J Electr Eng Technol.2018; 13(4): 1631-1637
http://doi.org/10.5370/JEET.2018.13.4.1631

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Analysis of Economic Replacement Cycle of Power Transformer Based on LCC Considering Maintenance Effect

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Abstract – Electric utilities has been considered the necessity to introduce asset management of electric power facilities in order to reduce maintenance cost of existing facilities and to maximize profit. This paper aims to provide data that can helpful to make profitable decision in terms of power transformers which have a significant part in the power system. Therefore, this study is modeling input cost for power transformer during its entire life and also the life cycle cost (LCC) technique is applied. In particular, the variation of transformer state related with maintenance and the variation of the EUAC curve based on cost and effect of maintenance is examined. In this study, the trend of the equivalent uniform annual cost (EUAC) according to maintenance cycle and cost of equipment is analyzed. In line with that, sensitivity analysis influenced by the changes of other cost factors was performed.

Keywords: Asset management, EUAC(equivalent uniform annual cost), LCC(life cycle cost), Overhaul, Power transformer.

1. Introduction

The electric power industry demand high reliability in that highly developed modern society is supported by that. As a result, the power industry become complicated and enormous over the past several years, and the cost for maintaining great reliability has been spending as well. However, due to the slowdown in the growth of the electric power industry and intense competition among companies, electric power companies are pressured to reduce maintenance costs and maximize profits of existing facilities. Based on this trend, cost analysis for making economical decision of power transformers, which have a significant portion in the power system is focused [1, 2].

In order to make decisions in terms of repairs and replacements for power transformers, not only measuring by counting parts and labor costs, but comprehensive comparison including reliability and cost is needed. Besides, loss costs, capital costs, and power outages should be considered for making economical decisions.

This paper analyzed the cost of the power transformer over its entire life by using the life cycle cost (LCC) method in order to determine the replacement priorities of long-term use power transformers.

For cost analysis indicators, the capital cost consisting of asset purchasing and disposal costs, and as the maintenance cost the cost of transformer loss, the periodic inspection cost, and the cost of transformer accident treatment was selected. Unequable costs incurred every year are calculated as the equivalent uniform annual cost (EUAC) for life cycle cost calculations, and finally, the study observe the trend of the EUAC due to the years and try to estimate the economic replacement period of power transformer with long service life. Also, we define the state recovery of the transformer according to the maintenance of the facility and define the change of the accident handling cost accordingly. In this case, the trend of the equivalent uniform annual cost (EUAC) according to the maintenance cycle and the maintenance intensity of the facility was examined and the sensitivity analysis was performed according to the change of other cost factors.

2. Power Transformer LCC Evaluation and Application Method

2.1 Define transformer status and failure rate

The failure rate of the power transformer during its life cycle is changing. The failure rate tends to decrease gradually in the section where the initial transformer is installed, and after certain period of time, the appropriate maintenance rate is maintained and the failure rate tends to be kept constant. If the installation period is long, the failurerate tends to increase due to equipment interruption. In this paper, the transformer failure rate is modeling in order to convert the ripple effect of equipment failure into a quantitative cost value [3].

$$\lambda(t) = \alpha_1 e^{-\frac{t}{\beta_1}} + \alpha_2 e^{\frac{t}{\beta_2}} \tag{1}$$
$$\alpha_1, \alpha_2, \beta_1, \beta_2 > 0$$

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Received: November 16, 2017; Accepted: January 25, 2018

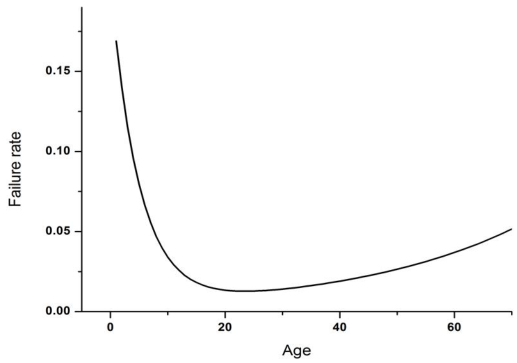

Fig. 1. Examples of failure rate modeling Examples of failure rate modeling

Eq. (1) is used to model the failure rate of the non-monotonic trend curve in the form of a bathtub curve. At this time, β_1, β_2>0, the failure rate in the form of a bathtub curve can be modeled. Model the reduced failure rate when the value of β_1 is greater than 0 and model the failure rate that increases when the value of β_2 is greater than zero.

Fig. 1 shows the modeled failure rate trend when $\alpha_1 = 0.2, \alpha_2 = 0.005, \beta_1 = 5, \beta_2 = 30$. Where α is the scale parameter and β is the shape parameter.

2.2 Calculation of capital cost

The investment cost can be represented as the present value of the asset, including the cost of the equipment before the planned design, procurement, construction and installation etc. are in operation. In order to simplify the calculation, the study present value of assets which is composed of purchase cost and disposal value. The present value of the asset ($PW(N)$) is calculated as the difference between the purchase cost (C) and the depreciation cost $D(n)$. This means that the longer the asset is retained, the more depreciation will increase and the present value of the asset will decrease, as shown in Eq. (2) [4, 5].

$$PW(N) = C - \sum_{n=1}^{N} D(n) \tag{2}$$

$$D_n = \frac{C - S_n}{n} \tag{3}$$

In Eq. (2), $D(n)$ represents the depreciation of the asset when the asset is held for up to n years and is calculated by the straight line depreciation method [4]. The straight line depreciation method is same with Eq. (3) and the annual depreciation cost is the difference between the purchase cost of the asset and the disposal value at the end of the year divided by the number of years of use n.

2.3 Calculation of operation cost

The operating cost of a power transformer means total cost spent for steady operating of the transformer during the life cycle. The operating cost of a power transformer is the total cost spent to keep the transformer running normally during the life cycle of the transformer. Operating costs typically include maintenance costs C_M, energy loss costs C_{EL}, and failure costs C_F Therefore, in this paper, the operating cost of the transformer is defined as Eq. (4).

$$C_0 = C_M + C_{EL} + C_F \tag{4}$$

2.4 Maintenance cost

Maintenance is essential to maintain proper functioning of the transformer. Maintenance costs are divided into routine maintenance costs, such as monitoring and fault prevention of transformer condition, labor costs, and non-routine costs, which are used to repair transformers due to problems with transformers. Non-routine maintenance cost includes the cost of failing to supply power in the event of a fault and the cost of troubleshooting. The maintenance cost C_M is shown in Eq. (5), and the daily cost C_R and the non-routine cost C_{NR} are shown in Equations (6) and (7), respectively.

$$C_M = C_R + C_{NR} \tag{5}$$

$$C_R = 0.00219 \cdot C \tag{6}$$

$$C_{NR} = \lambda(t)\left[\left(aW \cdot SCDF_j \cdot j\right) + (OC)\right] \tag{7}$$

where,

$\lambda(t)$	: Failure rate when transformer age is t
a	: Number of load lines
W	: Peak power
$SCDF_j$	: Sector customer damage functions
j	: Failure duration
OC	: Overhaul cost

2.5 Energy loss cost

The power grid loss rate is known to be about 10 [%], and most occurs in power transformers [6]. The losses occurring in the transformer consist largely of iron loss, which is no load loss, and copper loss, which is a load loss. Therefore, in this paper, the energy loss is given by the following Eq. (8).

$$C_{EL} = (NLL + L^2 \times LL) \times HPY \times P_E \tag{8}$$

where,

LL	: Load loss (kW)
C_{EL}	: Energy loss cost
NLL	: No load cost (kW)
L	: Load factor
HPY	: Annual transformer operating hours (normally 8760 hours)
PE	: Electricity charge(Won/kWh)

2.6 Failure cost

Failure cost is the cost of considering the ripple effects of unexpected transformer accident. Since the aging characteristics of a transformer are derived from the general tendency of a transformer group, it is difficult to reflect the characteristics of individual devices and individual diagnostic characteristics. Therefore, in this paper, we estimate the annual cost of accident handling by using the modeled failure rate. Because many accidents that comes from electronic line is unexpected and hard to generalize, the goal is just to make generalize first [7]. If lifespan of transformer is t, the expectation of accidental cost is Eq. (9), below.

$$C_F = \gamma \times \lambda_2(t) \times C \times \lambda(t) \qquad (9)$$

where,

γ : Accident handling factor
$\lambda(2t)$: Overhaul probability
C : Purchase cost of transformer
$\lambda(t)$: Modeled failure probability

2.7. Variation of transformer accident treatment factor (γ) by maintenance failure cost

If the transformer wore-out and show air inflow, insulation breakdown, gas leakage, precise inspection and overhaul is implemented. In this paper, it is assumed that the condition of the transformer is better than before when the repair of the transformer is performed, and the ripple effect is reduced when the transformer fails. Fig. 2 shows the transformer state change with the repair of the transformer. Whenever transformer is repaired, the state of the transformer is shown to be recovered by a constant value. The more the cost of repairing the transformer is, the greater the recovery effect is.

Fig. 3 is a graph showing the relationship between the overhaul cost and the recovery effect, and calculation method was same with the one used in [7]. As the cost of overhaul increases, the recovery effect increases, and the slope of the recovery effect varies based on the recovery index n. The higher the recovery index, the higher the recovery effect with low cost investment. However, if the recovery index is low, it is defined that it is difficult to obtain a relatively large recovery effect even if a large cost is invested. At this time, the overhaul cost is based on the generalization of the cost of purchasing the transformer to 1.

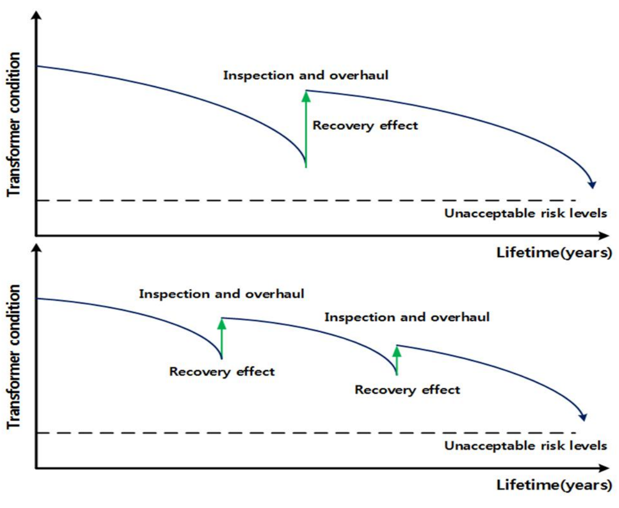

Fig. 2. Examples of transformer health status changes due to transformer maintenance

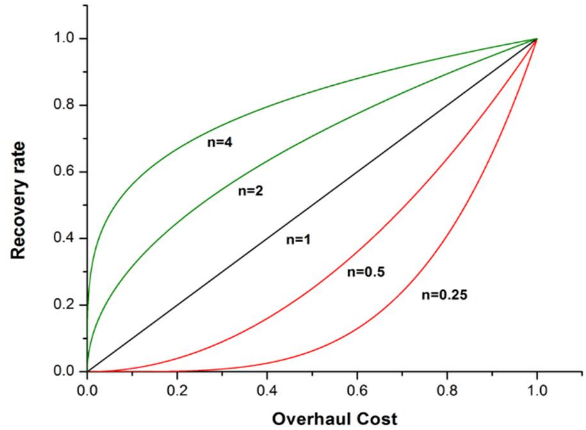

Fig. 3. Correlation between overhaul cost and recovery effect

The relationship between maintenance cost and recovery effect is as follows [7].

$$Recovery\ rate = (Overhaul\ cost)^{1/n} \qquad (10)$$

$$\gamma = \frac{1}{Recovery\ rate} \qquad (11)$$

3. Calculation of the Equivalent Uniform Annual Cost (EUAC) for LCC Analysis

The costs of managing the transformer mentioned in the previous section are not changed or inconstant every year so that it is difficult to compare them in a simple summing method. Therefore, this paper trying to look at the changes in cash flow depending on the economic life span of the transformer and the variable through the conversion of all non-uniform costs to the same cost every year [4, 8, 9].

Many of the transformer lifetime assessment studies assume increased cost trends. Also, the majority do not consider cash flows over time. Since the discount rate responds very sensitively to the increase or decrease in the cash flow, it is necessary to apply this factor to obtain accurate results. For this reason, EUAC was used in this study.

First, Eq. (12) is the calculation of capital cost. Eq. (12) represents the future value of capital cost excluding the current value of the transformer from the cost of purchasing the transformer. Since the present value of the transformer represents the future value according to the period N, we applied a single-payment future-worth factor to the cost of purchasing the transformer. And the sinking fund factor to obtain the EUAC for the period N is shown in Eq. (13).

$$FC_C = C(F/P, i, N) - PW(N) \quad (12)$$

$$EUAC_1 = FC_C(A/F, i, N) \quad (13)$$

$$(F/P, i, N) = (1+i)^N$$

$$(A/F, i, N) = \frac{i}{(1+i)^m - 1}$$

where,

FC_C Future value of transformer capital cost
C Purchase cost of transformer
$(F/P, i, N)$ The interest rate i and the single payment Future worth factor for the period N years
$PW(N)$ Current value of transformer
$(A/F, i, N)$ The sinking fund factor for interest rate i and period N years

Second, Eq. (14) is the sum of the operating costs applying to the EUAC and Eq. (15) is the EUAC of all the costs charged to the transformer.

$$EUAC_2 = \sum_{n=1}^{N}(C_M + C_{EL} + C_F)(A/P, i, N) \quad (14)$$

$$EUAC = EUAC_1 + EUAC_2 \quad (15)$$

$$(A/P, i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$

where,

$(A/F, i, N)$ The EUAC factor for interest rate i and period N

4. Simulation Results

This is case study of a bank of power transformers with a capacity of 154[kV]/60[MVA]. The interest rate is designated as 1~10[%], and the results are derived from the change of the EUAC depending on the overhaul period and overhaul investment cost. The larger the overhaul cost, the greater the effect of the state recovery of the transformer, and the lower the cost, the smaller the state recovery effect. The load factor is set at 60 [%]. Table 1 shows the data table used in the case study and Table 2 shows the loss cost data.

Fig. 4 shows the EUAC curves when interest rates are 1[%], 3[%], and 5[%], respectively, without considering periodic overhaul and overhaul. As the interest rate increases, the minimum value of the EUAC curve rises

Table 2. Loss due to capacity

Rated capacity [MVA]	No load loss [kW]	Load loss [kW]
15	18	46
31.5	38	135
40	45	157
45	49.5	173
50	54	189
63	63	220
90	80	288
120	99	346
150	116	405

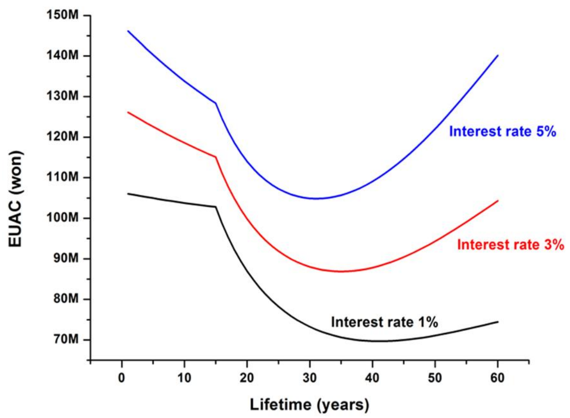

Fig. 4. EUAC curves with different interest rates

Table 1. Data table used in case study

Model parameter	Value	note	Failure handling cost data		
Interest rate	(1, 3, 5, 10) [%]		Average lifetime	60 [year]	
Capital cost data			Standard deviation	20	
Transformer purchasing cost	1,000,000,000 [Won]	Proportional to transformer capacity	Failure factor	(2, 3)	Proportional to transformer capacity
Asset disposal value	0 [%]	Proportional to cost of capital	Recovery index (n)	(1, 1.5)	Proportional to overhaul cost
Depreciation year	15 [year]		Energy loss cost data		
Operational cost data			No load loss	Proportional to transformer capacity	
Regular inspection cycle	5 [year]		Load factor	60[%]	
Overhaul cycle	(10, 20) [year]		Load loss	10[%]	
Periodic inspection costs	1 [%]	Proportional to the cost of purchasing a transformer	Electricity charge	88 [won] per kWh	
Overhaul costs	(5, 10) [%]	Proportional to overhaul cycle	Annual operating hours	8760 [hour]	

and the number of years reaching the minimum value point is increased.

Fig. 5 shows the annual average cost curve derived from previous studies before this study [10-12]. This line is expressed as a ratio of the purchase cost of the transformer and shows the average cost trend when the overhaul is carried out. The interest rate and the value of the depreciation are not taken into account. It is also assumed that the maintenance cost increases with lifetime. It does not consider the cash flow and residual value over time, so the cost does not increase even if the lifetime increases.

Therefore, the average cost is greatly reduced from the beginning of lifetime. This result shows that it is cost effective to replace it in the early period despite the residual value. Fig. 4, which is a curve derived from this study, reflects the residual value of the transformer early in the lifetime and indicates that it is inefficient to replace it in the early period. It also reflects the cash flow over time, allowing us to better understand the level of increase or decrease in cost depending on the interest rate.

The maintenance condition in Fig. 6 is the overhaul cycle 10 years and the overhaul cost 5[%]. When the recovery index is 1, it can be seen that it causes cost loss rather than overhaul. It can be confirmed that the increase in cost after 40 years is suppressed because the effect of overhauling the transformer lifetime is relatively large.

The maintenance condition in Fig. 7 is the overhaul cycle 10 years, the overhaul cost 5[%], and the interest rate is 10[%]. It can be seen that the cost gain cannot be obtained over the whole period even when the interest rate is 5[%].

Fig. 8 shows the EUAC curve at an interest rate of 5[%]. The conditions of Case 1 and Case 2 are shown in Table 3. Both cases result in a cost advantage over when they are not maintained near 40 years. It can be seen from the comparison of the two cases that it is advantageous in terms of cost advantage to perform high-intensity maintenance with a relatively long cycle time than the frequent maintenance cycle.

Table 3. Conditions of Case 1 and Case 2

	Overhaul cycle	Overhaul costs	Recovery index(n)
Case 1	10[years]	5[%]	1
Case 2	20[years]	10[%]	1.5

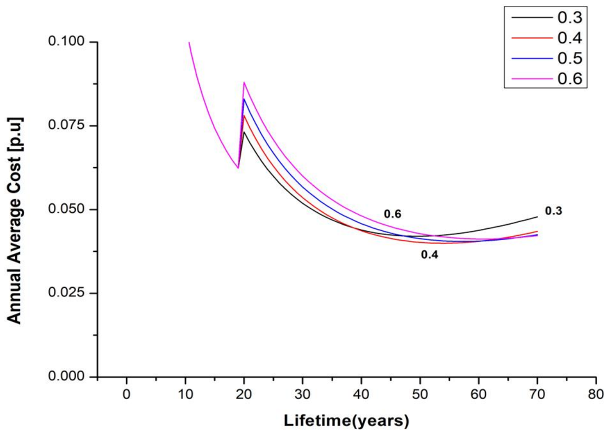

Fig. 5. The annual average cost curve of the preceding studies

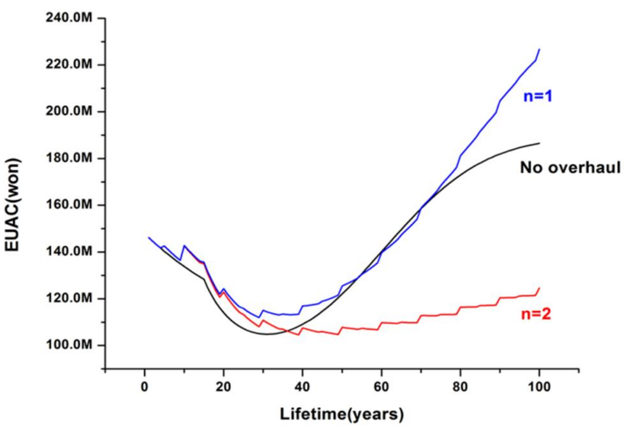

Fig. 6. EUAC curves with an interest rate of 5[%] and different recovery index

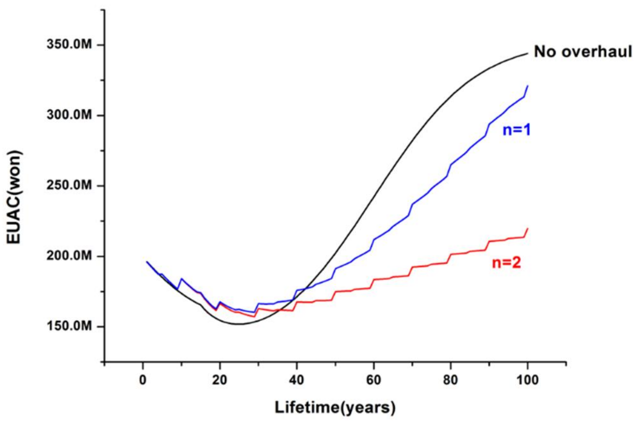

Fig. 7. Interest rate 10[%], overhaul cycle 10 [years], overhaul cost 5[%]

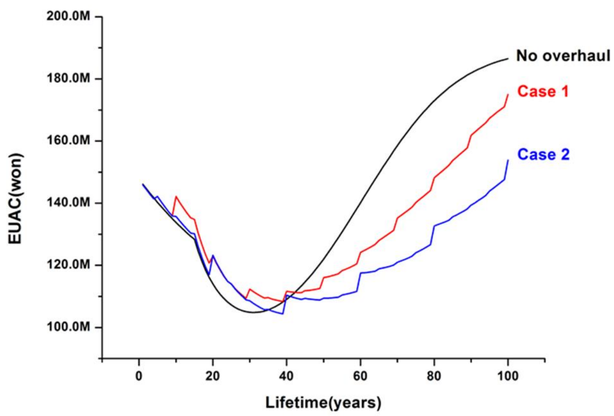

Fig. 8. Change of EUAC Curve according to Overhaul Cycle

5. Conclusion

In this paper, the variation of the EUAC curve based on various cost factors on power transformer was observed. In particular, we defined status change of transformer in terms of maintenance and focused on the EUAC curve change according to interest rate, maintenance cost, and effect. The lower the interest rate is, the more likely to reach the lowest point of the EUAC curve. If the interest rates are the same, it has been found that it is cost-effective to have a high overhaul for relatively long-time use of the transformer and a relatively low overhaul for short-time use. It was confirmed that the higher the recovery index n, which is efficiency of the overhaul, the more the cost gain was obtained.

In this paper, the change of the integrity of the transformer and the change of the failure cost are assumed based on the maintenance cost. This assumption, however, could be unrealistic. Therefore, the stability of the transformer and the level of actual maintenance effect will be considered as important factors in the future.

Acknowledgements

This research was supported by Korea Electric Power Corporation (Grant number: R15XA03-38).

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