Economic Life Prediction of Transformer Based on Repairing Profit and Decommissioning Profit

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Abstract. Transformer lifecycle management is an important research field that power grid enterprises pay great focus on. The economic life prediction of transformer can provide a basis for transformer equipment management and power grid planning, contribute to prolong the service time of transformer and improve the operation safety and economy of power grid. This paper proposes an economic life prediction model of transformer by analysing various economic factors of transformer and taking the maximum annual average net profit of transformer as the judging criterion, and achieves the economic life quantitative prediction of transformer by comparing the annual average net profit of repairing a transformer and the annual average net profit of decommissioning a transformer. Finally, a case study on the economic life prediction of transformer by selecting an 110kV transformer in service as an example is carried out according to the proposed model, and the results show that the proposed model can not only effectively analyse the economic factors of the transformer, but also reasonably predict the economic life of the transformer, which has a guiding significance for the decision-making of transformer management and the future planning of substation.

1. Introduction
The reliability of transformer is directly related to the safe operation of smart grid, and the power outage accident caused by transformer will probably bring about huge economic losses. At present, some transformers in power grid have been operating for more than 20 years and begin to enter the middle and late stage of the design life. Technically, these transformers can continue to be on service, but their failure probability will become higher and higher, which has a greater impact on the safe and reliable operation of the power grid. Economically, the operation and maintenance costs and failure probability of transformers will increase with the operation time increase and the component aging of transformer. Therefore, when to decommission these transformers to ensure the highest economic efficiency is an urgent problem to be solved. The economic life prediction of transformer is an effective method to solve the problem.

In order to make an objective life assessment of a transformer, it is necessary to clarify the life termination conditions of the transformer. Aiming at the large number of transformers in power grid, this paper selects the maximum annual average net profit as the judgement condition and presents an economic life predicting model of transformer by calculating the annual average net profit under two cases of repairing a transformer or decommissioning a transformer to help determine the economic life of the transformer and verifies the effectiveness of the proposed model with an actual case study.
2. Related Works
The equipment state analysis with various modern technologies has been widely researched to degrade the accident risk and improve traditional management methods. With the scale of power grid increasing, the power grid enterprises pay more focuses on the economy of equipment management [1]. The various economic information such as power supply income, operation and maintenance cost, failure repairing cost and environmental protection cost are both taken into consideration in the process of equipment lifecycle management [2]. In recent years, some research works begin to focus on the economic life evaluation of transformer [3-5]. Liu et al. consider that the decommissioning time of transformer is the time when its maximum annual average net income decreases to less than that of a new equipment [6]. Most of the calculation equations used in this work are empirical equations, which do not make full use of the historical information of transformers. With the technology development of online monitoring and asset management, the increase of transformer life data provides a good basis for the economic life study of transformer in power grid enterprises.

The economic life management of transformer has developed into an interdisciplinary, comprehensive and systematic subject [7]. In fact, with the advancement of digitalization power grid and the intensification of market competition, more and more attention has been paid to the economic life accurate evaluation of power transmission and transformation equipment. Therefore, broadening the research field of equipment renewal of power grid enterprises and proposing equipment renewal theories and methods suitable for the needs of power grid enterprises are not only of far-reaching theoretical value, but also of great practical significance [8].

3. Repairing Profit and Decommissioning Profit-Based Transformer Economic Life Prediction

To predict the economic life of transformer based on repairing profit and decommissioning profit, the relevant economic factors of transformer should be firstly analysed, and then the repairing profit and decommissioning profit of transformer can be calculated by considering synthetically the revenue and cost of transformer in different operation stages. When the decommissioning profit is bigger than the repairment profits, the economic life of transformer will be ended.

3.1. Economic Factors Analysis
The economic factors related to transformer include power supply income, operation and maintenance cost, accident risk cost, generalized depreciation cost, failure repairing cost, etc. The power supply income mainly refers to the income that is brought by a transformer by providing electric energy services. The operation and maintenance cost mainly include the expenses of energy consumption,
daily maintenance, etc. The energy consumption expenses come from two parts: main equipment and auxiliary equipment, the daily maintenance expenses refer to the expenses of components, materials, labour and others for daily maintenance. The accident risk cost refers to the direct and indirect losses caused by a transformer accident such as outage loss, accident processing expense and social responsibility loss. The generalized depreciation cost refers to all one-time investment of a transformer from commissioning to decommissioning, including equipment purchase expense, installation and commissioning expense, decommissioning expense, decommissioning residual value and other fees. The failure repairing cost mainly includes repairing expense and downtime loss.

3.2. Model Premise Assumptions
To simplify the model without losing its generality, the following assumptions are put forward based on the investigation and analysis of various operational experience data:

i. The operation and maintenance cost will increase linearly with the service age increasing.

ii. The repairing time will increase linearly with the service age increasing.

iii. All transformers have a basic failure probability curve.

iv. Repairing the failure of a transformer can reduce the failure probability, but the reduction magnitude of the failure probability first increases and then decreases with the service age increasing, which can be specifically described by the equation (i) and (ii).

\[
\Delta \lambda(t) = \frac{\lambda(t) \times 75}{125 + (t-26)^2}
\]

\[
\lambda'(t) = \lambda(t) - \Delta \lambda(t)
\]

In the equation (i) and (ii), \( \lambda(t) \) is the failure probability before the repairing at time t, \( \Delta \lambda(t) \) is the reduction magnitude of the failure probability made by the repairing at time t, \( \lambda'(t) \) is the failure probability after the repairing at time t.

v. The failure probability after repairing will start from a new base point, but still follow the same curve.

3.3. The Annual Average Net Profit Model of Transformer under Repairing

3.3.1. Power Supply Income. For a period of time, the power supply income is mainly related to the load rate of transformer and the price difference between power purchase and power sale. The total power supply revenue of a transformer is shown as follows:
\[ I_{p1} = \xi \times S \times \eta \times \Delta P \times (t + \Delta t - t_0) \tag{1} \]

In the equation (1), \( \xi \) is the contribution rate of the transformer in the whole power supply chain, \( S \) is the capacity of the transformer, \( \eta \) is the average load rate of the transformer, \( \Delta P \) is the price difference between power purchase and power sale.

3.3.2. Operation and Maintenance Cost. The operation and maintenance cost of a transformer can be calculated with the following equation:

\[ CO_1 = (P_0 + \eta^2 \times P_K) \times \mu \times (t + \Delta t - t_0) \times 8760 + CO_b \times \int_{t_0}^{t+\Delta t} (1 + a_1 t) \, dt \tag{2} \]

In the equation (2), \( P_0 \) is the energy loss of the transformer with empty load, \( P_K \) is the energy loss of the transformer with some load, \( \eta \) is the average load rate of the transformer, \( \mu \) is the annual loss rate, \( p_1 \) is the unit power cost paid by the transformer owner. \( (P_0 + \eta^2 \times P_K) \times \mu \times (t + \Delta t - t_0) \times 8760 \) is the annual energy loss of the transformer. \( CO_b \) is the annual basic maintenance expense, which can be obtained according to the relevant statistical data. \( a_1 \) is the linear coefficient of the maintenance expense increasing with the service age of the transformer. \( CO_b \times \int_{t_0}^{t+\Delta t} (1 + a_1 t) dt \) is the maintenance expense of the transformer.

3.3.3. Accident Risk Cost. The following equation can be used to determine the accident risk cost of a transformer:

\[ CR_1 = (\int_{t_0}^{t} \lambda(t) \, dt + \int_{t}^{t+\Delta t} \lambda(t) \, dt) \times (S \times \cos\phi \times \eta \times t \times F \times \theta \times (\beta_{11} \times \beta_{12} \times \beta_{13}) + C_f \times (\beta_{21} \times \beta_{22}) + \sum_{i=1}^{3} S_i \times r_i) \tag{3} \]

In the equation (3), \( CR_1 \) is the accident risk cost of the transformer. \( \int_{t_0}^{t} \lambda(t) \, dt + \int_{t}^{t+\Delta t} \lambda(t) \, dt \) is the accident probability of the transformer. \( S \times \cos\phi \times \eta \times t \times F \times \theta \times (\beta_{11} \times \beta_{12} \times \beta_{13}) + C_f \times (\beta_{21} \times \beta_{22}) + \sum_{i=1}^{3} S_i \times r_i \) is the economic loss when a transformer accident occurred and mainly includes load removing expense, accident repairing expense and personal injury compensation. \( S \) is the capacity of the transformer, \( \cos\phi \) is the average power factor of the transformer, \( \eta \) is the average load rate of the transformer, \( t \) is the failure repairing time of the transformer, \( F \) is the load removing probability under a sudden transformer failure, \( \theta \) is the value of unit power consumption. The correction factor of system accident risk includes mainly the importance of substation \( \beta_{11} \), the importance of load \( \beta_{12} \) and the importance \( \beta_{13} \) of repairing environment. Their values are listed in Table 1. \( S \times \cos\phi \times \eta \times t \times F \times \theta \times (\beta_{11} \times \beta_{12} \times \beta_{13}) \) is the load removing expense of the transformer under repairing.

| the correction factor | the value of the correction factor |
|----------------------|----------------------------------|
| \( \beta_{11} \)     | load-centre substation: \( \beta_{11} = 1.16 \); contact substation: \( \beta_{11} = 1 \); |
|                      | terminal substation: \( \beta_{11} = 0.8 \) |
| \( \beta_{12} \)     | the important load: \( \beta_{12} = 1.16 \); the general load: \( \beta_{12} = 1 \) |
| \( \beta_{13} \)     | indoor substation: \( \beta_{13} = 1.16 \); outdoor substation: \( \beta_{13} = 1 \) |

\( C_f \) represents the statistical average value of the accident repairing expense that can be obtained according to expert experiences. The correction factor of the accident repairing expense includes mainly the influence of transformer manufacturer address \( \beta_{21} \) and the influence of transformer maintenance environment \( \beta_{22} \). Their values are listed in Table 2. \( C \times (\beta_{21} \times \beta_{22}) \) is the accident repairing expense.

| the correction factor | the value of the correction factor |
|----------------------|----------------------------------|
| \( \beta_{21} \)     | local address: \( \beta_{21} = 0.9 \); domestic address: \( \beta_{21} = 1 \); foreign address: \( \beta_{21} = 1.3 \) |
|                      | indoor substation: \( \beta_{21} = 1 \); outdoor substation: \( \beta_{21} = 1.16 \) |

\( S_i (i=1,2,3) \) represents the compensation expenses corresponding to three levels of personal injury: slight injury, serious injury and death. \( r_i (i=1,2,3) \) represents the probability that a person is slightly injured, seriously injured or dead with taking the values of \( 2\% \), \( 0.5\% \) or \( 0.1\% \). \( \sum_{i=1}^{3} S_i \times r_i \) is the personal injury compensation to the injured persons caused by a transformer accident.
3.3.4. Generalized Depreciation Cost. According to the definition of generalized depreciation cost, its calculation equation is shown as follows:

\[
CD_1 = (Cl_E + Cl_I + Cl_o + Cl_D × CC_R - CD_R + C_{rc}) × t_{d0} / T_{dl}
\]  

(4)

In the equation (4), \(Cl_E\) is the initial investment expense of a transformer, including purchase expense \(Cl_E\), installation and commissioning expense \(Cl_I\), and other related expenses \(Cl_o\). \(Cl_D × CC_R - CD_R\) is the decommissioning expense of a transformer that mainly includes scrapping expense and residual income. The scrapping expense \(Cl_D × CC_R\) refers to the expenses of dismantling and transporting a scrapped transformer and labor charges, the residual income of an out-of-service transformer. \(C_{rc}\) is the outage loss caused by changing an old transformer with a new transformer, and \(T_{dl}\) is the design life of a transformer provided by the manufacturer.

3.3.5. Failure Repairing Cost. The failure repairing cost of a transformer can be calculated with the following equation:

\[
CM_1 = (1 + α_2 t) × C_b + (t_b + α_3 t)(S × Δp × 0.02)
\]  

(5)

In the equation (5), \(CM_1\) is the failure repairing cost that mainly includes repairing expense and downtime loss. \(α_2\) is the linear coefficient of the repairing cost increasing with the service age of the transformer and generally takes 0.005 as the default value, \(t\) is the service age of the transformer, \(C_b\) is the basic expense of a single repairing, \((1 + α_2 t) × C_b\) is the repairing expense at time \(t\). \(t_b\) is the basic overhaul time, \(α_3\) is the linear coefficient of the repairing time increasing with the service age of the transformer and generally takes 0.02 as the default value, \((t_b + α_3 t)(S × Δp × 0.02)\) is the downtime loss.

In summary, the cost sum of a transformer under the condition of repairing is shown as follows:

\[
C_1 = CO_1 + CR_1 + CD_1 + CM_1
\]  

(6)

The corresponding average annual net profit of a transformer under repairing:

\[
P_1 = \frac{P_{p1} - C_1}{1 + r × t_{d0}}
\]  

(7)

3.4. The Annual Average Net Profit Model of Transformer under Decommissioning

For the case of directly replacing an old transformer with a new one, assuming that the current time is \(t_0\) and an old transformer is replaced at time \(t\), the annual average net profit model of a transformer under decommissioning needs to know all income and cost factors during the period between \(t_0\) and \(t\).

3.4.1. Power Supply Income. The power supply income is mainly related to load rate and price difference between power purchase and power sale, and it is shown as follows:

\[
I_{p2} = \bar{\xi} × S × η × ΔP × (t + t_0)
\]  

(8)

In the equation (8), all parameters have the same meaning as the equation (1).

3.4.2. Operation and Maintenance Cost. The operation and maintenance cost of a transformer under decommissioning can be calculated with the following equation:

\[
CO_2 = (P_0 + η^2 × P_K) × p_1 × μ × (t + Δt - t_0) × 8760 + CO_b × \int_{t_0}^{t + Δt} (1 + α_1 t) dt
\]  

(9)

In the equation (9), \((P_0 + η^2 × P_K) × p_1 × μ \times (t + Δt - t_0) × 8760\) is the annual energy loss of the transformer, and \(CO_b × \int_{t_0}^{t + Δt} (1 + α_1 t) dt\) is the maintenance expense of the transformer. In the above three equations, all parameters have the same meaning as the equation (2).

3.4.3. Accident Risk Cost. The accident risk cost of a transformer under decommissioning can be calculated with the following equation that has the same parameters as the equation (3):

\[
CR_2 = \int_{t_0}^{t} λ(t) dt + \int_{Δt}^{t} λ(t) dt × S × cosφ × η × F × θ × (β_{11} × β_{12} × β_{13}) + CR × (β_{21} × β_{22}) + \sum_{i=1}^{3} S_i × r_i
\]  

(10)
3.4.4. Generalized Depreciation Cost. The generalized depreciation cost of a transformer under decommissioning can be calculated with the following equation:

$$CD_2 = (CI_E + CI_I + CI_O + CI_D \times CC_R \cdot CD_R + C_{rc}) \times \frac{t}{t_0}$$

(11)

In the equation (11), each parameter has the same meaning as the equation (6), but the transformer design life $T_{dl}$ is replaced by $t$.

In summary, the cost sum of a transformer under the condition of decommissioning is shown as follows:

$$C_2 = CO_2 + CR_2 + CD_2$$

(12)

The corresponding annual average net profit of a transformer under decommissioning:

$$P_2 = \frac{I_{p1} - C_2}{t - t_0}$$

(13)

3.5. The Economic Life Judging of Transformer

In order to objectively analysing the life of transformer, it is necessary to clarify the life termination conditions of transformer. For transformers, this paper takes the maximum annual average net profit of a transformer as the termination condition of its life. Two cases need to be considered during the economic life predicting of transformer: the transformer will be repaired when a failure occurred or the transformer will be decommissioned when a failure occurred.

If $P_1 > P_2$, it means that the annual average net profit obtained by selecting the repairing plan is bigger, so it is better to repair the failure of transformer.

If $P_1 < P_2$, it means that the average annual net income obtained by selecting the decommissioning plan is bigger, so it is better to replace the old transformer.

4. The Case Study

Taking a 110kV and 31.5 MVA transformer in a substation as an example to evaluate its economic life with the above models. The nameplate number of the transformer is SFSZ8-31500/110, and the economic life-related data are shown in Table 3. According to the above hypothesis, we can get the following equation:

$$\lambda(t) = \frac{m}{\eta} \cdot \left( \frac{1}{\eta} \right)^{m-1} = 0.1934 \times \left( \frac{t - 4.1}{28.65} \right)^{4.566}$$

(14)

Furthermore, we can get the following equations by combining the equation (i) and (ii):

$$\lambda(t) = \lambda(t) \cdot \frac{75}{125 + (t-26)^2} = \frac{14.505 \times (t+4.1)^{4.566}}{125 + (t-26)^2}$$

$$\lambda'(t) = \lambda(t) - \Delta \lambda(t)$$

(15)

(16)

Table 3. The main parameters of the example transformer.

| parameter             | value     | parameter | value |
|-----------------------|-----------|-----------|-------|
| S/MVA                 | 31.5      | cosφ      | 0.9   |
| ξ/%                   | 5         | p1/(yuan/kWh) | 0.3 |
| Δp/(yuan/kWh)         | 0.2       | CO2/(yuan/a) | 20000 |
| Energy consumption with empty-load or load/kW | 21.3 or 139.78 | Crc/yuan | 30000 |
| η/%                   | 60        | Cf/yuan   | 200000 |
| C/yuan                | 800000    | t/bday    | 5     |

4.1. The Annual Average Net Profit of the Example Transformer under Repairing

According to the data listed in Table 3, the power supply income of the example transformer under repairing is shown as follows:

$$I_{p1} = 1655640 \times (t + \Delta t - t_0)$$

(17)
The operation and maintenance cost of the example transformer under repairing is shown as follows:

\[ CO_1=149993.49 \times (t+\Delta t-t_0)+20000 \times \int_{t_0}^{t+\Delta t}(1+0.004t)dt \]  \hspace{1cm} (18)

The accident risk cost of the example transformer under repairing is shown as follows:

\[ CR_1=\left[ \int_{t_0}^{t} \lambda(t)dt + \int_{t}^{t+\Delta t} \lambda(t)dt \right] \times 1008487.57 \]  \hspace{1cm} (19)

The generalized depreciation cost of the example transformer under repairing is shown as follows:

\[ CD_1=2157000 \times \frac{t-t_0}{30} \]  \hspace{1cm} (20)

The failure repairing cost of the example transformer under repairing is shown as follows:

\[ CM_1=200000 \times (1+0.005t)+1260 \times (120+0.48 \times t) \]  \hspace{1cm} (21)

According to the sum of the equation (17)–(21), the annual average net profit curve of the example transformer under repairing can be obtained as shown in Figure 3.

4.2. The Annual Average Net Profit of the Example Transformer under Decommissioning

According to the data listed in Table 3, the power supply income of the example transformer under decommissioning is shown as follows:

\[ I_{p2}=165540 \times (t-t_0) \]  \hspace{1cm} (22)

The operational and maintenance cost of the example transformer under decommissioning is shown as follows:

\[ CO_2=149993.49 \times (t-t_0)+20000 \times \int_{t_0}^{t}(1+0.004t)dt \]  \hspace{1cm} (23)

The accident risk cost of the example transformer under decommissioning is shown as follows:

\[ CR_2=\int_{t_0}^{t} \lambda(t)dt \times 1008487.57 \]  \hspace{1cm} (24)

The generalized depreciation cost of the transformer under decommissioning is shown as follows:

\[ CD_2=2157000 \times \frac{t-t_0}{t} \]  \hspace{1cm} (25)

According to equations (22)–(25), the annual average net profit curve of the example transformer under decommissioning can be obtained as shown in Figure 3.

4.3. The Economic Life Judging of The Example Transformer

From the Figure 3, it can be seen that the current service age is 23a. Before the time T=27.52a, the annual average net profit of the example transformer under repairing is higher. After the time T=27.52a, the annual average net profit of the example transformer under decommissioning is higher.
According to the principle of the maximum annual average net profit, the optimal economic decommissioning time of the example transformer is 27.52 years, which proves the feasibility and validity of the above models.

5. Conclusion and Future Work

The economic life prediction of transformer has always been an important issue for the decision-making of equipment management and the future planning of power grid. Aiming at a large number of transformers in smart grid, an economic life prediction model of transformer under two cases of repairing a transformer or decommissioning a transformer when a failure occurred is designed by analysing the economic factors, investigating the failure laws and calculating the annual average net profit. A case study has been conducted to verify the proposed model and shows that the proposed model can effectively analyse the economic life of transformer. In the future, we will improve the proposed model with taking more economic factors of transformer into account.

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REFERENCES

[1] Zhang J.C., Lu Z.D. (2004) Exploration and Research on Equipment Management Model in Metallurgical Enterprises. Metallurgical Equipment, 18(2): 43-45.
[2] Liu K. (2006) Technical and Economic Analysis of Equipment Economic Life and Renewal Schemes. Filtration and Separation, 16(2): 42-44.
[3] Yang Q.P., Xue W.D., Lan Z.D. (2004) Diagnosis and Life Assessment of Transformer Insulation Aging. Transformer, 41(2): 13-17.
[4] Wang Y., Fang S.F., Lu W.Y. (2007) Economic Life Analysis of Equipment under Technological Progress. Journal of Northeast Agricultural University, 38(1): 85-88.
[5] Yu J.L., Wang C.F., Zhang B., et al. (2010). Economic life evaluation of power transformer in service. Proceedings of the CSU-EPSA, 22(3): 86-90.
[6] Liu Y.W., Ma L., Wu L.Y., et al. (2012) Economic life model of power transformer and its application. Power System Technology, 36(10): 235-240.
[7] Liu L., Wang H.J., Cheng H.Z, et al. (2012) Economic evaluation of power systems based on life cycle cost. Automation of Electric Power Systems, 36(15): 45-49.
[8] Yu B.J., Zhu Y.L. (2013) Application of Weighted Limit Learning Machine in Transformer Fault Diagnosis. Computer Engineering and Design, 34(12): 4340-4343.