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Condition Monitoring Techniques of Power Transformers: A Review

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ABSTRACT
Power transformers provide a vital link between the generation and distribution of produced energy. Such static equipment is subjected to abuse during operation in generation and distribution stations and leads to catastrophic failures. This paper reviewed the techniques in the field of condition monitoring of power transformers in recent years. Transformer monitoring and diagnosis are the effective techniques for preventing the eventual failures and contributing to ensure the plan's reliability. This paper provided a survey on the existing techniques for monitoring, diagnosis, condition evaluation, maintenance, life assessment and possibility of extending the life of the existing assets of power transformers with be appropriate classifications. Thus, this survey could help researchers through providing better techniques for condition monitoring of power transformers.

KEYWORDS: Ageing, Maintenance plans, Condition monitoring techniques, Power transformers.

1. INTRODUCTION

Power transformer condition monitoring is generally considered as one of the most important Condition Monitoring (CM) techniques in power systems. The unscheduled outages of transformers, due to unexpe-cted failures, are catastrophic in many cases. Diagnosis and proper monitoring play a key role in the life expectancy of a power transformer.

There are plenty of proper monitoring methods for evaluating the condition and possible incipient failure of a power transformer. Transformer monitoring, methods are usually too expensive and/or time- consuming to use. However, cost-efficient methods are needed for transformer monitoring and one possibility is to utilize loading and temperature information measured from the network. There are several general and useful references in this regard [1-3], which contain information on the CM of electrical equipment and mainly power transformers. This paper intended to review the overall literature on this subject by describing the current research situation. However, it should be pointed out that some papers might be missing due to the large number of publications in this area. The main activities of transformer asset management are summarized in Fig. 1. In the next section of this paper, the concept of CM is introduced, its features and functions, are presented, and the related techniques are provided to give a general picture of CM. In the third section, different CM techniques for power transformer are described and summarized. Sec. 4 elaborates on performing maintenance plans, Sec. 5 introduces the end of life assessments and aging, and finally Sec. 6 introduces life cycle cost.

2. GENERAL CONCEPT OF CONDITION MONITORING (CM) AND CONDITION ASSESSMENT (CA)

This Condition monitoring of power transformers has become a reality in recent years. CM is mostly considered for transformer insulation system and winding integrity.

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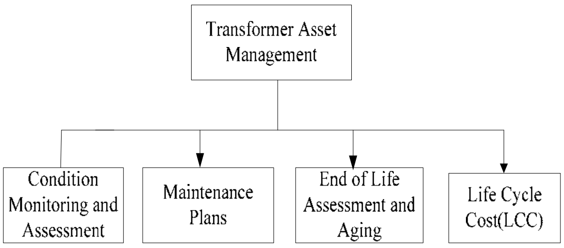

Fig. 1. Transformer asset management activities [3].

It mainly focuses on the detection of incipient faults inside the transformer, which are created from gradual deterioration [3]. The significance of a condition monitoring is in that it allows for the early identification of developing faults such as arcing before resulting in catastrophic failure.

Monitoring and periodic diagnosis together with operational/maintenance strategies would allow for the life extension of assets and ensure the enhanced reliability of the system. CM and life assessment of a costly and critical asset like transformer are aimed to:

-Detect faults at incipient stage and avoid catastrophic faults, and

-Reduce maintenance costs by doing condition-based rather than time-based maintenance.

Monitoring is done in energized as well as de-energized conditions; i.e. off-line and online. Condition assessment [3] means the development of new techniques for analyzing these data to both predict the trends of the monitored transformer and evaluate its current performance. In addition, the improvement of transformer CA renders benefit by giving a decision basis to asset managers. The main target of asset management is to manage transformers to serve longer with reduced lifetime operating cost.

3. DIFFERENT CM TECHNIQUES

In order to have information about the state-of-health of the transformer, the monitored data and the incipient faults detected by the CM system should be analyzed to assess the transformer condition. Transformer CM can be divided into six main categories. Fig. 2 shows the main categories of transformer CM techniques and on-line monitoring method of CM. Based on Fig. 2, each of the CM techniques will be discussed separately.

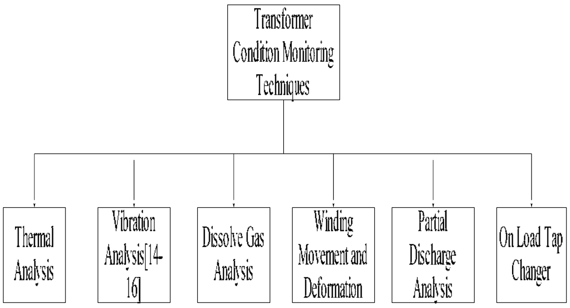

Fig. 2. Transformer condition monitoring techniques.

3.1. Condition monitoring by thermal analysis

Thermal analysis of transformers can provide useful information about their conditions and can be used to detect the inception of any fault [4]. Most of the faults cause change in the thermal behavior of transformers [5]. Abnormal conditions can be detected by analyzing HST (hot spot temperature) or Thermograph [6-12].

The HST is one of the major limiting factors that affect the useful life of the power transformer and its loading. The HST differential is defined by industrial standards (NEMA and ANSI) for each insulation class (type and temperature rating of insulation used on windings). Obviously, the HST is the limiting temperature for a transformer's insulation system [13].

3.2. Condition monitoring by winding vibration analysis

The transformer vibration consists of core vibrations, winding vibrations, on-load tap changer vibrations. The health condition of the core and windings can be assessed using the vibration signature of transformer tank.

Vibration analysis is a very powerful tool for assessing the health of the on load tap changer [14]. Winding vibration is due to the electro dynamic forces caused by the interaction of the current circulating by a winding with the leakage flux. These forces are proportional to the current squared and have components in axial and radial directions. Also, core vibration is caused by magnetostriction and magnetic Forces [15].

Moreover, the mounting place of a measuring transducer on the tank surface of the tested unit does not significantly influence the determined parameters of the registered vibrations and then the analysis of the results obtained in this way [16].

3.3. Condition monitoring by dissolve gas analysis

Dissolved gas analysis is a traditional way for monitoring insulation condition; concentration types and production rates of generated gasses can be used for fault diagnosis. Nevertheless, the concentration of these gases increases in the presence of an abnormality (fault) such as thermal and partial discharge and arcing faults [17]. The combustible gases are produced when insulating oils and cellulose materials are subjected to excessive electrical or thermal stresses. Multiple dissolved gas analysis tests should be taken over time so that the rate of increase of fault gases can be monitored, through which the progress of the fault can be monitored. Fig. 3 shows the classification of dissolve gas analysis.

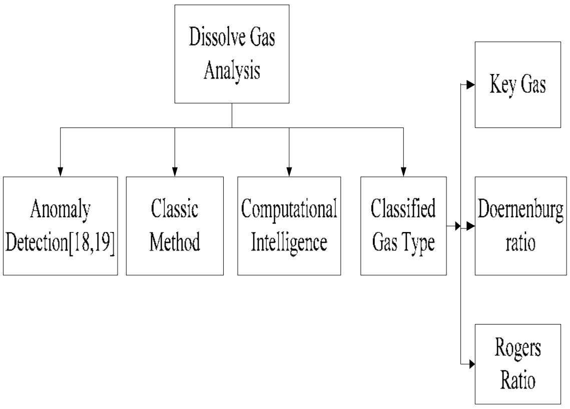

Fig. 3. Classification of dissolved gas analysis activities.

3.3.1. Anomaly detection

Anomaly detection techniques are a way of recognizing changes in plant behaviors. Rather than simply matching patterns of expected faults, a model of behavior specific to each studied transformer can be trained to represent the normal operation of that particular asset. This issue allows for the natural differences between the normal behavior of different transformers and low level of fault behavior can be trained into the model as normal for that unit [18, 19].

3.3.2. Classic methods

In these method, gas ratios and relative proportions of gases are always used to diagnose faults [20, 21]. Currently, DGA is not a science, but an art, subject to variability. IEEE Standard C57.104-2008 describes the key gases, Doernenburg ratios and Rogers ratio method. IEC Standard 60599 introduces the three basic gas ratio methods and the Duval triangle method. All of these classic methods have been generally described in [22-25].

3.3.3. Computational Intelligence (CI)

CI techniques attempt to emulate human and biological reasoning, decision-making, learning and optimization by applying computing techniques that mimic adaptive evolution in living beings. The CI techniques can be either used individually or in combination with other techniques to form complex hybrid methodologies for achieving systems with enhanced capabilities: e.g. a single system can make decisions under uncertainty by fuzzy logic, learn and adapt using artificial neural networks [26, 27], and undergo evolutionary optimization using genetic algorithms, bacterial swarming algorithm, and particle swarm optimization algorithms [28]. Most of the successful attempts for combining techniques have confirmed that fault diagnosis can greatly benefit from CI techniques. Because Condition Based Monitoring (CBM) uses advanced fault diagnostic techniques to identify on-line and off-line incipient faults and to provide real-time transformer conditions, it can also optimize maintenance schedules. CI techniques enable researchers to analyze fault phenomena and use the correlations in data for analyzing faults and diagnosing transformer faults with high accuracy.

3.3.4. Classified gas type

During internal faults, oil produces gases such as H2, CH4 etc. Initially only a hydrogen online monitor was available, but new tools detecting several gases are commercially available with a total-oil monitor recently launched [29-32]. Fig. 4 shows the main categories of classified gas type.

3.3.4.1. Types of faults and generated gases

Stresses due to operation (normal to extreme), ambient conditions, and contamination contribute to the deterioration of the insulation chain and thus shorten the transformer's design life [32, 33]. Table

1 shows the types of faults, generated gases and concentration-generated gases.

3.4. Condition monitoring by winding movement and deformation

When a transformer is subjected to high through fault currents, the windings are subjected to severe mechanical stresses, causing winding movement, deformation, and severe damage in some cases. Such deformities occur due to short circuit forces and sometimes may be caused due to unskilled handling during transportation [34].

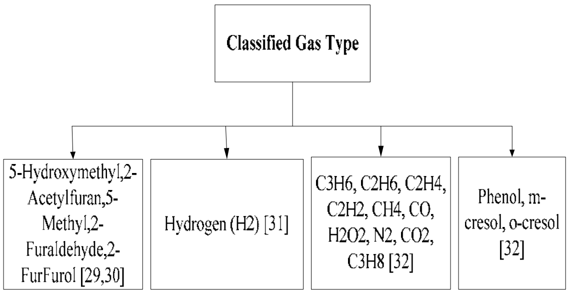

Fig. 4. Classification of gas types.

Table 1. Types of faults and generated gases

Types of Faults	Generated Gases	Concentration (ppm)
Thermal/Oil	C_2H_4, C_2H_6	50-200
Thermal/paper	CO	350-1400
Thermal/paper	CO_2	2500-10000
Electrical/Partial Discharge	H_2, CH_4	120-1000
Electrical/Arcing	H_2, C_2H_2	35-80

Deformation results in relative changes to the internal inductance and capacitance of winding, which can be detected externally by Frequency Response Analysis (FRA) method or transfer function analysis [35, 36]. There are two techniques for FRA measurements on power transformers: Low Voltage Impulse (LVI) based FRA and Sweep Frequency Response Analysis (SFRA), also called Swept Frequency Method (SFM) [37]. Characteristic impedance (Z_C) is more sensitive to changes in the winding structure than SFRA. In addition, the changes in the characteristic impedance signatures take place in different magnitude, ranges whereas the changes in the SFRA all occur in the same magnitude range. The Z_C signature changes most drastically for the radial expansion of the winding which can give the early indication of the winding structure beginning to come apart, especially important toward the end of a transformer's life where the clamps holding the winding in place may begin to fail [38,39]. Fig. 5 shows the classification of winding movement and deformation analysis activities.

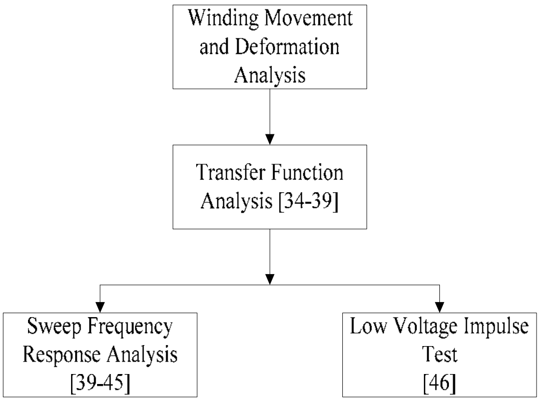

Fig. 5. Classification of winding movement and deformation activities.

3.4.1. Transfer function (TF) analysis

TF method is based on the concept that changes in the windings due to deformation and displacement cause changes in the parameters of transformer (capacitances, inductances,...) and consequently the modification of its TF [35].

Based on a set of TF traces (mainly the amplitude shown over the frequency), an evaluation of the transformers' mechanical condition can be made [35]. Organizations such as IEEE and CIGRE are attempting to develop standards, guidelines and tests for TF method on transformers [37]. For measurements, two test objects have been used: One of them is for the axial displacement modeling and measurements and the other is for the radial deformation tests [38]. All measurements are in the time domain.

In this domain, the test object is excited by low-voltage impulses. The input and output transients are measured and analyzed. Studying the effects of the changes in the parameters of the model on the TFs calculated in the model terminals helps in discovering the correlations between TF variations and fault information. The most important mechanical faults, which are most likely detected using the TF, can be categorized as follows [39-42]:

1) Disc-space variation (DSV)
2) Radial deformation (RD)

3) Axial displacement (AD)

3.4.1.1. Sweep frequency response analysis

Sweep Frequency Response Analysis (SFRA) is an analysis technique for detecting winding displaceme-nt and deformation (among other mechanical and electrical failures) in power and distribution transfor-mers [39]. The SFRA method as a diagnostic tool to detect inters turn winding faults [40, 41]. SFRA involves the injection of sinusoidal signals, one frequency at a time, into one end of the winding [39]. This method has succeeded in detecting mechanical fault conditions in windings where other signatures, such as short circuit impedance and leakage reactance tests [43] have failed to show any difference. Sweep frequency response analysis is diagnosed based on the comparison between two SFRA responses. Any significant difference in low frequency region, shift of existing resonance, creation of new resonance, and change in the shape of plot would potentially indicate mechanical or electrical problem with the winding and core of transformer [41]. It consists of measuring the frequency response of transformer windings over a wide range of frequencies and comparing the results of these measurements using a reference set. examples of fault conditions that can be detected by SFRA are as follows [44, 45]:

Mechanical faults:

i. Winding deformations (including hoop buckling)
ii. Partial collapse of winding
iii. Core displacements
iv. Broken or loosened winding or clamping structure.

Electrical faults:

i. Shorted turns or open circuit winding
ii. Bad ground connection of transformer tank

3.4.1.2. Low voltage impulse (LVI) test

LVI method is adapted from the initial impulse test method. The new technique represents an extension of the traditional low-voltage-impulse method of FRA. Traditional low-voltage-impulse methods have been used to detect mechanical displacements in transformer windings or clamping structures by detecting changes in the transfer function; but, they have been limited in practice due to the sensitivity of the transfer function to differences in the time parameters of the applied impulses as well as sensitivity of the transfer function to variables such as oil condition and temperature. The new technique offers improved repeatability in diagnosing winding movements, and is based on an objective numerical calculation to quantify changes through weighted normalized difference calculation [46].

Low voltage impulse method has the following advantages:

i) Several channels/transfer functions can be measured at the same time; thus, reducing outage time during revision, and
ii) Faster than SFRA. One measurement is usually conducted in one minute.

Low voltage impulse method has the following disadvantages:

i. Fixed frequency resolution resulting in low resolution at low frequencies, which might be a problem for the detection of electrical faults.
ii. Broad band noise cannot be filtered.
iii. Power spectrum of injected signal is frequency-dependent.
iv. Slowly decaying signals are not recorded.
v. Several pieces of equipment are needed.

3.5. Condition monitoring by partial discharge analysis (PD)

Experimental experiences have proved that partial discharges are a major source of insulation failure in power transformers. On the other hand, PD measurements have emerged as an indispensable, non-destructive, sensitive, and powerful diagnostic tool [47]. PD can be detected and measured using Piezo electric Acoustic Emission (AE), Ultra High Frequency (UHF) sensors and optical fiber sensors. PD measurement has been extensively used for the condition assessment of the transformer insulation due to the fact that large numbers of insulation problems start with PD activity.

3.5.1. Piezo electric acoustic emission

Acoustic partial discharge measurement is advantageous in terms of PD source location.

Acoustic sensors mounted on the model experimental transformer tank convert partial discharge acoustic emission (PDAE) signals into electrical signals and are stored on a computer [48].

Acoustic PD detection has following advantages over electrical methods:

i) Acoustic method is Immune to Electromagnetic Interference (EMI); hence, it can be applied for online detection.

ii) Acoustic method can provide an indication of PD source location within a complex system like transformer.

3.5.2. Ultra high frequency

In general, for the CA of a power transformer using UHF PD measuring technique, three steps have to be performed. First of all, detection of any partial discharge activity that indicates harmful insulation defects must be accomplished. After detecting and recording the PD, the analysis of the raw data would provide appropriate information in order to identify the defect in the transformer [49, 50]. The identification of the defect can be done by finding the location of the insulation defect and by comparing its pattern with that of other known defects from a reference database [51].

3.5.3. Fiber optic sensor

Optical fiber transmission is a standard technique for bringing information from high-voltage equipment to monitoring equipment, thus avoiding both hazard to the operator and electromagnetic interference; many examples exist in this regard for both plant management and research. The test of the sensor with real PD shows that it has suitable sensitivity and enough resolution to detect acoustic pressure as low as 1.3-Pa (Pascal). The sensor is found to be able to detect 1-Pa acoustic pressure waves under optimum conditions and to detect partial discharges in small artificial voids in an oil bath [52].

3.6. Condition monitoring by on load tap changer

An On-Load Tap Changer (OLTC) is a part of a power transformer, which allows the transformer output voltage to be regulated at the required levels without interrupting the load current [53]. On-load tap changer by adding or subtracting turns of the windings, regulates the voltage level of the transformer [54]. Thus, the operation of certain on-load tap changers has a significant influence on voltage instability using three objectives of $V_{stability}$, $V_{desired}$ and P_{loss} [55].

The majority of transformer failures are caused by a tap changer fault. Several systems for OLTC online monitoring are currently available [53-55]. However, predicting the online monitoring methods of OLTC can be done by four techniques. Fig. 6 shows the classification of the on load tap changer techniques.

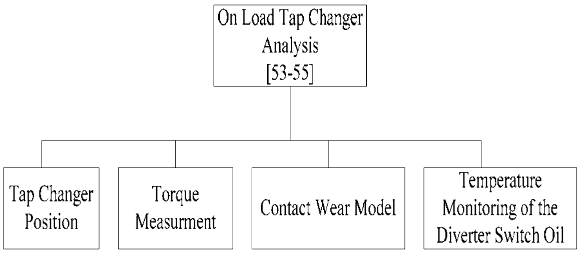

Fig. 6. On load tap changer activities.

4. PERFORMING MAINTENANCE PLANS

Performing maintenance plans is the second transformer asset management activity.

Transformer ageing may also accelerate if the transformer does not undergo proper maintenance and fault diagnosis. Proper fault diagnosis plays a vital role in enhancing the life of a transformer. According to Fig. 7, the maintenance types can be classified into corrective maintenance, preventive maintenance, and reliability centered maintenance.

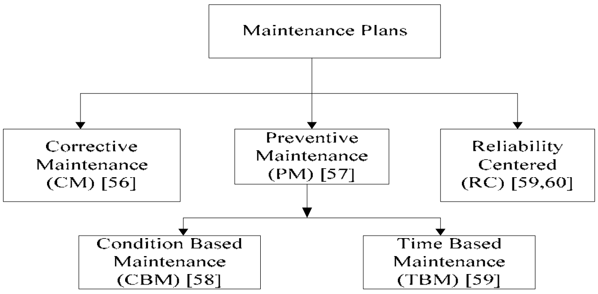

Fig. 7. Classification of maintenance activities.

4.1. Corrective maintenance

Corrective maintenance is designed to perform maintenance activity upon occurrence of failure. The advantages of corrective maintenance are as follow:

i) It saves manpower; *ii*) It spares the system from un-necessary shutdowns; and *iii*) It performs the maintenance only when it is needed, saving unnecessary inspections. In addition, disadvantages of corrective maintenance are:

i) Some transformer failure may be un-repairable if not detected early; and *ii*) Some transformer failure may cause complete shutdown of the production line or the power system for long time [56].

4.2. Preventive maintenance

Preventive maintenance aims to prevent the occurrence of failure. In addition, it aims to guarantee long lifetime of the asset. The preventive maintenance can be classified into condition based maintenance and time based maintenance [57].

4.2.1. Condition based maintenance (CBM)

The main goal is to achieve a cost effective solution through effective asset management. CBM relies on performing maintenance when the CM system detects an incipient fault. Using this technique, the risk of complete failure is reduced.

The advantages of CBM are:

i) Saving costly un-necessary inspections; *ii*) Saving manpower; and *iii*) Reducing the unnecessary shutdowns of the system.

In addition, disadvantages of CBM are:

i) Needing fast data communication and manipulation facilities for successful online monitoring; and *ii*) Being less understood by maintenance engineers and technicians [58].

4.2.2. Time based maintenance (TBM)

TBM is the current maintenance strategy for many industries and utilities. The general meaning of TBM is to perform maintenance in regular intervals. The advantages of the TBM are:

i) It can detect the inception of faults to some extent if the inspection interval is reduced; and *ii*) It increases the lifecycle of the transformer due to regular inspections and maintenance. In addition, its disadvantages are:

i) It is expensive due to regular un-necessary inspections and the large number of the needed maintenance staff; and *ii*) It needs un-necessary shutdowns, which add extra cost to the maintenance activity [59].

4.3. Reliability centered maintenance (RCM)

The fundamental goal of RCM is to preserve the function or operation of a system with a reasonable cost. The general meaning of the RCM maintenance is in optimizing the maintenance plan based on risk analysis [59]. The advantages of RCM are:

i) It guarantees low possibility of occurrence of high-risk failures; *ii*) It saves money paid for unnecessary close timed inspections in case of TBM; and *iii*) It reduces the unnecessary shutdowns for low risk failures. Its disadvantages are:

i) Being less understood by maintenance engineers and technicians; and *ii*) needing for a large amount of data about failure rates, modes, and consequences [60].

5. END OF LIFE ASSESSMENTS AND AGEING

Equipment ageing is a fact of life in power system components. As a piece of equipment ages, it fails more frequently and needs more repair time until reaching its end of life. There are three different concepts of lifetime for power transformers: physical, technical and economic lifetime [59, 60].

5.1. Transformer physical ageing

Transformer life mainly depends on the integrity of its solid insulation (cellulose). The ageing of paper insulation is irreversible [44]. According to Fig. 8, transformers' physical ageing mechanisms can be divided into intransitive and transitive aging.

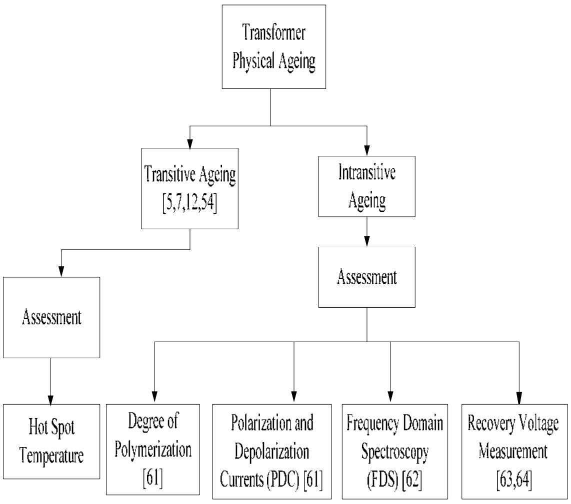

Fig. 8. Complete classification of transformers' physical ageing mechanisms.

5.1.1. Intransitive ageing

The Intransitive Aging is the ability of the solid insulating material to withstand the designed stresses such as electrical, mechanical, and thermal stresses with the passage of time [3].

5.1.1.1. Degree of polymerization (DP)

DP is the main indication of paper health. Paper fibers are composed of cellulose. Glucose monomer molecules are bonded together with glycoside bonds to form cellulose. The average length of the cellulose polymer, measured as the average number of glucose monomers in the polymer chins, is referred to as DP [61]. DP cannot be measured without the opening of transformers. Because of the recent advancement in instrumentation, diagnosing the liquid insulation by Furan detection has been facilitated [61].

5.1.1.2. Polarization/depolarization currents (PDC)

Transformers' polarization/depolarization current measurement method (PDC) is the dielectric response measurement technique in time domain. Owing to the polarization characteristic of the insulation material change with the insulating status, it is possible to realize the non-destructive testing of insulation status using PDC method, which is also a convenient on-site test due to its good noise-proof feature [61].

5.1.1.3. Frequency domain spectroscopy

Frequency Domain Spectroscopy (FDS) measures dielectric loss factor ($tan\delta$) versus frequency. On-line dielectric loss factor $tan\delta$ testing is an extensively used and effective way for insulation aging diagnosis [62]. In Iran, the insulation $tan\delta$ value is being measured under the operating voltage. The structure of this measuring system consists of three parts, of electric bridge method, standard capacitance potentiometer (operating voltage 10kV), and potential transformer (PT). Measurement of the value of $tan\delta$ can reflect a series of defects in insulation and the insulation aging status [62].

5.1.1.4. Recovery voltage measurement

The specific method of Recovery Voltage Measurement called RVM is widely spread in commercial terms [63]. It is used for measuring transformers' oil-paper polarization frequency spectrum [64].

5.1.2. Transitive ageing

It is rapid aging of the asset when subjected to abnormal condition. The abnormal conditions may be overloading, supplying non-sinusoidal loads, or exposure to higher ambient temperature than normal. The main reason for accelerating the end of life of a transformer under the above-mentioned abnormal conditions is its increased HST over the normally accepted values [5, 7], which has an effect on reducing insulation life [12, 54].

5.2. Mechanisms and modeling of economic ageing

This method develops a more systematic approach for determining the life expectancy of transformers. It is based on the economic analysis of the operational characteristics of transformers in conjunction with the technical issues involved in the decision process. The annual lost part of the asset cost is called depreciation cost. The time-based depreciation has two main types: Straight-line depreciation method and accelerated depreciation method. The works [65-68] show these methods.

6. LIFE CYCLE COST

Life Cycle Cost (LCC) refers to all expenses paid in the demonstration, development, production, operation, maintenance, security and post-processing of the equipment in the life cycle [69]. The concept of LCC means to take into account not only the manufacturing cost, but also to consider the operational and disposal costs [70]. Also, LCC analysis structurally deciding and equalizing costs arising within overall life cycle which can be referred to as capital cost and operating cost is a method of analysis essential in economic evaluation [71].

7. CONCLUSIONS

This literature survey is presented a comprehensive overview in the field of fault detection techniques for power transformers, which has evolved rapidly during the last ten years. In addition, advantages and disadvantages of all the techniques and their related applications in detecting transformers' fault were separately explained.

The potential functions of failure prediction and life estimation bring a series of advantages for utility companies: reducing maintenance cost, lengthening equipment's life, enhancing safety of operators, minimizing accident and severity of destruction, as well as improving power quality.

The development of CM for power transformers is now at different stages. Several types of transformer monitoring systems have been already put into practice. However, monitoring and data analysis methods are not satisfactory in terms of special problems such as hot spot temperature, DGA and OLTC analysis.

Research in recent years have clearly shown that advanced signal processing techniques and computational intelligent techniques such as evolutionnary algorithm, analysis of vibroacoustic signals, SFRA and etc are indispensable in developing novel CM systems. Finally, these studies and methods could be effective in terms of timely counteraction to threatening failures.

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