ASSET MANAGEMENT OF POWER TRANSFORMER, PRACTICAL EXPERIENCE IN THAILAND

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Abstract: An asset management strategy of power transformer is presented in this work to reduce the maintenance costs of power transformer. The risk-based maintenance consisting of condition and importance assessment of each transformer is developed to manage the maintenance tasks of power transformers. The condition assessment is performed by analysis of electrical test, insulating oil test and visual inspection. The importance is evaluated from load criticality, impact on system stability, possibility of failure, failure consequence, damage to property, as well as social impact and environmental concern. Therefore, risk-based maintenance is developed for evaluating the risk of each transformer. Then economic analysis considering life cycle cost and net present value analysis is applied to make a decision for repair, refurbish or replace the failed transformer by a new one. Moreover, sensitivity analysis is performed to perceive any changes on the decision. The computerized web-application program is developed for practical use and already implemented in a utility. Finally, maintenance of power transformer fleet can be effectively managed. The proposed method will be further applied to other high voltage equipment in Thailand.

1 INTRODUCTION

Nowadays, the demands on high reliability, good power quality and acquiring more benefits from the electrical asset in power system have forced many utilities to focus on the better asset management approach. To gain more benefit with fixed revenue from electricity business, the cost reduction is now of primary concern, especially maintenance costs. Due to high acquisition and maintenance cost as well as its catastrophic failure consequences, power transformer is firstly focussed. The routine preventive maintenance is gradually changing to condition-based maintenance and further to risk-based maintenance strategy in the near future.

This paper aims to present the development of risk-based maintenance strategy for power transformer in a formal and systematic method. Firstly, the condition of magnetic core, windings, insulating oil, bushing, arrester, on load tap changer, tank and protective devices are accessed with several diagnostic tests, such as electrical test, insulating oil test and visual inspection. The scoring and weighting techniques have been applied to evaluate the condition of such components and overall condition. Thus, the condition-based maintenance is now successfully developed in this step. After that, the importance of each transformer in the network is also accessed from loading criticality, impact on system stability, possibility of failure, failure consequence, damage to property, as well as social impact and environmental concern.

Then the combination of condition and importance create the risk-based maintenance in form of risk matrix. The risk of each transformer is now able to access and the whole maintenance tasks of power transformer fleet can be effectively managed. Moreover, the economic analysis considering life cycle cost and net present value analysis is applied to make a decision for repair, refurbish or replace the failed transformer by a new one. Besides, parameters such as interest rate, inflation rate and refurbishment cost are varied so as to recognize the sensitivity on the decision changes. With the software development program for maintenance strategy, power transformers in the network can be effectively managed. This results in high availability, low risk of failure, ability to extend the useful lifetime and minimizing costs. This method will be further applied to other high voltage equipments.

2 POWER TRANSFORMER ASSET MANAGEMENT PROCESS

The asset management process of power transformer as shown in Figure 1 consists of:

- database of equipment, test records, and network data
- condition assessment
- importance assessment
- risk assessment
- economic consideration
- decision making and planning

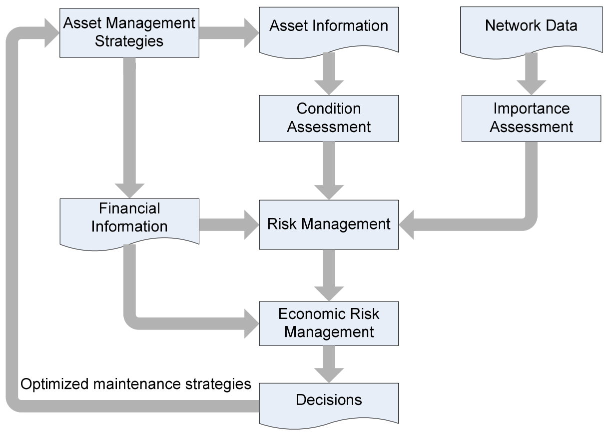


Figure 1: Power transformer asset management

2.1 Database setup

The systematic record of periodic test and measurement results during inspection and overhaul together with visual inspection into database is the first part of developing condition-based maintenance. The key parameters for further analysis must be clearly defined to collect only useful data and prevent unnecessary works. The database is setup by using Microsoft SQL Server program.

2.2 Condition-based maintenance

Power transformer components are classified into seven groups such as active part, insulating oil, bushing, arrester, on load tap changer, main tank, and protective devices. The electrical tests and insulating oil tests [1] are usually obtained from periodic online and offline test while visual inspection are regularly performed on daily and weekly basis. Then these diagnostic tests, which are appropriate to access the actual condition of those components, are specified for each component. The technique with the better ability to access the actual condition of transformer components will be assigned with the higher weighting number.

2.1.1 Diagnosis Test:

Active part*:* Active part consists of magnetic core and windings. The diagnosis techniques with condition classification and weighting number are summarized in Table 1.

Insulating oil*:* Insulating oil is evaluated from dielectric breakdown, moisture content, power factor, color, acidity and interfacial tension tests.

Bushing*:* Bushing is evaluated from visual inspection, power factor test and capacitance C_1 and C_2 test.

Arrester: Arrester is assessed from leakage current, watt loss, insulation resistance tests and visual inspection.

On load tap changer: On load tap changer is evaluated from visual inspection and several diagnostics such as transition resistance, contact wear, dissolved gas analysis (DGA), color, water content, dielectric breakdown and power factor tests.

Main tank: Main tank is performed only by visual inspection such as oil leakage, oil level, color of silica gel and breather condition.

Protective devices: Protective devices are inspected by visual inspection such as leakage, oil level and performance checks.

Table 1: Diagnostic method for active part

Diagnosis	Condition		Weight
	Good	Poor	
Core insulation resistance	>100	<10	5
Exciting current	0-1	>10	3
1ϕ impedance	<0.5	>3	4
3ϕ impedance	<0.5	>3	4
Ratio	<0.1	>0.5	4
DC resistance	<1	>5	3
Winding insulation (%PF)	<0.5	>2	5

2.1.2 Scoring and Weighting Technique:

Scoring and weighting technique, a form of multi-criterion analysis [2], is applied in the analysis. The scoring is used for classifying the condition into several levels such as good, suspect and poor. The weighting is used for ranking the precision and importance of each test method [3-5].

With this technique, the condition of the transformer component is evaluated in form of the percentage of component condition index or %index as written in Equation (1).

$$\%\text{Index} = \frac{\sum_{i=1}^{n}\left(S_i * W_i\right)}{\sum_{i=1}^{n}\left(S_{max_i} * W_i\right)} * 100 \qquad (1)$$

where: S_i = Score of each test
$S_{max,i}$ = Maximum score of each test
W_i = Weighting number
n = Number of diagnostic tests

The percentage of component condition index is ranked within the determined intervals in order to indicate the health index (HI) of component condition as color indicators: green, yellow and red, which stands for good, suspect and poor conditions, respectively.

To evaluate the overall condition (%HI), the known condition and the weighting of each component are evaluated together as shown in Figure 2.

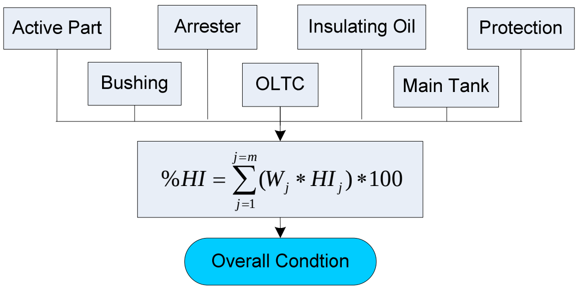


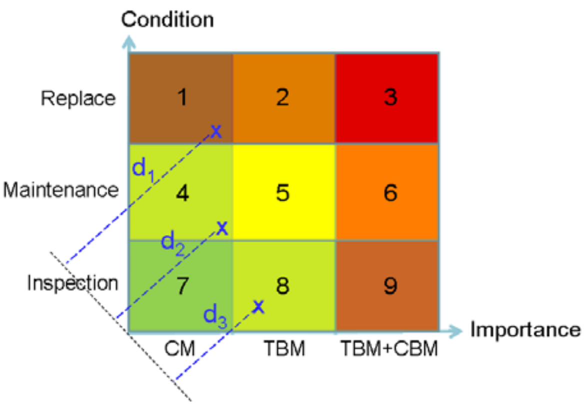
Figure 2: Working procedure of overall condition

2.3 Importance index of power transformer

The importance of each transformer location in the network is evaluated from several criteria such as load criticality, impact on system stability, possibility of failure, failure consequence, damage to property, as well as social impact and environmental concern. The importance index is further evaluated by using the scoring and weighting technique, which is similar to that in the condition evaluation. The criteria are scored into various levels such as low, moderate and high importance. The criteria with more impacts to supply interruption and system availability will be assigned with higher weighting factor. Actually, the assigned weighting numbers depends on several points of view of each utility.

2.4 Risk-based maintenance

Risk-based maintenance in form of risk matrix can be created from the combination of condition and importance assessment as shown in Figure 3. The condition index is classified into good, fair and poor, whereas the importance index is divided into low, moderate and high. The rough classification of accessed risk according to evaluated condition and importance is divided into 9 groups. The appropriate maintenance strategies for each group can be subsequently set up.



Note: 1=Repair/Replace when fail (without blackout), 2=Replace/Repair/Refurbish by economic condition, 3=Replace/Repair/Refurbish immediately, 4=Corrective Maintenance (CM) with normal maintenance, 5=Time-based Maintenance (TBM) and normal maintenance, 6=Condition-based Maintenance (CBM) and online monitoring, 7=CM with routine inspection, 8=TBM, 9= TBM and CBM.

Figure 3: Risk matrix with maintenance strategy

The risk of each transformer is measured by the distance 'd' with respect to 45 degree reference line [6], which specifies the equal weighting between condition and importance. The transformer with longer distance 'd' encounters higher risk and should be maintained first. By this method, the systematic maintenance task of transformer fleet can be scheduled.

3 ECONOMIC ANALYSIS

Besides the risk management, economic aspect should be taken into account so as to recognize the most cost-effective task of maintenance activity. To achieve this, life cycle cost (LCC) analysis is performed. The LCC is analyzed on a basis of discounted cash flow techniques with net present value method (NPV), which discounts all cash flows into the present year. The scenario with the lowest net present value means the lowest life cycle cost of transformer alternatives.

3.1 Life cycle cost items

The associated costs for LCC analysis with an economical estimation are written in Equation (2) [7-8]. The total cost comprises six terms which are acquisition cost, operating cost, investment cost, outage cost, maintenance cost and salvage value, respectively.

$$CR = C_R + \left(\Delta P_0 + f^2 \Delta P_{Cu}\right) 8760 k_j \frac{(1+P)^N - 1}{P(1+P)^N} + K_{inw} \frac{1}{(1+P)^n} +$$
$$P_{end} P_n f k_{nen} 8760 \frac{(1+P)^N - 1}{P(1+P)^N} + k_{ma} \frac{(1+P)^N - 1}{P(1+P)^N} - k_{scr} \frac{1}{(1+P)^n} \quad (2)$$

Acquisition cost is the total cost of new transformer or refurbished transformer. Operating cost considers no-load loss and load loss over the lifetime of the transformer. Investment cost is a purchasing cost of new or rebuilding transformer which is substituted the installed one after 'n' years. Outage cost is a cost of scheduled outage due to preventive maintenance and energy not supply by unscheduled outage. Maintenance cost is an average annual cost of routine maintenance. Depreciation is calculated by straight-line method and its financial lifetime is 25 years.

3.2 Proposed scenarios

When the existing transformer fails, three alternatives, such as refurbishment-refurbishment, refurbishment-replacement and replacement by new, should be considered within an equal time span.

3.1.1 Refurbishment-Refurbishment

The failed or damaged transformer is refurbished and subsequently put in service for a specific time, n years. Then this transformer is replaced by another refurbished transformer and continually used until end of project life, N years. Cash flows in LCC model are represented in Figure 4. The NPV of these cash flows is calculated by using Equation (3), where fr means inflation rate.

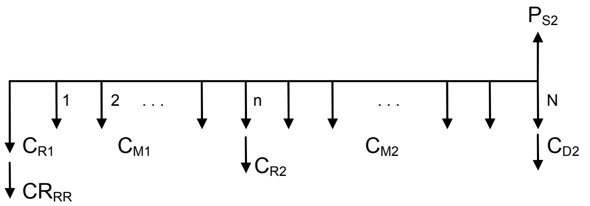


Figure 4: LCC model of first scenario

$$CR_{RR} = \text{LCC Cost of } 1^{st}\text{ Tr} + \text{LCC Cost of } 2^{nd}\text{ Tr} = CR_{R1} + CR_{R2} \quad (3)$$

where:

$$CR_{R1} = \text{Refurbishment Cost} + \text{Maintenance Cost} = C_{R1} + C_{M1}\frac{(1+P)^n - 1}{P(1+P)^n}$$

$$CR_{R2} = \text{Refurbishment Cost} + \text{Maintenance Cost} + \text{Disposal-Salvage} = C_{R2}\frac{(1+fr)^n}{(1+P)^n} + C_{M2}\frac{(1+P)^{N-n} - 1}{P(1+P)^{N-n}} + (C_{D2} - P_{S2})\frac{1}{(1+P)^N}$$

3.1.2 Refurbishment- Replacement

The failed or damaged transformer is refurbished and subsequently put in service for a specific time, n years. Then this transformer is replaced by a new transformer and continually used until end of project life, N years. Cash flows in LCC model are shown in Figure 5. The NPV of these cash flows is calculated by using Equation (4).

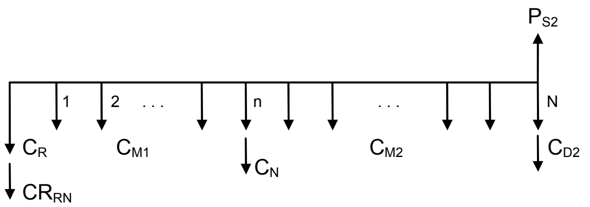


Figure 5: LCC model of second scenario

$$CR_{RN} = \text{LCC Cost of } 1^{st}\text{ Tr} + \text{LCC Cost of New Tr} = CR_R + CR_N \quad (4)$$

where:

$$CR_R = \text{Refurbishment Cost} + \text{Maintenance Cost} = C_R + C_{M1}\frac{(1+P)^n - 1}{P(1+P)^n}$$

$$CR_N = \text{Purchasing Cost} + \text{Maintenance Cost} + \text{Disposal-Salvage} = C_N\frac{(1+fr)^n}{(1+P)^n} + C_{M2}\frac{(1+P)^{N-n} - 1}{P(1+P)^{N-n}} + (C_{D2} - P_{S2})\frac{1}{(1+P)^N}$$

3.1.3 Replacement by New

The failed transformer is replaced by a new one, usually with better specification due to advanced technology on that date. Its LCC model is shown in Figure 6 and the NPV is given by using Equation (5).

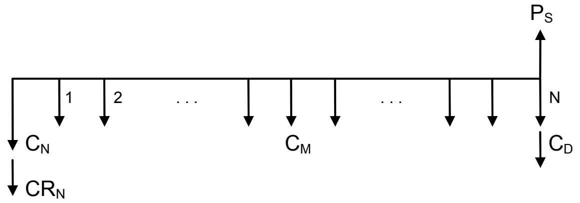


Figure 6: LCC model of third scenario

$$CR_N = \text{Purchasing Cost} + \text{Maintenance Cost} + \text{Disposal-Salvage} = C_N + C_M\frac{(1+P)^n - 1}{P(1+P)^n} + (C_D - P_S)\frac{1}{(1+P)^N} \quad (5)$$

4 SENSITIVITY ANALYSIS

In practice, long-time span projects encounter some uncertainties regarding project lifetime, interest rate, inflation rate and other variables when considering economic analysis. Therefore, sensitivity analysis should be performed to measure the influence of such variable changes on project outcomes. Hence, three mentioned alternatives of the LCC should be examined in this section to perceive decision changes caused by input variation.

5 SOFTWARE PROGRAM DEVELOPMENT

It is necessary to develop a decision support tool for risk-based maintenance of power transformer. The tool consists of database management system for a convenient data record, analytical process and user interface module via web application. In Figure 7, the database module is developed to work with web application program in order to retrieve the information from database for analyzing and back-recording the data. Web application is created by using Spring MVC framework with JAVA language application.

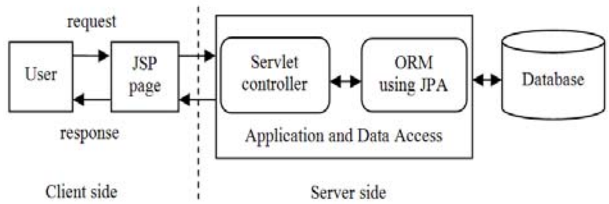


Figure 7: Database management program using Spring MVC framework

6 ANALYSIS AND RESULTS

The risk assessment of 18 transformers is presented, but analysis and result of only one transformer (T1) is described here as an example. Then economic and sensitivity analysis are discussed.

6.1 Condition of transformer (T1)

The transformer T1 with rating 230/115 kV, 200 MVA and installed in 1979, has the insulating oil test result as shown in Table 2. Because there are several diagnostic methods for electrical tests, all of the test results can not be shown in this section. Therefore, only diagnostic test result of high voltage winding is presented in Table 3. After that, the assessed condition of transformer T1 component is illustrated in Table 4.

Table 2: Diagnostic test result of insulating oil

Dielectric BD	Moisture	IFT	Acidity	Color	PF
[kV]	[ppm]	[dynes/cm]	[mg KOH/gm]	-	[%]
79.08	14	35	0.01	1	0.3

Table 3: Diagnostic test result of HV winding

Exciting Current	Leakage Impedance	Ratio	DC Winding	Winding Insulation
[%error]	[%Error]	[%error]	[%error]	[%PF]
5.06	0.026 (1ϕ), 0.35 (3ϕ)	54.18	10.81	0.38

Table 4: Component condition of transformer T1

Component	Subcomponent	Result	Condition
Active Part	Core	Green	Good
	HV Winding	Red	Poor
	LV Winding	Yellow	Fair
	TV Winding	Red	Poor
Bushing	HV, LV, TV	Yellow	Fair
Arrester	HV, LV, TV	Green	Good
OLTC	-	Green	Good
Insulating Oil	-	Yellow	Fair
Main Tank	-	Green	Good
Protective Device	-	Green	Good

From the recent measurement, the values of exciting current, ratio measurement, DC winding resistance and winding insulation tests are above the maximum limit. After the analysis, the condition of high voltage and tertiary windings are poor and indicated by red color. After intensive investigation, the windings have a problem of short-turn and insulation deterioration. This is confirmed by high amount of CO_2 gas from dissolved gas analysis test. For insulating oil condition, the oil is contaminated due to over limit values of power factor and water content as well as low value of interfacial tension. Bushing is also in fair condition due to dark color of oil observed by visual inspection. Therefore, the critical components needed to be firstly maintained are windings, insulating oil and bushing. Finally, the actual condition of seven components is used to calculate the overall condition as a condition input for risk assessment. The overall condition is approximately 40%, which is suspect and needs careful intension.

6.2 Importance index of transformer (T1)

The importance of transformer T1 in the network is assessed and summarized in Table 5.

Table 5: Importance index of power transformer

Criteria	Result	Importance
Load quantity	Green	Low
Load importance	Red	High
System stability	Yellow	Moderate
Failure consequence	Green	Low
Possibility of damage	Yellow	Moderate
Social impact	Green	Low
Environment concern	Yellow	Moderate

It is seen that the importance of this power transformer is moderate even though its load is highly important shown with red color. The other criteria are moderate and low important. This results in 58% as the importance index.

6.3 Risk-based maintenance

The condition and the importance of 18 sample transformers are evaluated and plotted in a risk matrix for risk assessment, as shown in Figure 8.

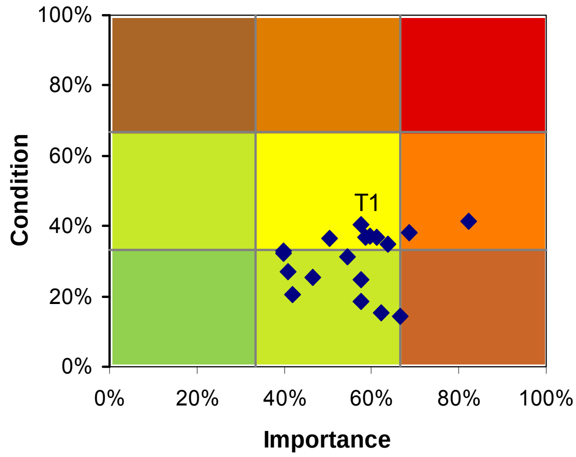


Figure 8: Risk assessment of power transformer

The overall conditions of 10 transformers are good whereas the others are suspect. Most of these transformers are moderately important. Two transformers with the longest distance 'd', the highest importance and suspect condition, need to be firstly maintained with condition-based maintenance and online monitoring should be installed. Transformer T1 normally needs time-based and normal maintenance because its overall condition is suspect and moderate importance. However, it should be taken out of service for winding inspection due to the poor condition of windings as indicated in Table 4.

6.4 Economic and sensitivity analysis

Two transformers rating 115/22 kV 50 MVA are analyzed as examples. With NPV method, the assumption is as follows: inflation rate 2%, lifetime of new transformer or project life 55 years, lifetime of rebuild transformer 30 years, and average loading factor 70%. In the analysis the interest rate is varied from 4-16%. Cost ratio (CR) represents the comparison of the LCC of refurbishment-refurbishment or refurbishment-replacement by new with that of replacement by new alternative.

6.4.1 *Case Studies*

In the first case, the following works have been performed: replacing short-turn low voltage winding by new, changing rubber bag, overhauling and refurbishing other components. In the second case, the end-of-life transformer is refurbished by replacing by all new windings, inspecting and repairing other components in manufacturer factory.

From Figure 9 of the first case, when the interest rate is below 10%, the replacement by new is the most cost-effective alternative. When the interest rate is between 10-14%, the refurbishment-refurbishment alternative is preferred. The refurbishment-replacement by new is preferred when the interest rate is more than 14%. Further analysis is performed by fixing the interest rate at 10% and changing the inflation rate as well as the lifetime of rebuild transformer. The refurbishment-refurbishment is the most cost-effective option until either the inflation rate is below 5% or the lifetime of the rebuild transformer is above 15 years.

The second case shown in Figure 9, when the interest rate is below 14%, the replacement by new is the most cost-effective alternative. When the interest rate is above 14%, the refurbishment-refurbishment alternative is preferred. Further analysis is performed by fixing the interest rate at 15% and changing the inflation rate as well as the lifetime of rebuild transformer. The refurbishment-refurbishment is the most cost-effective option until either the inflation rate is below 6% or the lifetime of the rebuild transformer is above 20 years.

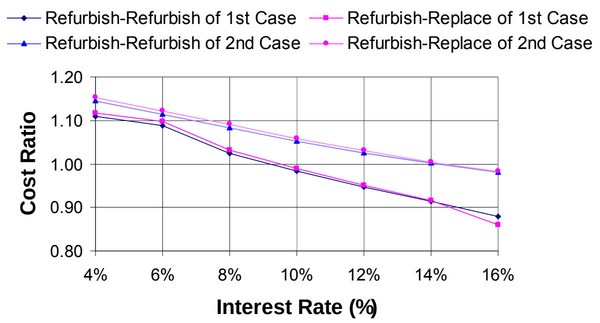


Figure 9: Cost ratios of two case studies

7 CONCLUSION

The condition-based maintenance strategy of power transformer management is achieved by the condition evaluation using scoring and weighting technique. The importance of each transformer in the network is also assessed. The combination of condition and importance develops the risk-based maintenance in form of risk matrix. From economic analysis by considering life cycle cost and discounted cash flow analysis, the replacement by new alternative is preferred when the interest rate is low, in this case less than 10%. When the interest rate is high, the refurbishment-refurbishment option is preferred. Since there are a large number of transformers in the network, the computerized web-application program is developed to facilitate the maintenance tasks. In this paper only 18 transformers have been analyzed and presented as examples. The obtained risk of each transformer is useful information for risk-based maintenance. Therefore, the effective maintenance tasks can be setup, which results in high availability, low risk of failure, lower overall maintenance costs and ability to extend the useful lifetime. Finally, this method can be applied for other high voltage equipments.

8 ACKNOWLEDGMENTS

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