Maintenance Management for Risk Reduction of High Voltage Transformer

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Abstract

Power transformer is one of significant electrical equipments in power system. As it has high acquisition cost and failure consequences to the network, its proper maintenance task should be planned effectively. Nowadays, risk-based maintenance of power transformer in substation has played a critical role increasingly. The maintenance management is recommended by combining two evaluations: transformer condition and transformer importance. The condition evaluation is performed by electrical and insulating oil testing with their associated limitation to classify into good, suspect and poor condition. The importance evaluation is performed by load criticality, system stability, failure possibility, and failure consequence with three levels of low, moderate and high impacts. Score and weighting techniques are utilized in the analysis. The risk matrix is then developed by these two evaluations with nine zones of recommended maintenance actions for the power transformers in order to reduce the risk. A number of power transformers installed in 115 kV and 230 kV transmission systems are selected for the risk evaluation due to available and qualified data. The sample power transformer with rating of 230 kV, 200 MVA is presented as an example with its test results. Finally, the proposed method can be applied with the fleet of power transformers and other high voltage equipments in the network.

Keywords : Power transformer, Condition-based maintenance, Importance evaluation, Risk-based maintenance

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1. Introduction

Power transformer is one of the most important equipments in the electrical network. Its function is to transfer electrical power from one voltage level to another for achieving the required network. It is firstly focused due to its extremely high acquisition costs and failure consequences to the network. In practice, high reliability is increasingly required but there are a large number of in-service power transformers that are nearly reached their designed end of life. Some electric utilities need to extend the replacement of old equipments due to financial constraint. Thus, maintenance strategy of power transformer is desired to maintain stability and reliability of the system.

This paper aims to evaluate power transformer risk and provide recommended maintenance strategies with risk-based maintenance. The purpose of the maintenance strategies is to maintain equipments to properly be operated until reaching its lifetime.

2. Maintenance management

Maintenance management for power transformer risk reduction is mainly categorized into corrective maintenance, time-based maintenance, condition-based maintenance, and reliability-centered maintenance [1]. As the preventive maintenance is very costly and might be inappropriate task due to neglecting the actual transformer condition, the condition-based maintenance is introduced for planning the maintenance strategy [2]. The time-based maintenance is a routine maintenance task by which the periodical time is different for each electrical utility. Nowadays, the reliability centered maintenance or so called risk based maintenance has played significant role in several countries. Not only it focuses on the transformer condition, but also the importance of the transformer is taken into account. Subsequently, the risk of each transformer can be recognized. Therefore, this section reviews techniques that are used to assess the condition index and the importance index. Then the condition evaluation and the importance evaluation are expressed, respectively. Lastly, a risk matrix developed by combining the two evaluations is clarified for the transformer maintenance management.

2.1 Scoring and weighting techniques

Score and weighting techniques [6] are utilized in the risk evaluation. The score refers to a classified level of the considered criterion. For example, in the condition evaluation, the scoring is classified into three levels: score “1” for good, score “2” for suspect, and score “3” for poor. For the importance evaluation, the scoring is classified into three levels: score “1” for low consequence, score “2” for moderate consequence, and score “3” for high consequence. The weighting refers to a level or a ranking of an importance or a precision of considered criterion. In this paper, the weighting is represented by a percentage or a numerical data. Then the score and weighting techniques for the evaluation are applied and presented as a percentage, *%index*, as shown in Eq. (1).

$$\%index = \frac{\sum_{i=1}^{n} S_i \times W_i}{\sum_{i=1}^{n} S_{i,\max} \times W_i} x100 \qquad (1)$$

Where S_i is the score of the considered criterion, W_i is the weighting of the criterion, $S_{i,max}$ is the maximum score of the criterion, and n is the number of the criterion.

2.2 Condition evaluation

The overall condition of each power transformer is evaluated on its main equipments by using electrical and insulating oil tests [3, 7-12]. The components are active part, on load tap changer (OLTC), bushing, arrester, and insulating oil. The active part that is located in the main tank of the transformer contains magnetic core and winding (high voltage, low voltage and tertiary voltage sides). The OLTC is a mechanical device to modify the voltage ratio of the transformer by adding or subtracting the tapping turns from the main windings. The bushing is a porcelain insulator to enable one or several conductors to pass through the transformer tank. The surge arrester is a porcelain protector to avoid damage from lightning disturbances, switching operations or circuit faults. The insulating oil is acted as arc extinguisher, electrical insulation and coolant to dissipate heat losses. The diagnostic tests are different for each component. The diagnosis of the active part includes core insulation resistance, exciting current, leakage impedance, ratio, DC winding resistance, and winding insulation. For OLTC [13], the diagnosis consists of the electrical tests: contact wear, and transition resistance, as well as the insulating oil tests: color, water content, dielectric breakdown, and power factor. The limitation of the OLTC evaluation is gathered and represented in Table 1.

Table 1 Diagnostic test for on load tap changer

Diagnosis	Score			W_i
	Good (1)	Suspect (2)	Poor (3)	
Transition resistance (%deviation)	≤5	-	>5	5
Contact wear (mm/100,000 operations)	≤1	-	>1	5
Color (level)	<1.0	1.0-5.4	≥5.5	2
Water content (ppm)	<20	20-44	≥45	4

For the bushing condition evaluation, power factor and capacitance tests are concerned, while watt loss and insulation resistance tests are for the arrester assessment. The insulating oil tests e.g., dielectric breakdown, interfacial tension, acidity, water content, color, and power factor are performed for assessing the insulating oil condition, as written in Table 2.

The overall condition, *%CI*, is then assessed by applying the condition of the main components with the score and weighting techniques, as written in Eq. (2).

$$\%CI = \sum_{i=1}^{n} \%CCI_i \times W_i \quad (2)$$

Where $\%CCI_i$ is the condition of each transformer component, and W_i is the weighting of the components.

Table 2 Diagnostic test for insulating oil

Diagnosis for 230 kV power transformer	Score			W_i
	Good (1)	Suspect (2)	Poor (3)	
Dielectric strength (kV)	≤32	25-31	<25	5
Interfacial tension (dynes/cm)	≤38	25-37	<25	3
Acidity (mg KOH/gm)	≤0.015	0.016-0.49	≥0.5	2
Water content (ppm)	≤10	11-25	≥26	4
Color (level)	≤1.0	1.1-4.0	>4.0	1
Power factor	≤0.1	0.2-1.0	>1.0	3

The obtained condition of the transformer is then used for managing maintenance tasks properly. The different maintenance recommendation can be separated into three or more levels depending on electric utilities. For example, three maintenance levels are for good, suspect and poor conditions. The transformer with good condition needs routine maintenance, while maintenance with recondition of components is required for the transformer with suspect condition. If the transformer condition is poor, defective components of the transformer should be refurbished.

2.3 Importance evaluation

The importance of the transformers is evaluated by the significant criteria that are concerned by the utility's experiences. The criteria are shown in Table 3 with the limitation of the scores and the weights. The criteria with higher consequences to supply interruption and system availability are allowed with higher weighting number, and vice versa [5]. Firstly, load factor is calculated by load quantity of the transformer compared to its rated power. Load shedding is a scheme that allows less important load be disconnected first from the system. N-1 criterion is a backup technique meaning that when the transformer with N-1 criterion is interrupted, other transformer nearby will be serviced for existing load instead. System stability specifies a type of the transformers: tie or loading transformers. Application or usage is an operating type of the transformer. System fault level is a level of three phase fault at the location in which the transformer is installed. Lastly, probability of forced outage is a frequency of forced outage at the transformer locations in the related system.

The overall importance, *%II*, is then assessed by applying the score and weighting techniques with the criteria, as written in Eq. (3).

$$\%II = \frac{\sum_{j=1}^{m} S_j \times W_j}{\sum_{j=1}^{m} S_{j,\max} \times W_j} x100 \qquad (3)$$

Table 3 Criteria for importance evaluation

Criteria	Score			W_i
	Low (1)	**Moderate (2)**	**High (3)**	
Load factor	<0.6	0.6-1.0	>1.0	2
Load shedding	Step 1 or Step 2	Step 3 or Step 4	Step 5 or None	3
N-1 criterion	Yes	-	No	7
System stability	Loading (115/22kV, or 115/33 kV)	Loading (230/69kV, or 230/115 kV)	Tie (230/115 kV, or 500/230 kV)	3
Application	Mobile	Cold/Hot standby	In-Service	2
System fault level (MVA)	≤10,000	10,001-30,000	>30,000	7
Probability of forced outage per 5 years	0	1-2	≥3	2

Where S_j is the score of the considered criteria, W_j is the weighting of the criteria, $S_{j,max}$ is the maximum score of the criteria, and m is the number of the criteria.

2.4 Risk matrix

The risk-based maintenance [14-25] in a form of the risk matrix is developed by combining the condition and the importance indices. The risk matrix as shown in Fig. 1 can be divided into nine different zones with specific recommended maintenance strategies. For the condition, the maintenance tasks are categorized into 3 levels: routine maintenance for good condition, reconditioning for suspect condition, and refurbishing for poor condition. Similarly, the importance focuses on 3 levels: corrective maintenance (CM) for low importance, time-based maintenance (TBM) for moderate importance, as well as TBM and condition-based maintenance (CBM) for high importance.

To separate the condition and the importance into 3 levels each ending up with 9 zones of maintenance planning, experts with experiences on transformer operation and maintenance in electric utilities should design and plan the maintenance tasks suitably.

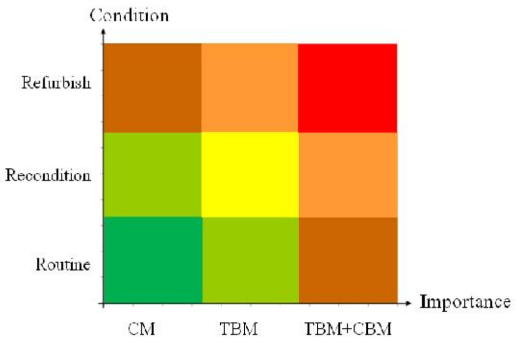

Fig. 1. Risk matrix with recommended maintenance

3. Results and analysis

The sample transformer, TR1, is with rating of 230/115 kV with 30 years in a service. Its risk evaluation is clarified as it is planned to be untanked for checking the actual condition compared to the condition evaluation performed by the proposed method. Subsequently, the risk management of the transformer is discussed to adjust the score and weighting numbers for achieving the estimated risk properly.

3.1 Condition evaluation

The test results of the power transformer, TR1, are presented in Table 4 and Table 5 for the OLTC and the insulating oil, respectively. The condition of the main components are calculated as %CCI and collected in Table 6 with their color indicators. It shows that the defective component with high %CCI is active part (63.33%), following with insulating oil (60%) and surge arrester (55.56%). In addition, the overall condition represented by %CI is determined and equal to 51.50% represented by red indicator. It means that the transformer needs careful intention.

Table 4 Diagnostic test results of OLTC

Transition resistance (%deviation)	Contact wear (mm/100,000 operations)	Color	Water (ppm)	Dielectric BD [kV]	PF [%]
2.50	0.50	3	27	47.6	0.02

Table 5 Diagnostic test results of insulating oil

Dielectric BD [kV]	Water [ppm]	IFT [dynes/cm]	Acidity [mg KOH/gm]	Color	PF [%]
39.18	16	27.70	0.009	2	0.01

Table 6 Condition of main components of TR1

Component	%CCI	Color	Condition	%CI	Color
Active part	63.33	Red	Poor		
OLTC	40.00	Yellow	Suspect		
Bushing	42.22	Yellow	Suspect	51.50	Red
Arrester	55.56	Red	Poor		
Oil	60.00	Red	Poor		

3.2 Importance index

The importance of the sample power transformer, TR1, is evaluated and summarized in Table 7. It shows that the transformer is in high importance represented by the red indicator due to no load shedding and put into the service with high impacts to the network.

Table 7 Importance evaluation of TR1

Criteria	Result	Color	Importance	%II	Color
Load factor	0.6	Y	Moderate	66.67	Red
Load shedding	No Shedding	R	High		
N-1 criterion	Yes	G	Low		
System stability	Loading Tr. (230/115 kV)	Y	Moderate		
Application and usage	In-Service	R	High		
System fault level (MVA)	13,878	Y	Moderate		
Probability of forced outage per 5 years	3	R	High		

3.3 Maintenance management

Combining the condition, %CI, and the importance, %II, can develops the risk-based maintenance in form of the risk matrix. The %CI and the %II of the sample transformer, TR1, are plotted in the risk matrix form as shown in Fig. 2 with other nine sample power transformers in the network. The overall condition is classified into three condition zones: good for 0-35%, suspect for 36-45%, and poor for 46-100% due to early warn needed. Similarly, the overall importance is classified into three importance zones: low for 0-40%, moderate for 41-50%, and high for 51-100%.

The five transformers are with rating of 115 kV 50 MVA, while the others are 230 kV 200 MVA. It shows that most transformers are in the highest risk with the poor condition and high importance, but only one is in poor condition with moderate importance, but almost in high importance. The recommended maintenance strategy is that the TBM plus the CBM should be concerned for the high risky transformers. Subsequently, the components with poor condition should be refurbished to achieve better overall condition. To get lower impacts on the importance evaluation, the transformers should be relocated. Finally, the transformers will face with lower risk, which are represented by lower coordinate points in the risk matrix.

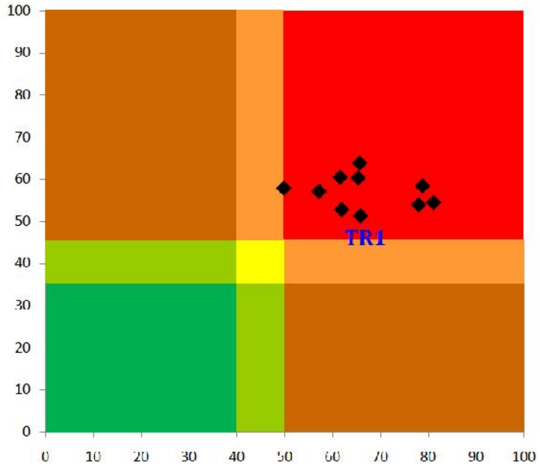

Fig. 2. Risk matrix of the sample transformers.

4. Conclusion

The risk-based maintenance of power transformer is accomplished by combining the transformer condition and the transformer importance together with applying the score and weighting techniques. The condition of the five main transformer components: active part, OLTC, bushing, arrester, and insulating oil is evaluated for the overall condition of the power transformer. The diagnostic tests are the electrical and insulating oil tests. The importance of each power transformer is assessed by the key criteria that affect the network shutdown and the system availability. As there are a large number of power transformers in the network, only one transformer with rating 230 kV, 200 MVA is shown as an example with its test results. Additionally, other nine power transformers with rating of 230 kV 200 MVA and 115 kV 50 MVA are plotted in the risk matrix with the sample transformer to get better understanding of the proposed method. All transformers are risky and should be focused immediately due to their poor condition and high importance. The obtained risk from the calculation is utilized for the maintenance management. Thus, the effective maintenance strategy can be planned suitably in order to prolong the useful lifetime and reduce the maintenance costs as well as the transformer risk. Finally, this proposed method can be applied for other high voltage equipments in the network.

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