An Overview on Condition Monitoring & Health Assessment Techniques for Distribution Transformers

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***Abstract*—The demand to improve grid infrastructure is of utmost importance especially with the increased expansion and addition of distributed generation units to cope with today's era of transforming to smart grids. The health status of distribution transformers in an electrical grid plays a vital role in maintaining network service continuity, safety from catastrophic events, and reliability of utility operation. Monitoring transformer's health is essential for minimizing outages and extending its life in service. Various diagnostic tests and fault detection techniques have developed to effectively support utility operators in predicting failure, estimating life expectancy and condition monitor its status. For these reasons, traditional and advanced methods are required to reduce maintenance time, cost, and help in finding fault causes and location easily. This paper gives a thorough overview about widely used and latest condition monitoring techniques while highlighting strengths and limitations of each.**

Keywords*—Distribution transformer condition monitoring, health assessment, fault, AI, transformer tests, smart grid

I. INTRODUCTION

Technological innovations, economics, and policies are the main drivers to changes in electric power systems and energy market. With constant increase in electricity demand, new challenges arise that threatens power system reliability, security, and control. Shifting to a smarter grid is therefore vital to cope with these disputes especially with the large integration of renewables and distributed generators onto the utility network. The smart grid is a new modernized network where power generation, transmission, and distribution are intelligently managed to efficiently deliver sustainable, economic, and secure electricity thus increasing power grid resilience to disruptions and optimize its operation [1], [2].

Due to the aforementioned impacts, monitoring and protecting power system critical devices is essential to ensure healthy status [2]. In a distribution network, the power transformer is a key element as one of the most critical and expensive components in power systems that should be protected and kept monitored. Nevertheless, its importance also relies on the fact that there may be hundreds of small sized transformers in a medium sized city which may be quite difficult to routinely maintained [3]. Moreover, being designed for lifetime operation, scheduled fault inspection is a necessity since any failure can lead to either service disruption or even accidents if maintenance is not carefully considered [4].

Failure and accelerated degradation of distribution transformers can occur due to many reasons leading to internal or external damages in the transformer. Common failures were reported in [5] for oil type transformers which were broken down into insulation failure, windings damage, bushing failure, core deformation, flash over and oil leakage due to tank breakdown. For these reasons, estimating transformer loss of life gained researchers attention to help network operators create and implement periodical inspections and maneuvers as well as define suitable transformer loading to minimize failures and outages [6].

This paper aims to overview various preventive tests and diagnostic techniques for distribution transformers that can be utilized in fault prediction for a more optimized condition monitoring, enhanced maintenance, and higher power system reliability. The techniques covered in this paper explores different equipment involving tests, hardware, control, signal analysis and intelligent systems.

II. TRANSFORMER FAILURE AND MONITORING METHODS

Transformer faults can be broadly classified into developed and incipient faults. Developed faults are those that cause immediate damage to a transformer once they occurred, while incipient faults are those that cause an evolving damage that are magnified over time [7]. Authors have broadly categorized root cause of failure in distribution transformers into 1) electrical, 2) thermal, and 3) mechanical or a combination of these factors as listed in Table I. These failures can be further categorized into internal and external causes and recent studies have shown that the highest rates of failure among frequent causes are due to winding/coil failures as demonstrated in Fig. (1) [8].

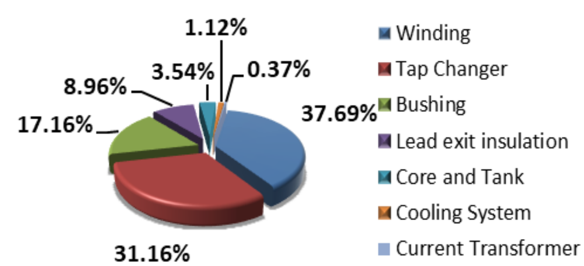

Fig. 1. Transformer Equipment Failure Percentages.

TABLE I. FACTORS AND CAUSES OF TRANSFORMER FAILURE

Factors	Causes
Electrical Factors	Transient or overvoltage conditions Surges (Lightening and switching) Partial discharge
Mechanical Factors	Electromagnetic Forces Mishandling of the transformer Winding Buckling Conductor tipping Spiral Tightening End ring crushing Coil clamping system failure Transformers leads displacement
Thermal Factors	Cellulose insulation degradation Overloading Operation with nonlinear loads Cooling system failure Oil ducts blockage Overexcited condition operation Operation in high ambient temperature.

The field of transformer condition monitoring and predictive maintenance has gained a lot of attention in the last few years due to the advancement in sensing technology, computational tools and mathematical algorithms. As shown in Fig. (2), diagnostic techniques applied for transformer health assessment can be divided into Chemical, Electrical, Miscellaneous, and Computational Intelligence based tools. These techniques can be used alone or in combination for more accurate and definitive decisions. The following sections present an overview on condition monitoring and fault detection techniques for distribution transformers' health assessment as discussed in literature [9]-[58].

III. CHEMICAL DIAGNOSTICE TECHNIQUES

These tests are carried out in laboratories to measure parameters such as dissolved gases, moisture and oxygen content in oil, acidity, power factor, and dielectric strength. Chemical tests are routine tests which can be divided into as follows:

A. Dissolved Gas Analysis (DGA)

Identifying transformer health through monitoring its insulation system is a common procedure to estimate its useful remnant life. DGA is a chemical diagnostic technique for incipient faults detection in oil-type transformers. Fault gases are produced due to transformer oil and solid insulating materials degradation (such as paper and pressboard) which increases significantly in presence of internal transformer fault [9]. Accordingly, gases are evolved where each fault category evolves certain characteristic gases. Analyzing ratios of specific dissolved gas concentrations as well as their discharging rates help in defining the fault type and severity [10]. DGA can commonly identify failures due to hot spot, corona, partial discharge, arcing and thermal heating of oil. Various schemes are used to interpret the gas analysis such as the key gas method, Rogers ratio method, Duval triangle as well as the three-key gas ratios method used by the IEC standard which are compared in [11], [12]. Due to lack of uncertainty, computational methods can be further applied to DGA for more precise and accurate fault diagnosis. DGA can be achieved through on-line gas monitoring which can be expensive especially with distribution transformers.

B. Physical and Chemical Tests of Oil Quality:

Insulating fluid quality in the transformer is vital for a longer life expectancy thus oil tests such as moisture test, interfacial tension test, oxygen test, acidity test, power factor test, and dielectric breakdown test can indicate the health status and operational characteristics of the transformer tested [13]. These types of tests are often called "screen tests" and are performed at the same time to understand the insulating liquid's degradation [14]. Screen tests comply with specified standards derived from IEEE and IEC such as IEC 60422 and IEEE 62-1995 [13].

IV. ELECTRICAL DIAGNOSTICE TECHNIQUES

These are tests that rely on electrical testing both in time domain and frequency domain. They are a powerful tool in windings, contacts, bushing and cores deterioration detection and are commonly divided into the following:

A. Partial Discharge Test (PD)

PD are small electrical sparks occurring in a slight area in an insulation due to high-voltage stresses and electrical breakdown of an air pocket within the insulation. PDs in a transformer deteriorates its insulation and may lead to failure and can be due to many reasons such as voids formation in bushing, due to gas bubbles in the insulating oil as a result of aging and oil impurities…etc [8]. Therefore, PD test is often used to assess and monitor insulation condition (for bushing,

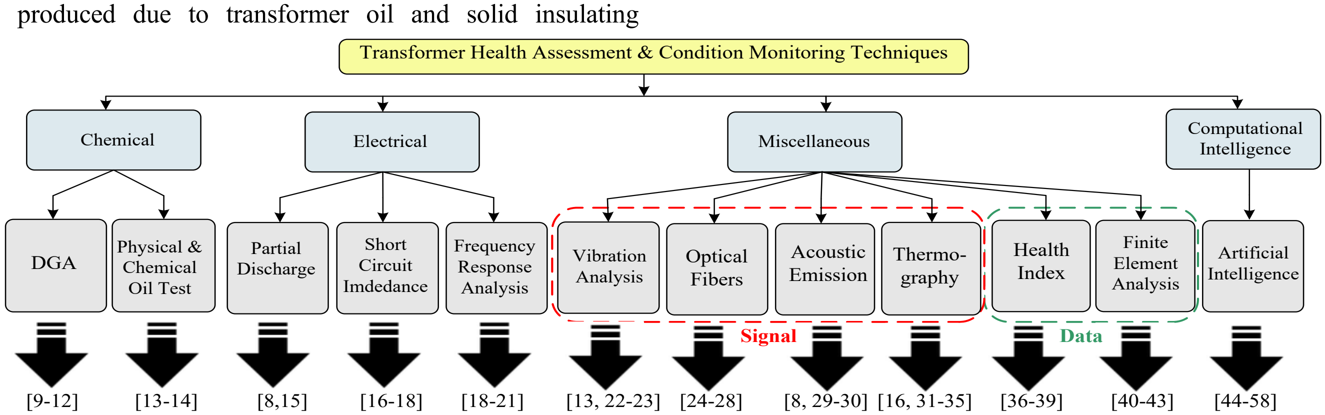

Fig. 2. Transformer Health and Condition Monitoring Techniques.

HV and LV insulation as well as inter-turn insulation) of transformers whether offline or in-service (online). Offline tests are conducted while the transformer is out of service according to a standardized test using PD pulse. Based on IEC 60270, an electrical PD pulse (which is either a current or voltage) that results from a PD is measured using suitable detector circuits where the level of charge due to PD is calculated to identify the condition level of insulation. PD test is a high voltage, non-destructive testing procedure that are regarded as a predictive qualitative analysis tool which can warn of a potential upcoming system failure and can be used in routine tests or pre-commissioning [15]

B. *Short Circuit Impedance (SCI)*

SCI is traditionally used to detect mechanical defects in transformer windings in accordance to IEC guidelines in IEC 60076-5 2000, to detect imperfect magnetic coupling between them [16].

SCI is an electrical test which is carried out on HV winding where the LV side being short-circuited [17]. The measured SCI parameters for a transformer are compared to values present on the transformer nameplate or obtained from factory tests [18].

C. *Frequency Response Analysis (FRA)*

FRA is a non-destructive technique that measures a transformer response in a broad frequency bandwidth. FRA is employed to detect winding deformation and displacement which are hard to identify with other techniques such as DGA, PD and thermal monitoring. Transformers represent a complex RLC network, and the frequency response represents a fingerprint for each unit. Any physical damage to the transformer will alter the effective RLC network, thus FRA method is used to identify small changes in the RLC network parameters within the transformer by examining the frequency response of the transformer. By injecting a low voltage signal of varying frequencies to the transformer winding, the input and the output signal are recorded to derive the FRA signatures where the ratio of these two signals is called the transfer function [19]. Transfer functions are being related to the RLC network structure of the transformer being tested where the magnitude and phase angle variations with frequency are measured and the health status of the transformer is determined. Four different popular test configurations exist such as open circuit test, short circuit test, capacitive inter-winding test and inductive inter-winding test. FRA can be modified as an online procedure and the signals are injected while the transformer is in service [20]. Despite being an effective fault identification tool, online FRA response can be affected by network conditions, thus complicating measurements [21].

V. Miscellaneous Techniques

These are divided to 1) signal based techniques such as thermal, vibration, optical or acoustical or 2) Data based techniques such as statistics, standards and modeling techniques:

A. *Signal Based Techniques*

Are those that rely on analyzing signals whether from mechanical vibrations, sound, thermal or optical. Signal based tools are optimal for aging assessment and provide online monitoring capability. They are further divided into:

1) *Vibration Analysis (VA)*

VA-based fault diagnosis is a very common low-cost, offline, non-intrusive procedure for transformer winding condition monitoring. Transformer vibration occurs due to the consecutive movement of transformer inner parts or due to the movement of active part in dry-type transformer occurring due to several reasons such as short circuits, environmental factors, or explosion of combustible gases accumulating in the transformer oil or due to improper handling [22]. Vibration signal extraction can be achieved relying on time-frequency characteristics of a transformer using FRA, where an energy spectrum analysis is carried out after noise-reduction (using several filtering stages), then the effective signal is separated and analyzed [13]. Despite considered a non-complicated procedure, FRA can be quite challenging especially if the signal is mixed with undesirable combination of environmental oscillations and noise signals. It may also require large amounts of historical data which are obtained through electrical modeling [4]. Other techniques employ numerical indices along with FRA and VA to evaluate transformer situation [23].

2) *Optical Fibers*

Optical Fibers sensing technology has various benefits such as lightweight, ease of installation, compact size and immunity to EMI. Being able to operate online, fiber optics provide real-time monitoring of transformer's health through direct temperature measurement of hot spot by distributing these sensors in the transformer. They can measure the internal temperature of the transformer's primary and secondary cores as well as the windings temperature and can successfully measure partial discharge and humidity besides measuring insulation oil temperature during in-service operation [24]. Optical fibers can be used in vibration monitoring and winding deformation [25], analyze dissolved gasses generated during the decomposition of dielectric fluid and solid insulation and detect transformer oil level [26, 27]. Optical fibers technology is an effective way to measure electrical, mechanical and chemical parameter changes in transformers [28].

3) *Acoustic Emission (AE)*

Noise is an inherent characteristic of transformers which may occurs due to many normal core vibrations produced by magnetostriction effect and winding vibration or due to PD. AE technique is a very common online methodology based on sound wave propagation analysis to detect PD activity using commonly a piezoelectric contact sensor [8]. AE amplitude measurement takes place in different areas of a transformer tank and thereby in different distance from the PD source. AE may require more than one sensor and can possibly detect multiple PDs, however, they are insensitive to PD energy fluctuation measurements are highly affected by the distance from the discharge source [29]. Despite being regarded as a non-invasive technique, it may be subject to inaccuracy due to noise and random signals from mechanical vibrations and external noise [30]. Although being regarded as an expensive approach, AE can successfully distinguish PD in oil, inter-turn windings and in oil -paper insulation

4) Thermography

Thermography is the use of thermographic detector or an infra-red (IR) camera to observe the temperature of an object without any contact with the body examined. Thus, thermography is a non-invasive, low cost technique [31] used as an indication of overheating where the areas having higher temperatures are indication of anomalies indicating possible issues in an electrical or mechanical component in a transformer [32]. An increase in transformer temperature can arise from several factors such as cooling problems, higher winding losses, core defects, hot spot, insulation failure and low-level arcing [33]. Temperature abnormalities have been categorized in literature and actions are decided whether transformers require immediate maintenance, as soon as possible, or when possible [34]. Recent works applies advanced image processing and pattern recognition techniques to the IR images for more accurate detection of various transformer fault types, yet some limitations still exist as infrared interference from other sources [16], [35].

B. Data Based Techniques

Data based tools are those that employ data, statistics, standards, numerical methods and mathematical modeling for analysis. They are very common tools offering high reliable results. Data based tools can be divided into the following:

1) Health index (HI) & standards

HI as a conventional practical tool used by power utilities to assess the overall health condition of a transformer. HI calculations are performed for lifetime expectancy determination through utilizing large amount of data from diagnostic, inspection and routine tests [36]. Based on the gathered data and by using a mathematical formula, each transformer is given a score such that each parameter in the formula has a predefined weighting factor based on historical data, statistics, and past experiences. Among these parameters are DGS (as per IEEE standard C 57.104 -2008), furan analysis and oil insulation scoring (as per the IEEE standard C57.106-2006) [37]. According to the HI score, the life expectancy of a transformer can be corelated. HI score is usually incorporated with additional methods in case if results are poor (due to uncertainty in determining the weight of each test) [38], [39]. Recent work applies non-conventional computational methods such as fuzzy logic, multivariant analysis and neural networks to overcome the weight problem which will be discussed in the following sections.

2) Finite Element Analysis (FEA)

Certain approaches such DGA, acoustic methodologies and optical fibers can be quite expensive to be implement on distribution transformers. Moreover, some techniques are non-convenient for dry type transformers while others would jeopardize personnel to dangers. For these reasons, simulation and modeling transformer behavior can be more economical and convenient to provide data for health assessment [40]. Many transformer models exist and FEA is a useful numerical technique to obtain an accurate characterization of the electromagnetic behavior of transformers by providing a high accuracy model of the transformer nonlinear parts [41]. FEA are commonly used to detect interturn faults inside transformer windings which can happen due to insulation deterioration and hotspot temperature prediction in windings and bushing [42], [43].

VI. Artificial Intelligence (AI)

All previous techniques mentioned; whether on-line or off-line based; suffer from inaccuracy in fault prediction and uncertainty in health assessment. Transformer models for instance rely on mathematical calculations that may be complex and require time for calculation. Moreover, transformer temperature prediction can be hard to determine since empirical formulas are specific for each transformer and variable over time. In DGA on the other hand, not all gas ratios have direct mapping to specific faults and evaluating a transformer health status requires human experience for determination, while FRA requires intricate accurate modeling of transformer parameters for fault identification. With the development of computational intelligence tools and combining advanced sensing, learning, experience, and training to create intelligent programs, more accurate and definite assessment of transformers can be achieved. Table II shows AI techniques employed for fault diagnosis and condition assessment. Fuzzy logic is used to represent vague concepts and uncertain information thus provides effective solution to complex issues with inexpensive sensing. Bayesian Network is a classification model-based tool on statistical analysis which enables accurate modelling even with missing data sets, thus overcomes uncertainty. Genetic Algorithms (GA) is used for thermal parameters identification by searching for global solutions using on-site measurements. Artificial Neural Networks (ANN) on the other hand can perform complex functions such as those requiring pattern recognition and classification. The ANFIS is a hybrid computational methodology that utilizes both capabilities of an ANN and neuro-fuzzy logic for logical analysis, thus it has noticeable capability of modelling nonlinear systems.

Machine learning (ML) algorithms have attracted researchers' attention as a powerful intelligent based tool that improves and trains automatically through experience. Various ML techniques such as Support Vector Regression (SVR), Support Vector Machine (SVM), Random Forest, and Convolution Neural Network (CNN) are demonstrated in Table II with their prospect application for fault diagnosis and health assessment [3].

TABLE II. AI Techniques for Health Assessment

Technique	Condition Assessment & Fault Diagnosis
Fuzzy logic [44], [45]	• HI calculation • Used with FRA for hotspot detection
Bayesian Network [46]-[48]	• DGA and oil analysis
Genetic Algorithm [49], [50]	• Thermal model parameters • HI calculation for optimized weighted approach • Incipient fault prediction
ANN [51], [52]	• DGA online detection • HI • Health condition estimation
ANFIS [53]-[55]	• Aging • HI parameter determination
SVR [56]	• Hotspot detection • Insulation diagnosis

SVM [50]	• Incipient fault detection • Classify power transformer faults with DGA
CNN [4], [57]	• Winding condition monitoring with vibration images • Fault detection with IR images • Bushing failure detection with IR imaging
Random Forest [58]	• Assess transformer health using top oil temperature, vibration & loading data

VII. CONCLUSION

Power grids are susceptible to many types of faults that have different impacts and propagations leading to disrupted services. A power transformer is one of the most crucial equipment in the power system and by having an early warning system that predicts its health status and lifetime makes it possible to avoid long- lasting outages. This paper surveyed different condition monitoring techniques for transformer health assessment and fault diagnosis. According to the problem and equipment being assessed, particular tests are carried out, which involves chemical, electrical, numerical and mechanical procedures. In addition to human experience and standards, artificial intelligence can be used in transformer health assessment with high accuracy and certainty.

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