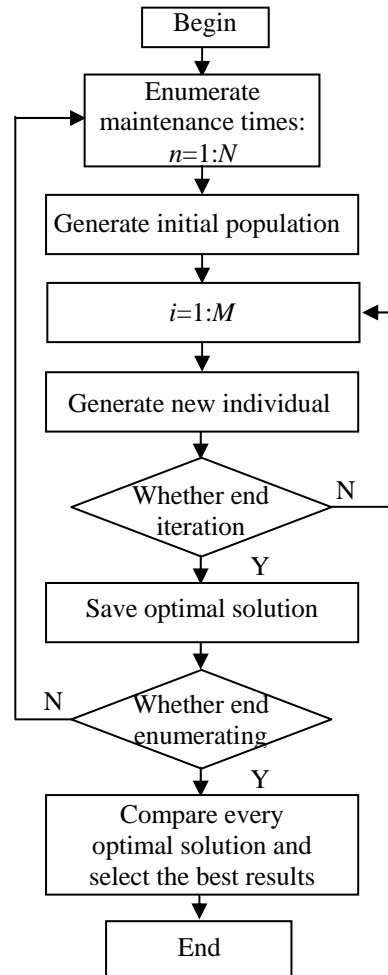


Figure 3. Flow chart of optimization algorithm

From the objective function of optimization problem, the difficult points lie in calculating the failure times. When calculating the total maintenance cost and failure cost, failure times are closely related to the failure rate function of each maintenance interval. Then from Eq. (8), that is deduced based on equal deterioration theory. After knowing the failure rate  $\lambda_{11}$  of the initial period, the key problem is transformed to judge the sequence number of major maintenance and minor maintenance in maintenance interval. The order of major maintenance and minor maintenance is irregular. It is necessary to discuss the sequence number of major maintenance and minor maintenance of each maintenance interval in 4 situations.

The times and order of major maintenance are counted and stored. Assuming maintenance times is  $n$ , the sum of interval is  $(n+1)$ . For the No.  $r$  string,  $g(r)$  is the times of major maintenance, and  $xh(r, k)$  is the maintenance order of No.  $k$  major maintenance of No.  $r$  string.

Situation 1: no major overhaul,  $g(r) = 0$ . For each maintenance interval, the sequence number of major maintenance is 1, and the sequence number of minor maintenance is sequence number of maintenance interval.

Situation 2: at least one major maintenance. For the interval before the first major maintenance,  $g(r) > 0$  &  $j \leq xh(r, 1)$ , and the sequence number of major maintenance is 1, the sequence number of minor maintenance is sequence number of maintenance interval.

Situation 3: at least one major overhaul. For the interval between two adjacent major maintenance, the sequence number of major maintenance is the number of former major plus one, and the sequence number of minor maintenance is the sequence number of maintenance interval minus the number corresponding to former major maintenance.

Situation 4: at least one major maintenance. Maintenance interval locates behind the last major maintenance,  $g(r) > 0$  &  $j > xh(r, g(r))$ . At this moment, the sequence number of major maintenance is the total times of major maintenance plus one, and the sequence number of minor maintenance is the sequence number of maintenance interval minus the sequence number corresponding to the last major maintenance ( $j$  is the sequence number of maintenance interval, range from 1 to  $r+1$ ).

### 3.3. Example Analysis

Take a distribution transformer for an example to optimize the maintenance strategy in order to minimize the sum of maintenance cost and failure cost. Life time distribution of the distribution transformer is expressed with two-parameter Weibull distribution and picked typical distribution parameter,  $m=2$ ,  $\eta_{11}=14$ . Mean restoration expense after single failure is 4000 Yuan. Loss of power cut caused by failure of distribution transformer is 40000 Yuan, and major maintenance cost are 2000 Yuan, and minor maintenance cost are 500 Yuan. Designed life of distribution transformer is 25 years and the deterioration rate is 0.15. Assume the sum of maintenance times during the life of distribution transformer is at most 24. A minimum question is to be solved. The reciprocal of objective function is used as the fitness function in the optimization process. For the sake of speeding up to search for the optimal results, the value of crossover probability and mutation probability are appropriately bigger, and are 0.8 and 0.15, respectively. The population size in each cycle corresponds to the number of maintenance times, and the population iteration times are 600. In order to overcome the disadvantages of initial population oversize and easily falling into local optimum, initial population generates and optimizes repeatedly. The entire optimal result as the optimal solution under such maintenance times in the end is reserved. We can know when the maintenance times are 19, there exists the entire optimal solution and the string correspond to the optimal maintenance strategy at this moment is {0000100001000010001}, which means 4 times of major maintenance and 15 times of minor maintenance. The major maintenance happens at the No. 5, No. 10, No. 15, and No. 19 regular maintenance. The minor maintenance is carried out in the rest maintenance periods.

Secondly, Loss of power cut caused by failure of distribution transformer is 30000 Yuan, and major maintenance cost are 1800 Yuan, and minor maintenance cost are 800 Yuan. The optimal maintenance times are 18. The minor maintenance times are 10. The major maintenance times are 8. The comparison results demonstrate the feasibility and validity of the proposed method.

### 3.4. Comparison of Optimization Results and Analysis on Influence Factors

Comparing two optimal results, the optimized solutions actually have closely relationship with single major maintenance cost, minor maintenance cost, and single failure loss. In order to explain conveniently,  $R_1$  represents the ratio of single major maintenance cost and failure cost, and  $R_2$  represents the ratio of single minor maintenance cost and failure cost. When  $R_1$  and  $R_2$  are comparatively small, appropriately decreasing failure cost which is brought from increasing maintenance times can offset the increase of maintenance cost due to the increase of maintenance times. So there will be more maintenance times in optimization results. On the contrary, when  $R_1$  and  $R_2$  are comparatively big, optimization results tend to be obtained under the condition of less maintenance times. For major maintenance and minor maintenance, when the difference between single major maintenance cost and minor maintenance cost is decreasing, the major maintenance times are relatively increasing. Otherwise, the major maintenance times are decreasing. The optimization results are also related to parameters of Weibull distribution. The maintenance frequency will be lower with the shape parameter  $m$  and scale parameter  $\eta$  increasing. Otherwise, it will be higher.

#### 4. Conclusion

This paper studies the optimal maintenance strategy of distribution transformer. Based on equal deterioration theory, the relationship among distribution transformer failure rate in each period of maintenance is deduced. After analyzing the maintenance cost and the failure cost in detail, the model of optimal life cycle cost for distribution transformer is established. Then the genetic algorithm is used to solve the model for obtaining the optimal maintenance strategy. Finally, the optimization results and the influence factors are analyzed. There is certain use for reference to decide the maintenance strategy of other power equipments.

#### Acknowledgements

This work is supported by the National Natural Science Foundation of China Grant No. 51105183, the Research Fund for the Doctoral Program of Higher Education Grant No. 20115314120003, the Applied Basic Research Programs of Science and Technology Commission Foundation of Yunnan Province Grant No. 2010ZC050, the Foundation of Yunnan Educational Committee Grant No. KKJA201004006, the National College Student Innovation Training Program Funded Projects, the Science and Technology Project of Yunnan Power Grid Corporation.

#### References

- [1] Jorge RS, Hawkins TR, Hertwich EG. Life Cycle Assessment of Electricity Transmission and Distribution-part 2: Transformers and Substation Equipment. *International Journal of Life Cycle Assessment*. 2012; 17(2): 184-191.
- [2] Ma Z, Zhong L, Lu K, Xia C. Study on the Maintenance Strategy of Power Equipment Based on the Optimal Life Cycle Cost. *Power System Protection and Control*. 2011; 39(6): 34-39.
- [3] Agah SMM, Abyaneh HA. Effect of Modeling Non-Normality and Stochastic Dependence of Variables on Distribution Transformer Loss of Life Inference. *IEEE Transactions on Power Delivery*. 2012; 27(4): 1700-1709.
- [4] Gouda OE, Ali MD, Ali H. Comparison between Oil Immersed and SF6 Gas: Power transformers Ratings. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(1): 43-54.
- [5] Yun SY, Park CH, Song IK. Development of Overload Evaluation System for Distribution Transformers Using Load Monitoring Data. *International Journal of Electrical Power & Energy Systems*. 2013; 44(1): 60-69.
- [6] Chitra T. *Life Based Maintenance Policy for Minimum Cost*. Annual Reliability and Maintainability Symposium, 2003 Proceedings. Tampa Florida. 2003: 470-474.
- [7] Usher JS, Kamal AH, Syed WH. Cost Optimal Preventive Maintenance and Replacement Scheduling. *IIE Transactions*. 1998; 30(12): 1121-1128.
- [8] Long J, Sheno RA, Jiang W. *A Reliability-centred Maintenance Strategy Based on Maintenance-free Operating Period Philosophy and Total Lifetime Operating Cost Analysis*. Proceedings of the Institution of Mechanical Engineers Part G-journal of Aerospace Engineering. 2009; 223(G6): 711-719.
- [9] Zhao Y, Zhang Z. New Model for Predicting Machine Reliability and Performance Degradation between Neighboring Overhaul Circles. *Chinese Journal of Mechanical Engineering*. 1996; 32(1): 23-27.
- [10] Deb K, Pratap A, Agarwal S, Meyarivan T. A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*. 2002; 6(2): 182-197.
- [11] Bhaskar MM, Maheswarapu S. A Hybrid Genetic Algorithm Approach for Optimal Power Flow. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2011; 9(2): 211-216.
- [12] Zhang JJ, Liu WJ, Liu GY. Parallel Genetic Algorithm Based on the MPI Environment. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(7): 1708-1715.