EXPLORING ADVANCED TECHNIQUES FOR POWER TRANSFORMER LIFETIME ESTIMATION

Prakash Sundaram, Ritesh Tirole
E-Mail Id: prakash.sundaram@spsu.ac.in
Sir Padampat Singhania University, Department of Electrical Engineering, Rajasthan, India

Abstract- Power transformers play a critical role in electrical networks, and their maintenance and longevity are paramount due to the challenges and costs associated with replacements. This paper delves into the realm of condition monitoring for power transformers, focusing on diagnostic tests and techniques used to estimate their remaining lifetime. By examining methods such as dissolved gas analysis, dielectric response, partial discharge testing, and more, this review aims to provide a comprehensive overview of the tools and strategies employed in assessing transformer health and predicting potential failures. Through a synthesis of industry and academic insights, the strengths, limitations, and correlations between various testing approaches are explored, offering a holistic perspective on transformer condition assessment and management.
Keywords: Power transformers, Condition monitoring, Asset management.

1. INTRODUCTION

Power transformers are often regarded as the most financially significant component within electric power systems, typically constituting around 60% of the total investment in high-voltage substations [1]. The focus of this paper is to evaluate established routine and diagnostic tests utilized for condition monitoring and lifetime estimation, emphasizing the inherent limitations of each method. Routine tests are conducted at regular intervals to evaluate overall transformer condition and performance. Should any performance degradation be identified in routine tests, diagnostic tests may be necessary for further assessment.

Additionally, following any fault occurrence, commissioning process, or transportation, diagnostic tests are routinely conducted to verify the integrity of a transformer. These tests yield measurements that are leveraged by many utilities to generate health indices, offering insights into the operational state, and facilitating estimations of remaining lifetime. Scheduled maintenance poses a risk wherein faults may arise between inspection intervals, potentially leading to catastrophic outcomes. This limitation encourages utilities to transition from scheduled maintenance to condition-based maintenance, emphasizing proactive monitoring and response strategies [2,3].

Condition-based monitoring adjusts test schedules according to the transformer's current condition, informed by past test results. This approach involves more frequent monitoring of transformers in poor condition compared to scheduled maintenance rates. It aids in preventing unexpected failures by enhancing insulation assessment, thereby saving downtime and costs associated with routine maintenance. Notably, condition-based monitoring does not inherently include online monitoring, which employs remote sensing for real-time monitoring, although online monitoring is increasingly adopted for critical assets.

2. STATISTICS ON TRANSFORMER FAILURES

As transformers age, their insulation gradually loses both dielectric strength and mechanical resilience. This escalating degradation heightens the likelihood of failure while concurrently reducing the remaining operational lifespan. Condition monitoring and diagnostic techniques are employed to enhance service quality and lower operational costs for aging transformers. Fig. 2.1 illustrates the age distribution of power transformers within a prominent utility firm in Australia.

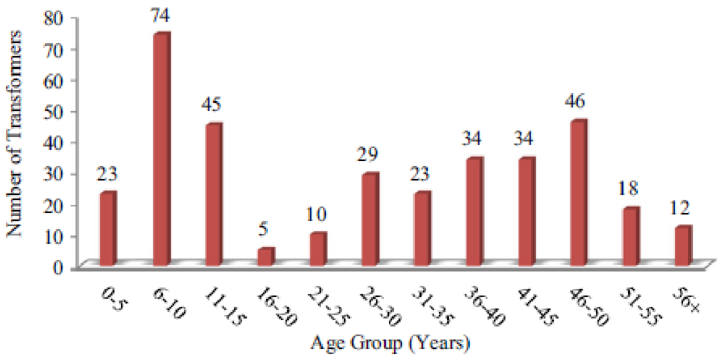

Fig. 2.1 Power Transformers Age Profile

Various factors, both internal and external, impact the failure rate and lifespan of transformers. These include electrical stresses such as switching surges and lightning impulses, which weaken insulation over time, leading to failures. Additionally, issues like increased contact resistance, partial discharge, and cooling system problems elevate operating temperatures. Mechanical deformation, caused by short-circuits or during transportation, is another concern. When thermal stresses and mechanical defects interact with moisture and contamination, they accelerate insulation aging and contribute to electrical failures.

3. ENHANCING TRANSFORMER PERFORMANCE THROUGH MONITORING AND DIAGNOSTICS

Once power transformers are installed and commissioned, utilities aim for uninterrupted operation throughout their lifespan with minimal ad hoc maintenance. To mitigate unplanned outages and lower operational expenses, utilities routinely perform a series of diagnostic and routine tests. These tests help evaluate the insulation condition and mechanical robustness of each transformer.
Dissolved gas analysis (DGA) stands as a widely recognized and established technique for monitoring the condition of power transformers. It effectively detects faults like arcing, partial discharge, overheating, and early-stage hot spots without disrupting operations. This method involves analyzing both combustible and non-combustible gases dissolved in transformer oil. Throughout their operational lifespan, transformers encounter various faults and stresses, including thermal, electrical, chemical, and mechanical factors. These factors generate fragments, aging products, and polar oxidative substances within the oil-paper insulation, leading to molecular property changes over time [6,7].

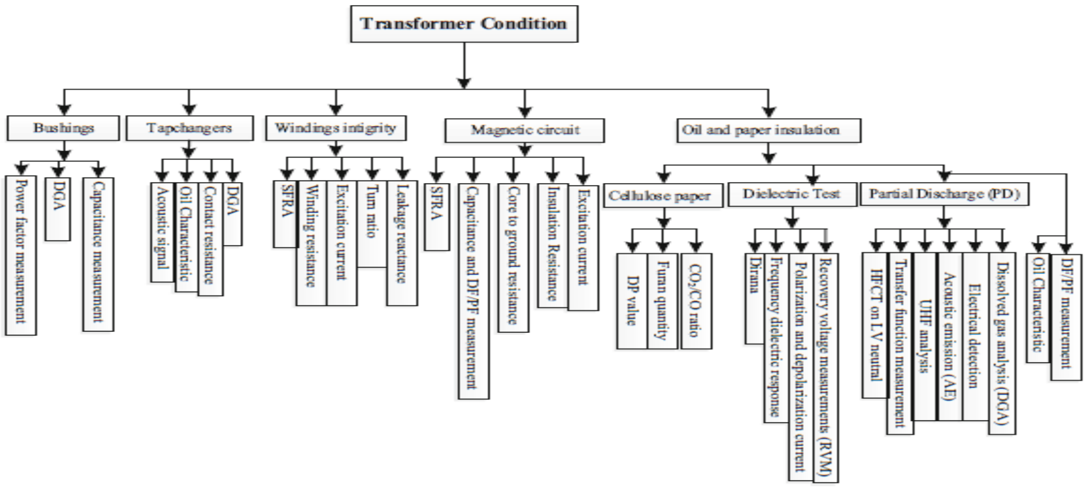

Fig. 3.1 Condition Monitoring and Diagnostic Techniques

Evaluating the condition of transformers in operation often involves testing the quality of insulating oil. Given the direct impact of oil condition on transformer performance and longevity, monitoring oil condition has proven highly effective. Throughout the service life, oil undergoes changes due to oxidation, chemical reactions, and various stresses (thermal, electrical, and chemical). To assess these changes and diagnose their severity, a range of physical, chemical, and electrical tests are conducted. These tests include measuring dielectric breakdown voltage (DBV), power factor, interfacial tension (IFT), acidity, viscosity, color, and flash point. DBV indicates the oil's ability to withstand electrical stress without failure, while the power factor test assesses dielectric losses. These tests are sensitive to aging products and contaminants, helping to quantify their concentration in the insulating oil. Additionally, during service, transformer oil can accumulate acids from atmospheric contamination and oxidation products.

Table-3.1 Heating Severity Classification [11]

Increased temperature ◦C	Classification
0-09	Attention
10-20	Intermediate
21-49	Serious
>50	Critical

Infrared thermography offers a non-invasive and rapid method for capturing images of the external surface temperature of transformers without disrupting their functionality. Typically, transformers operate within a temperature range of 65 to 100 degrees Celsius. However, various factors such as short-circuit currents, high winding resistance, poor contact in cable joints, oil leaks, and cooling system malfunctions can cause temperature

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increases. As the temperature rises, the aging rate of insulation accelerates, leading to a faster deterioration of the transformer's remaining operational life. In contrast, infrared thermography is limited in its ability to measure the internal temperature of a transformer tank [11]. Table 1 provides a classification of heating severity based on infrared thermography findings.

3.1 Excitation Current Test

The purpose of this test is to identify various issues such as short-circuited turns, ground faults, core de-laminations, core lamination shorts, poor electrical connections, and problems with the load tap changer (LTC). It is conducted by energizing the high-voltage (HV) side while keeping the low-voltage (LV) neutral grounded and all other terminals floating. The grounded neutral ensures that any ground fault causes a significant current flow into the HV side despite the low excitation voltage, aiding in the detection of faults.

3.2 Power factor/dielectric dissipation factor Test

The dielectric dissipation factor (tan δ) test is employed to assess the insulation integrity in various parts of transformers, including windings, bushings, and the oil tank. When an alternating voltage is applied across the insulation, it generates a leakage current comprising reactive (capacitive) and resistive components. The resistive component's magnitude is influenced by factors like moisture, aging, and conductive contaminants in the oil, whereas the capacitive current depends on the frequency. The dissipation factor is determined by the ratio of the resistive and capacitive currents, providing insights into the insulation's condition.

The polarization index (PI) measurement is one of the common methods to assess the dryness and cleanness of windings solid insulation that depends on the insulation classes (A, B or C) and winding components [14]. A PI measurement determines the ratio of 10-min resistance to 1-min resistance after applying the test voltage to assess the insulation condition [15].

Capacitance measurement serves to evaluate the state of bushings and identify significant winding displacement. Bushings within a transformer can be likened to a series of capacitors in terms of their electrical behavior.

Transfer function (TF) measurement is a recognized technique that can anticipate the moisture levels within solid insulation [16]. It is also effective in identifying mechanical faults such as winding deformations and displacements caused by short-circuit currents, switching impulses, and transportation factors [17–19].

The load tap changer (LTC) in a transformer plays a crucial role in maintaining voltage stability amidst load fluctuations. It incorporates various insulation materials such as oil, fiberglass, cardboard, and epoxy resin. If a tap changer fails, it can lead to a catastrophic failure affecting nearby transformers.

3.3 Cellulose paper insulation Tests

The solid insulation (paper) found in transformers consists predominantly of cellulose (around 90%), along with hemicelluloses (6-7%) and lignin (3-4%), which are characterized by long chains of glucose rings [13]. This paper serves a dual purpose: providing insulation and mechanical support to withstand forces generated by short-circuit and inrush currents, while also securing the windings in place.

Dielectric response analysis (DRA) is a commonly used technique for assessing the moisture content in the oil-paper insulation of transformers. In power transformers, both the oil and cellulose paper contribute to insulation. Moisture within transformers is generated through chemical processes and is absorbed primarily in the solid insulation (up to 99%) as well as in the oil.

Partial discharge (PD) refers to a localized electrical discharge that occurs within a specific area of an insulation system experiencing high electrical field intensity. PD events are often seen as an early indication of potential insulation breakdown. Therefore, to monitor the health of power transformers and prevent unexpected hazards, PD measurements are conducted over extended periods. In transformers, PD can occur within cellulose paper, oil, or at the oil-paper interface when the electrical field stress exceeds the insulation's breakdown strength. Various defects such as cavities, voids in solid insulation, gas bubbles, or small metal particles in oil can disrupt the uniform distribution of electrical stress across the insulation, potentially triggering PD events that might lead to a flashover.

Moreover, the dielectric strength of insulating materials diminishes over time due to continuous exposure to electrical, thermal, and dielectric stresses. This degradation directly affects the likelihood of PD occurrences. Research indicates that the inception voltage of PD decreases as the temperature increases, as noted in [21, 22].

A comparison of different available PD measurement methods have been summarized in Table 3.2.

Table-3.2 Comparison of different PD Measurement Techniques

Method	Advantage	Disadvantage
Electrical	High sensitivity, High measurement precision	Difficult to apply on-site measurement
UHF	Higher immunity against noise	Sensitivity needs to check for individual transformer due to identical internal impedance

Chemical	Good in laboratory environment	High uncertainty due to unknown relationship between glucose and severity
AE	High sensitivity, AE Good in real-time monitoring	Low sensitivity, Influenced by external noise
Optical	Immune to electromagnetic interference, Visualization of PD is possible	No significant disadvantage
HFCT	Capable to do real-time monitoring, Easy to install	Cannot detect source even the nearby phase
TF	Good in laboratory environment, Capable to detect and locate PD	On-site test, vulnerable to background noise

3.4 Short-circuit Impedance Measurement

Short-circuit impedance (SCI) is a parameter that varies with frequency and has long been employed to identify winding deformation and core displacement in transformers. The presence of a short-circuit current is a key indicator of mechanical issues in the core and windings. Any alteration in the mechanical structure of a transformer can lead to changes in its SCI. A high SCI value directly affects voltage regulation because of the considerable voltage drop it causes. Conversely, low SCI values indicate the presence of short-circuit currents.

The turn ratio test (TTR) for transformers is utilized to identify any open circuits or short circuits within the turns of the same winding. A deviation exceeding 0.5% serves as an indicator of potential insulation failure, short circuits, or open turns within the transformer.

The winding resistance test is effective in identifying issues like loose connections, broken strands, or inadequate contacts within the load tap changer (LTC). It's crucial to measure resistance across all taps to assess LTC contact resistances thoroughly. These results are then analyzed by comparing them with nameplate information, historical records, or across different phases. When comparing nameplate values, it's essential to adjust the test data to the reference temperature used during factory testing.

The core-to-ground resistance test serves to identify accidental core grounding and validate the reliability of intentional ground points. It can complement Dissolved Gas Analysis (DGA) findings, especially when indicating the presence of hot metal gases. To check for multiple grounds, the insulation resistance between the core and tank is measured while keeping the intentional ground cable open.

Sweep Frequency Response Analysis (SFRA) is a non-invasive, precise, cost-effective, and highly sensitive technique utilized to identify mechanical deformations and displacements within transformer cores and windings [23].

4. STATISTICS STRATEGIC LIFECYCLE MANAGEMENT: ENHANCING TRANSFORMER EFFICIENCY AND INVESTMENT PLANNING

In response to economic and technical considerations, utilities are increasingly focusing on estimating the lifespan of transformers alongside condition monitoring efforts. This estimated lifespan plays a crucial role in formulating refurbishment strategies and developing robust forecasting systems for future investments. Over the years, various techniques such as health index calculation, probability of failure estimation, statistical depreciation analysis, and correlation of operating temperature and dielectric power with insulation life have been employed to calculate the remaining service life of transformers.

The hot spot temperature (HST) of a transformer significantly influences its insulation lifespan. As the HST rises, the aging rate of insulation accelerates. Industry loading guidelines such as those from IEE, IEC, CIGRE, and ANSI highlight temperature as the primary factor impacting the service life of transformers. The typical nominal HST for transformer oil-paper insulation is around 110°C, and it's generally considered acceptable up to 140°C [11].

Calculating the DP value and measuring furan concentrations are additional methods used to estimate a transformer's remaining lifespan by evaluating the degradation of its cellulosic paper insulation. Typically, unaged paper is expected to have a DP value of 1000–1200 [29,30], while a DP value of 200–300 indicates that the paper has reached the end of its service life [31].

4.1 Probability of failure Calculation

The probability of transformer failure is determined by assessing the insulation and performance degradation over time. Once the insulation and performance reach a certain level of deterioration, the likelihood of failure can be calculated by modeling this degradation as a function of time.

4.2 Health Index Calculation

The percentage health index (HI) calculation stands as a dependable approach for estimating the lifespan of a transformer. This method combines numerous routine and diagnostic tests to comprehensively evaluate the overall condition of the transformer.

The calculated HI can be correlated with approximate expected lifetime as follows in Table 4.1.

Table-4.1 Health index and remaining Lifetime [1]

Health index	Description	Approximate expected lifetime
85–100	Minor deterioration of a limited number of components	More than 15 years
70–85	Significant deterioration of some components	More than 10 years
50–70	Widespread significant deterioration	Up to 10 years
30–50	Widespread serious deterioration	Less than 3 years
0–30	Extensive serious deterioration	At end-of-life

CONCLUSIONS

Transformers pose a unique challenge compared to other industrial plants because their operational components are often hidden within an oil bath, making direct visual inspection impossible. As a result, various innovative techniques have been developed to assess a transformer's condition using indirect measurements. This paper explores a variety of well-established diagnostic tests to determine the key parameters influencing transformer performance and longevity. The organization of testing methods is based on their sensitivity and capability to detect different types of faults and insulation degradation, aiming to enhance measurement accuracy and fault detection.

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