Condition-Based Maintenance of Power Transformers

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I. Introduction

Power transformer is the most important equipment in electrical energy system. It also represents the greatest cost in electrical substation, in terms of initial investment costs, operational costs and appropriate periodical maintenance costs. If unexpected failure occurs, repair costs can be bigger than initial costs of power transformer. This is why appropriate maintenance actions must be performed according to the real condition of the transformer. This type of maintenance is called Condition-Based Maintenance (CBM).

This paper analyzes the most important parts and parameters of transformer which are subject to premature failures, and issues that occur and cause these failures. It also presents current practices of monitoring and diagnostic procedures of transformers, and reviews practical examples of methodologies widely used for transformer's condition assessment.

II. Power transformer's condition assessment

Insulation is the most important part of transformer in term of failures, and ageing of transformer is proportional with ageing of insulation. The unexpected and premature failures of insulation can be caused due to electrical stresses, dielectric stresses, electromagnetic stresses, thermal stresses and chemical stresses. Ageing of transformer's insulation can be represented with "degradation" curve and it is shown in Figure 1.

Since the ageing of other individual transformer components, such as core, windings, cooling system, bushings, mechanical parts, control switches and other is not uniform and not simultaneously as insulation ageing, it is necessary to implement certain partial maintenance and monitoring activities for certain individual transformer's component. It can generally be concluded that the main impact on the aging of the transformer have moisture, oxygen and heat. The main causes of transformer's aging depend mostly on the operating conditions to which the transformer is exposed during its utilization.

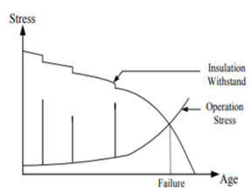

Figure 1. Degradation curve of power transfomer's insulation

Various diagnostic procedures and tests are used to evaluate the transformer's condition such as oil analysis, dissolved gas analysis, moisture and temperature measurements, sample testing of paper insulation, furan analysis, frequency response measurements, vibration measurements and other procedures. One comprehensive list of mostly used diagnostic tests and parameters found in literature is presented in Table 1. The references that have used these parameters are listed in Reference part of the paper [1-3, 5, 10-12, 14-21, 23-39].

Table 1. List of parameters obtained by different tests and diagnostic inspections of transformer

Test/Analyses/ Inspection/Records	Parameter
Dissolved gas analyses of oil and/or tap changer	Oxygen Carbon Monoxide Hydrogen Acetylene Carbon Dioxide Methane Ethan Nytrogene Ethylene
Other insulation tests Electrical tests Mechanical tests Visual inspection	Furan Dielectric losses in oil Power factor Dissipation factor Moisture Breakdown voltage Partial discharge analyses results (PDA) Hot-Spot temperature Overheating temperature Acidity Oil leakage Interfacial tension Degree of polymerization Color and feculence Corrosion Tensile strength Dielectric losses of windings Dielectric losses of bushings DC windings' resistance Insulation resistance Grounding current Vibration signals Short circuit impedance Frequency response analyses results (FRA)
Environment inspection Operation records Maintenance records Failure records	Commissioning year Installation year Operational year Load rate Overloading records Environmental temperature Environmental pressure Environmental humidity Average lifetime Cooling type Failure rate Overhauls records

III. Techniques and practical examples of their application for transformer's condition assessment

All mentioned tests, monitoring inspections and diagnostic procedures from the paper give results that need analyses and interpretation in order to get conclusions about transformer's health state. If monitoring is performed on-line continuously, and tests are carried out regularly, the collected results can be enormous and unclear, so-called "big data", and often must be analyzed with appropriate mining technique, which is called "data mining". This is done in order to extract useful information from collected data, primarily information about transformer's health condition..

The most commonly used and the simplest method is Health Index method (HI), and it uses different techniques to obtain overall health index of transformer. This method is often found in literature. References [14-21] from the Reference part of the paper explain HI methodology with practical application on power transformers to obtain their health state for the purpose of CBM.

It should be emphasized that nowadays HI methodology is most often used only because of its simplicity. However, the biggest disadvantage of this method is that subjective impact cannot be removed, so distribution utilities are challenged to replace this method with other that are less subjective. Such methods are based mostly on artificial intelligence (AI).

In recent decades, computer science has progressed a lot, and as a branch of computer science, artificial intelligence stands out as the most applicable computational discipline in industry. In well-developed electrical energy systems, with on-line monitoring systems and sensors, condition-based maintenance is always performed with some of AI-based methods. Concrete examples of AI-based methods applied to power transformers are presented in references [23-39]. Table 2. summarizes all methods applied in [23-39].

Table 2. Review of AI-based methods used for CBM

Method/Technique	Number of input parameters	Type of output	Accuracy	Reference
Multilayer 2-tier ANN	10	Health index [1-3] (1-poor, 2-warning, 3-good)	99.5 %	[23]
Back-propagation ANN	6	Fault class (normal, overheating, corona, arcing)	86.8-95 %	[24]
Structured ANN with Ensemble Technique	>5	Remaining useful life (in years)	96 %	[25]
Feed-forward ANN	11	Health index [0-1] (0-new transformer, 1-old transformer that should be replaced)	96.55 %	[26]
Support Vector Machine with Particle Swarm Optimization/Genetic Algorithm	13	Condition class (excellent, good, fair, poor) Fault class (normal, discharge fault, partial discharge fault, thermal fault)	93-95 %	[27]
Logistic Regression Model with Poisson Distribution	6	Condition class (good, moderate, bad)	83.3 %	[28]
Machine Learning Techniques with Particle Filtering Method	3	Remaining useful life (in years)	91.6-99.5 %	[29]
Fuzzy Logic	9	Health index [0-1] (0-good, 1-bad) Fault class (partial discharge, low discharge, high discharge, low thermal fault, medium thermal fault, high thermal fault)	Not determined	[30, 31]
Fuzzy Logic	10	Health index [0-1] (0-good/normal/excellent, 1-very poor/critical/severe)	Not determined	[32]
Fuzzy Logic	3	Condition class (poor, fair, good)	80%	[33]
Fuzzy Logic	30	Health index [0-1] (0-worst, 1-excellent) Condition class (excellent, good, poor, worst)	96 %	[34]
Neuro-Fuzzy System	8	Age of transformer (in years)	Not determined	[35]
Fuzzy Logic	4	Fault class (no fault, partial discharge, thermal fault)	70-80 %	[36]
Neuro-Fuzzy System	3	Age of transformer (in years)	89.3-99.3 %	[37]
Fuzzy Logic	5	Health index [0-1] (0-good, 1-deteriorated) Probability of failure and probability of maintenance [0-1] (0-low probability, 1-high probability)	Not determined	[38]
Neuro-Fuzzy System	15	Condition class (very good, good, moderate, bad, very bad)	Not determined	[39]

The greatest benefit of using artificial intelligence methods over standard ranking and scoring HI method is that subjective perspective of diagnostic is totally excluded. On the other hand, HI method is very simple and practical if there is no on-line condition monitoring and if there is no big data for analyzing. Depending on complexity of the system and information collected, appropriate method can be chosen. One of the most commonly used method is Artificial Neural Networks (ANN). In [23] artificial neural network (ANN) is applied to evaluate the health state of power transformer by using multilayer 2-tier neural network with back propagation. Beside ANN, some other AI-based methods can be found in literature. Another often used approach for condition assessment based on computational intelligence is Fuzzy Logic Systems method. An excessive number of references proposes this technique for overall health condition evaluation and remaining useful life prediction. References [30-39] are practical examples of fuzzy logic application on power transformers.

Reference [34] is very specific and very good example because it uses almost all parameters from Table 1. in order to obtain overall health condition of five transformers, by using fuzzy logic. This approach is one of the most comprehensive found in literature and has been proven to be very accurate.

It is worth mentioning that fuzzy logic method and ANN are sometimes used together, or in combination with ranking health index method. This approach improves these methods' accuracy, because some parameters need subjective assessment, and combination with fuzzy logic systems or ANN eliminates ambiguity. This combination can be found in references [21, 35, 37, 39] from the Reference part of the paper.

All mentioned references in the paper represent good examples of implementation of different advanced methodologies for transformer's condition assessment for the purpose of CBM.

IV. Conclusion

Condition-based maintenance represents "future" of maintenance practices worldwide, and so in Serbia's EES. Power transformer is the most important part of electrical substation's equipment, and it is necessary to improve its condition monitoring and diagnostics, especially if economic aspect is considered, which means that overall costs of maintenance must be minimized. This paper has presented the most important parameters that affect transformer's health condition and reviewed practical examples from scientific papers. It can be concluded that different techniques can be used for transformers' condition assessment, and the future work can be based on their practical implementation on power transformers in Serbia's EES.

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