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Condition Monitoring and Performance Evaluation of Power Transformers Solid Insulating Materials Based on Operational Stresses

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ABSTRACT

Power transformers are vital parts of electric energy transmission and generation systems. This article evaluates the causes of solid insulating dielectric degradation in power transformers based on operational stresses. Dissipation Factor (DF) or tan delta (Tan **δ**) and power factor (PF) tests was conducted on the transformer windings based on the guard-to-ground-to-shield (GST) method using the Delta-3000 Megger instrument to measure winding capacitance (PF), leakage current, and Tan **δ** values. Findings revealed that there were large, sudden increases in variations in the winding capacitance values ranges from 2954 to 9638 and tan **δ** values from 0.9976 % to 1.241% measured after failure at 40℃ when compared to base value capacitance from 2569 to 8381 and tan **δ** values from 0.344 % to 0.428% measured at 30 ℃ before transformer failure. These higher changes in tan **δ** overtime, capacitance (PF), and leakage current indicated deteriorating insulating material conditions, contaminations, dielectric losses and degradation. Also, thermal stress caused mechanical deterioration with time at an elevated temperature and degradation; Mechanical stress caused transient currents during switching on power transformer, damaged insulation due to mechanical vibration; Electrical stresses create significant high-voltage exposure to voltage transients; and Environmental stresses results due to presence of moisture, dirt, chemicals, radiation, or other contaminants. The proposed Condition monitoring can be used to monitor transformers parameters such as dissolving gas analysis, partial discharge, oil quality, vibration, moisture, windings temperatures, detect faults at incipient stage; avoid catastrophic events; Optimized maintenance and prevent failures.

Keywords: Condition monitoring, degradation, dielectric losses, insulating materials, thermal stresses, transformers.

INTRODUCTION

Today, electrical power supply systems use many power transformers, which are the key energy system components designed to increase or decrease voltage (Ivan V.B. *et al,* 2022). Notwithstanding the fact that most power transformers are highly reliable, failures occur during their operation, which is undesirable and unacceptable for a power system. Such failures can also entail significant financial costs, exacerbation of safety issues, and unexpected interruptions in power supply to consumers. Therefore, early fault diagnostics and detection in power transformers, largely determining the reliability of the entire power system, while costing more than all other power grid equipment, require closer attention according to authors (Simkova, M. *et al*, 2010; Singh, R. P. *et al*, 2020; Kim, Y. *et al*, 2019). In their literatures, Pravin Rathod, et al, (2016); Amol Nikam and Arun Thorat (2021) stated that failures of transformer usually lead to substantial profit loss to the utility, potential environmental damage, explosion and fire hazards and expensive repairing or replacement costs; thus, it is desirable that the maximum service life of transformer is required. Condition monitoring of transformer can help to increase the life of the transformer and reduce the maintenance cost. On-line monitoring is the record of significant data of a transformer and analysis of data including the history of the transformer. Power Transformers are made up of major components such as primary winding, secondary winding, magnetic iron core, coolant, bushings, and tank. Insulating materials used in power transformers are of solid insulation system like enameled conductors, pressboard, Kraft paper, cellulose, thermoplastic insulating tape, and insulating oil according to (E.P. Dick, and E.P. Erwin (2018); Revindra A. and Wolfgang, M. (2022). Similarly, in their research, Revindra, A. and Bharat S. R. (2019); and Rickley A. L.(2018), stated that transformer's life span is determined amongst others by the insulation system's mechanical resistance to withstand short circuit current forces. Electric load losses in the transformer cause thermal stress in the active part. Norghen, W. (2019); Nguyen, T. T. (2005) in their articles expressed that cellulose insulation is one of the most important insulating materials for oil-filled transformers. In transformer insulation system, pressboards and Kraft papers are impregnated by insulating oil to increase their dielectric strength and reduced dielectric losses. Degradation of oil in transformer initiates premature aging of solid insulation and visa-versa. In oil-filled transformers, impregnated solid insulation is subject to variable thermal excursions, resulting to the cellulose insulation to either expand or shrink accompanied by degradation. According to L. Pettersson, *et al*, (2018), the life of a transformer can be significantly reduced as the change of its condition with time under impact of thermal, electric, electromagnetic and electrodynamics stresses, as well as under the impact of various contamination and aging processes. Large numbers of transformers in service are approaching the end of their design lives. It is not unusual to find units more than 40 years old being the backbone of a network or to find more than 50 percent of transformer population in a Utility being more than 20 years old.

The article analyses the causes of solid insulating materials dielectric degradation in power transformers based on operating stresses. Condition monitoring of power transformers parameters such as Dissolving Gas Analysis (DGA), partial discharge (PD), vibration, moisture, windings temperatures, etc. as well as identifying significant changes that can detect faults at incipient stage; avoid catastrophic events; prevent failures; optimizing maintenance and predict their future is proposed.

MATERIALS AND METHODS

Dielectric Theory

Dielectric is a term used to identify a medium, such as insulation in which an electric field charge can be produced and maintained. The dielectric strength of a material is the potential gradient at which breakdown occurs and is a function of the insulating material thickness and its electrical properties. Dielectric strength is measured as the maximum voltage required producing a dielectric breakdown through a material and its ability to withstand electric stress without breaking down. It is expressed for wide range of environmental conditions such as temperature, moisture, chemicals, other contaminants, and exposure to weather. Several factors affecting insulation life includes mechanical, thermal, electrical and environmental degradation, although moisture, contamination, voltage stress, and other factors can also contribute to its degradation. Another significant aspect of all insulating materials is the maximum temperature at which they will perform satisfactorily. Insulating materials deteriorate more quickly at higher temperatures and the deterioration can reach a point at which the insulation ceases to perform its required function. This characteristic is known as ageing, and for each material it was usual to assign a maximum temperature beyond which it is unwise to operate. The ageing of insulation depends not only on the physical and chemical properties of the material and the thermal stress to which it is exposed, but also on the presence and degree of influence of mechanical, electrical and environmental stresses.

Formulation of Dielectric Theory

All electrical circuits use insulation which is supposed to be nonconductive confines and guides the electric current to the inside of the circuit. Therefore, the electrical insulation materials should exhibit high resistance to the flow of electrical current, high strength to withstand electrical stress, and excellent heat-conducting properties. There are three fundamental electrical circuits which are (i) the electric circuit, (ii) the dielectric circuit, and (iii) the magnetic circuit. These three circuits are analogous in many respects and are all governed by Ohm's law. Each of these three circuits can be expressed as in equations (1) to (3)

The electric circuit is $I = \frac{E}{R}$ Amps (1)

Where I is the current in the electrical circuit, E is the electromotive force, and R is the electrical resistance

Similarly, the dielectric circuit is $\psi = \frac{E}{S}$ (2)

Where $\psi =$ the electrical flux in the dielectric circuit, E is the electromotive force and S is the dielectric resistance.

While the magnetic circuit is $\Phi = \frac{\mathcal{F}}{\Re}$ (3)

Where Φ is the magnetic flux in the magnetic circuit, F is the magnetic motive force and $\Re$ is the magnetic reluctance. Correspondingly, the formulas for electrical, dielectric, and magnetic resistance are also similar; that is

$$S = (1/e_r)(L/A) \quad (4)$$

Where S is the dielectric resistance, e_r is the relative capacitivity (dielectric constant), L is the length of the material and A is the cross-sectional area. Similarly,

$$\Re = (1/u_r)(L/A) \quad (5)$$

Where u_r is the relative permeability and ρ is the resistivity

$$R = \rho\ (L/A) \quad (6)$$

In the electrical circuit, the circuit is confined to the inside of the conductor and its path is along the conductor, whereas in the dielectric and magnetic circuits the length of the path is short, irregular, and there is a large proportion of leakage flux usually into the air. The dielectric circuit involves several terms and parameters that need to be understood in order to assess the characteristics and performance of the dielectric circuit.

Similarly, the life of transformer solid insulations is related to temperature, as temperature increases, the dielectric strength of the solid insulations reduces. Due to an increase in the dielectric loss, the temperature goes up further. The ohmic resistance of the insulation reduces with increasing temperature, which results in flow of more current through it. This can be expressed by

$$L_H = Ae^{-E/RT} \quad (7)$$

where LH is the specific reaction rate; A is the frequency of molecular encounters; E is the activation energy (constant for a given reaction); R is the universal gas constant; T is the absolute temperature (K). An approximation of the above equation states that life of insulation will be reduced by half for every 10°C rise in temperature. Transformer insulation deteriorates as a function of time and temperature (W.J. McNutt, 2019). Since the temperature distribution in most transformers is not uniform, the most common practice is to consider the aging effects produced by the winding hottest-spot temperature. For power transformers rated above l00 MVA, there are many other stress factors such as mechanical stresses, bushing dielectric stress, and leakage flux density, all of which increase with transformer loading (ANSI/IEEE C57.115 (2011). From the above equation, it is apparent that higher the temperature, the shorter the expected life of the insulation. Also, the strength of an electric field E at any point can be, expressed as

$$E = {}^{F}/_{q} \quad (8)$$

where force F exerts per unit positive electric charge q at that point.

When insulation is energized with an AC voltage, the insulation draws a charging current. This charging current comprises of two components called capacitive current and resistive current. Where I_T= total current;

I_{cap} = capacitive current; I_R = resistive current; δ= PF angle; and θ= dissipation angle. The capacitive current leads the applied test voltage by 90°, whereas the resistive current is in phase with the voltage as shown in Figure 1. The ratio of the resistive current to the capacitive current is expressed as the loss tangent (tan. δ). Tan δ is equivalent to the tangent of the loss angle tan δ, where δ , is the phase angle between the current and voltage. According to IEC 60851-3 (2021) states that Tan delta values less than 0.7% is considered good and acceptable while higher values above 1% indicates deteriorating insulation, contaminations and degradation. Dissipation factor (DF) is a measure of the dielectric losses in an insulating material or component, representing the amount of energy lost as heat when an alternating current (AC) passes through it.

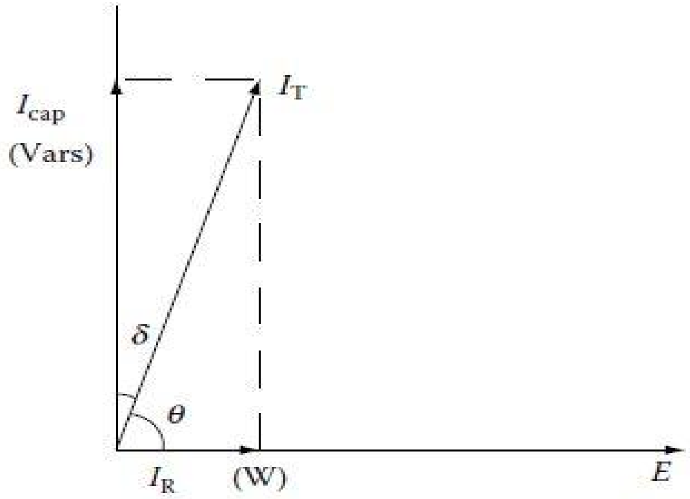

Figure 1: Vector relationship of voltage, resistive, and capacitive current.

The DF indicates how much electrical energy is absorbed and lost as heat within an insulating material. Lower DF indicates better insulating quality and less energy waste, and it is a function of temperature and frequency. Whereas, high energy loss from a high DF can cause overheating, shortening the life of capacitors and other nearby components. The capacitive current is directly proportional to the dielectric constant, area, and voltage and inversely proportional to the thickness of the insulation under test. The capacitive current is calculated using equation (9):

$$I_{cap} = \frac{E}{X_c} = \mathrm{E}\omega C$$

$$= \mathrm{E}\omega\varepsilon_o\varepsilon_r\left(\frac{A}{d}\right)\left[Ex2\pi fx\,0.08854x10^{-12}\,x\,\varepsilon_r x\left(\frac{A}{d}\right)\right] \tag{9}$$

Where E = the test voltage; C = the capacitance; ε_o = the dielectric constant of vacuum; ε_r = the dielectric constant of the insulation; A = the Area (cm^2); d = the thickness of insulation and f = the frequency.

The changes in the capacitive current indicate degradation in the insulation, such as wetness or shorted layers, or change in the geometry of the insulation. The resistive current supplies the energy lost due to dielectric losses such as carbon tracking, volumetric leakage, surface conduction, and corona.

Dielectric Breakdown

A perfect dielectric is a material with zero electrical conductivity, counterpart of a perfect conductor, thus exhibiting only a displacement current; therefore, it stores and returns electrical energy as if it were an ideal capacitor. Insulation breakdown can be classified as failure due to excessive dielectric loss and failure due to over-potential stress. Dielectric losses or electrical dissipation factor is the ratio of the power loss in a dielectric material to the total power transmitted through it. It is given by the tangent of the loss angle (tan δ). Excessive dielectric loss is the result of deteriorated insulation or the contamination of the insulation with a poor dielectric such as water. As the dielectric losses increase, the temperature of the insulation increases resulting in even greater dielectric loss. Over time, the phenomenon eventually results in complete failure of the insulation. The contamination of the oil insulation with water increases the dielectric losses in the oil and simultaneously reduces the dielectric strength of the insulation. Because of increased losses in the oil insulation over time, it will become degraded and eventually fail. Dielectric loss is a measure of energy dissipation through and over the surface of the insulation. The dielectric losses of insulations increase with increase in temperature, moisture, and corona.

Over-potential stress

Over-potential stress occurs when a voltage is applied across insulation greater than its dielectric strength. The molecular forces are overwhelmed and the insulation becomes a conductor. The causes of insulation failure due to over-potential stress are external increase in applied voltage, decrease of insulation thickness, and air bubbles or pockets in the insulation. This failure mode occurs when air is introduced into the insulation. Air, although a good dielectric at low voltages becomes overstressed at higher voltages. Field experienced shown that the air voids become overstressed at 2500 V and begin ionizing, thus resulting in corona which will eventually deteriorate the paper insulation. In this case, the reduced thickness of the insulation and the resulting voltage overstress causes the insulation to fail.

Condition Monitoring of Power Transformers.

In this article, we present different analytical methods for condition monitoring of power transformers. In the study, measurements of dissipation factor (DF), also known as power factor (PF) or Tan delta (Tan δ) of an aged 150 MVA, 330/132 kV, three-phase power transformer in the field was performed to evaluate the quality, performance, and reliability of the transformer solid materials insulation. The main technical specification of the transformer is presented in Table 1.

Table 1: Transformer Specifications

Parameters	Ratings
Manufacture Date	May 1987
Rated Voltage (kV)	330/132
Rated power (MVA)	150
Rated current in Amp	252/656
Vector group	Dy11
Number of coolers	12
No-Load current (%)	0.37
Number of phases	3
Number of limbs	5
S.C. voltage HV-LV (%)	11.81
Frequency (Hz)	50
Cooling system	OFAF, Detached

Dissipation Factor (DF) or Tan delta (Tan δ) and Power Factor (PF) Tests Set-up

The Dissipation Factor (DF) and power factor (PF) measurements are searching diagnostics tool for evaluating performance of enamel wire insulation under specified temperature and frequency conditions. It is a fundamental concept that changes in insulation quality result in measurable changes in electrical characteristics of the insulation, such as capacitance, dielectric loss, and PF. It is important we considered the following conditions while conducting dissipation factor (DF) and power factor (PF) tests, this include:

- The transformer was de-energized and completely isolated from the power source.
- Transformer housing was properly grounded.
- All high voltage (HV) bushing of the three phase units were shorted together to make them into an equivalent single bushing. Similarly, the low voltage (LV) bushing of three phase unit were also shorted together to make them into an equivalent bushing; and the neutrals ungrounded.

The dissipation factor (DF) and power factor (PF) testing was performed on a three-phase two-winding power transformer, using the transformer specifications in Table 1. The transformer windings insulation system comprises of three insulation system namely; High Voltage (HV) capacitance *(C*H) winding insulation, Low Voltage (LV) winding capacitance *(C*L) insulation, and High-to-Low winding capacitance *(C*HL) insulation. These tests measurements were conducted based on the Guard-to-ground-to-shield (GST) mode method using the Delta-3000 Megger test instrument set at 10 kV to measures capacitance values, leakage current, and Tan delta (Tan δ) of the insulations.

Four different dissipation factors (or tan δ) and power factor (PF) tests were conducted on the transformer windings by applying a high potential voltage of 10 kV to determine the capacitance values, leakage current, and percentage values of Tan. δ of the insulations. The following tests include: Tests No1: HV winding was energized by injecting test voltage while LV winding was grounded, and meter reading was obtained. No 2: HV winding was energized and the LV winding guarded. The meter reading of the capacitance obtained. No 3: energized the LV winding while HV winding was grounded, and meter reading of the LV winding capacitance *(C*L) insulation, and High-to-Low winding capacitance *(C*HL) insulation were obtained. Similarly, No 4: LV winding was energized; HV winding was guarded and the meter reading for LV winding capacitance *(C*L) insulation was taken. The values of tan delta (Tan δ), leakage current, and insulation capacitance were measured and recorded. Tests results obtained were tabulated as shown in Table 2. The tests were performed to evaluate the quality, performance, and reliability of the transformer windings insulations. It's capable of detecting / tracking dielectric deterioration, contamination, and insulation degradation.

Operating Stresses and Their Causes

The following operating stresses contributing to insulation degradation failures occurring in different parts of power transformers include mechanical, environmental, electrical, and thermal stresses were analyzed in the section below.

Mechanical Stress

Mechanical stress can be caused by power frequency transient currents such as when switching on power transformer, that give rise to transient power frequency currents. In the case of a transformer, the power frequency current can be as high as 10–12 times the normal current. The magnetically induced mechanical forces in the equipment are the square of the transient current; therefore, a transformer experiences mechanical forces of 100 or more times stronger than normal service. When these transients occur frequently, such as frequent energizing of transformers and these forces cannot be withstood it will eventually lead to mechanical damage. Also, insulation can be damaged by mechanical vibration and expansion and contraction at power frequency operation. That is, when current is applied, the end turns of transformer windings can be twisted. If the twisting force is strong enough to break the bond of insulating varnish, the turns of magnetic wire will wear against each other and cause a turn-to-turn short. Once the turns are shorted, localized heating is caused by the current induced onto the closed loop. These heats rapidly degrade the surrounding insulation and over time destroy the ground-wall insulation. As the transformer insulation ages, the paper insulation shrinks resulting in a reduction of clamping pressure, thereby reducing mechanical strength.

Environmental Stresses

Environmental factors that degrade insulation over time include moisture, dirt, dust, oils, acids, and alkalies. Moisture is conductive because it contains impurities. When insulation is laden with moisture it decreases the insulation resistance. The moisture penetrates the cracks and pores of the insulation, and provides low resistance paths for creepage currents and potential sources of dielectric failure. Chemical fumes such as acids and alkalies often found in the industrial environment directly attack insulation and permanently lower its insulation resistance. Dirt and dust in combination with moisture can become conductive and therefore cause creepage currents and insulation degradation as well as reduce the ability of the insulation to dissipate heat. The life of the transformer is dependent to a considerable extent upon the degree of exclusion of oxygen, moisture, dirt, and chemicals from the interior of the insulating structure. Chemical deterioration agents can be contaminants in oil such as moisture and acids in oil which break cellulose chains and reduce mechanical strength of cellulose and also corrode metal, corrosive sulphur in oil, can form copper sulphide deposits on paper, Oxygen forms organic acids and sludge which can impair cooling, the combination of moisture, heat and oxygen are the key conditions for degradation of the cellulose.

Electrical Stresses

Electrical transformers are always subjected to internally generated or external voltage and current surges. A physical rupture of insulation with the destruction of molecular bonds can occur during voltage surge due to switching of a large inductive load or lightning. This transitory over potential stresses the molecular structure of the insulating material causing ionization and failure of the insulating material itself. The nitrogen oxides produced by the ionization of air form acids when combined with moisture also degrade the insulation. The voids in the cable- extruded insulation once electrified begin to conduct and grow larger. This phenomenon is known as partial discharge in the winding insulation and over time makes the void to grow larger and eventually cause winding to fail. Electrical stresses are more significant with high-voltage power transformer exposed to voltage transients. Electrical stresses due to operating voltage and transient over voltages causes ageing under dielectric stress mainly due to partial discharges (PD). Apart from over-voltages, stress enhancement, particularly at insulation surface, can also take place due to the presence of conductive particles and wet fibers. The rate of degradation due to PD depends on its location and energy dissipated.

Thermal Stresses

The temperature at which insulation operates determines its useful life. Thermal stress is one of the most recognized causes of insulation degradation. Insulation does not always fail when reaching some critical temperature, but by gradual mechanical deterioration with time at an elevated temperature. The time–temperature relationship determines the rate at which the mechanical strength of organic material decreases. Thereafter, electrical failure can occur because of physical disintegration of the insulating materials.

Thermal aging mechanisms include Loss of volatile constituents; oxidation that can lead to molecular cross-linking and embrittlement; hydrolytic degradation in which moisture reacts with the insulation under the influence of heat, pressure, and other factors to cause molecular deterioration; and chemical breakdown of constituents with formation of products that act to degrade the material further, such as hydrochloric acid. Thermal aging progressively decreases elongation to rupture so that embrittlement finally leads to cracking and that contribute to electrical failure.

Operation of transformer at hottest-spot temperatures above 140 ℃ can cause gassing in the solid insulation and oil. Gassing can produce a potential risk to the dielectric strength integrity of the transformer. The rate of physical deterioration of insulation under thermal aging increases rapidly with an increase in temperature. Temperature of the insulation can increase above design levels due to overload, or over fluxing. It can also be due to insufficient cooling due to deposition of sludge on solid insulation or the failure of cooling fans. Beyond temperatures of about 130 degree Celsius, the polymeric chains of cellulose will be affected thereby reducing its mechanical strength.

The rate of degradation increases with temperature. For every 6 to 8 degree rise in temperature from its designed temperature class can halve the life. Secondary effects of high temperature include decomposition of paper and oil and resulting in the production of water, acids and gases each of which progressively deteriorate the insulation. According to IEEE Standard 1-2000 Recommended practice – General principles for temperature limits in the rating of electrical equipment and for the evaluation electrical insulation expressed that, insulation system classes are designated by letters and can be defined as assemblies of electrical insulating materials in association with equipment parts.

These systems were assigned temperature rating based on service experience or on an accepted test procedure that can demonstrate an equivalent life expectancy. The thermal classification of electrical insulating systems established by IEEE Standard 1-2000 IEEE Recommended practice – General principles for temperature limits in the rating of electrical equipment and for the evaluation electrical insulation is given in Table 3.

Table 3: Thermal Classification of Electrical Insulating Systems

Thermal Classification	A	E	B	F	H	N	R	S	C
Class Temperature (°C)	105	120	130	155	180	200	220	250	>250

Apart from accidental electrical and mechanical failures, the life expectancy of electrical apparatus can be limited by the temperature of its insulation: the higher the temperature, the shorter its life. Based on experienced from field tests performed on several insulating materials shown that service life of electrical apparatus diminishes approximately by half every time the temperature increases by 10°C. This means that if a transformer has a normal life expectancy of eight years at a temperature of 105°C, it will have a service life of only four years at a temperature of 115°C. Factors contributing to deterioration of insulating materials were heat; humidity; vibration; acidity; oxidation; and time. As a result, the state of the insulation changes gradually; it slowly begins to crystallize and the transformation takes place more rapidly as the temperature rises according to Theodore Wildi.

Proposed Condition Monitoring Techniques (CMT)

Based on practical experience in recent years revealed that having a complete knowledge of a transformer's history and being able to identify potential issues early enough can be very beneficial. The proposed condition monitoring is a technique that can be used to evaluate present condition of power transformers; easily detect, prevent and correcting measures taking to avert failures, reduce downtime and maintenance cost and improved the life of the transformer. Condition monitoring technique (CMT) principle is based on using sensors and data analysis tools embedded in the power transformers tank to track and recording of the voltage and current as well as monitoring of the top oil temperature and the performance of power transformers.

Different methods of condition monitoring of power transformers can be categorized to include: a) Dissolved gas analysis (DGA); b) Partial discharge (PD); c) Temperature; d) Vibrations; e) Tangent delta etc. This technique allows for more accurate evaluation of the transformers condition, effective planning of maintenance measures, record, evaluate different types of faults and analyze electrical characteristics in power transformers. These measurements are compared with expected values to identify variation in parameters that can indicate potential failures.

This article presents a proposal for on-line condition monitoring system for power transformers applications to include

- Dissolved Gas Analysis (DGA): A transformer is subject to electrical and thermal stresses. These stresses can break down the insulating materials and release gaseous decomposition products. The analysis of dissolved gases is a powerful tool to diagnose developing faults in oil-filled power transformers. By sampling and examining the ageing insulation oil of transformers, ratios of specific dissolved gas concentrations, their generation rates, and total combustible gases can be analyzed. Analyzing the gases dissolved in the transformer oil can reveal insulation degradation and overheating.
- Partial Discharge (PD): Partial discharges in a transformer deteriorate the insulation system to the point of destruction. Partial discharges pulses generate at their point of origin electromagnetic waves, acoustic waves, local heating and chemical reactions. These phenomena, if detectable, would constitute possible indicators of a partial discharge defect. So, detecting partial discharges can be precursors to insulation failure.
- Temperature: Making use of an optical fibre transmitter connected to crystal sensors, which convert the incoming light beam into an optical signal characteristic of the sensor temperature. Using sensors to track oil and winding temperature to detect overheating.
- Vibrations: The vibration sensors can be magnetically mounted piezo-electric accelerometers attached to the sides and top of the transformer tanks. The signals are optically isolated for

transmission to a data recorder. Using sensors to detect abnormal vibrations that can lead to mechanical problems.

Advantages of Condition Monitoring Technique (CMT)

The benefits of the CMT in power transformers on-line include providing early detection of faults; optimizing maintenance; avoids catastrophic events and improves reliability. It simply means that, the techniques can detect overheating, insulation breakdown or winding distortion which can prevent transformer failures; it helps schedule maintenance activities based on actual needs, rather than on a fixed schedule, optimized maintenance cost and reduced downtime; preventing transformer failures that can avert costly repairs, environmental hazards, safety risks and reduced failures which contribute to a more reliable power supply.

RESULTS AND DISCUSSIONS

Analytical results of the transformers solid insulating materials showed that as the insulation ageing, Kraft paper, cellulose and pressboard insulations shrinks resulting in a reduction of clamping pressure, and reducing mechanical strengths. Dielectrics failures in transformers were direct results of reduced mechanical strength due to various operating factors. Measurements of dissipation factor (DF), also known as power factor (PF) or Tan delta (Tan δ) of a 150 MVA, 330/132 kV, three-phase power transformer results are shown in Table 2.

Table 2: Results of Transformer's Capacitance Measurements

S/No	Windings Configuration	Methods	Before Failure 30℃		After Failure 40℃	
			Capacitance (pf)	tan δ [%]	Capacitance (Pf)	tan δ [%]
1	HV/LV	GST	7671	0.367	8822	1.064
2	HV/LV+G	GST	15391	0.428	15948	1.241
3	HV/LV Guard	GST	8381	0.362	9638	1.05
4	HV/LV	GST	7668	0.371	8818	1.076
5	HV-IV/LV+G	GST	2569	0.344	2954	0.9976
6	HV-IV/LVG	GAR-R	16447	0.349	18752	1.012

The dissipation factor (DF) or tan δ is a property of the electrical insulation system and it measures the electrical losses in the insulation. Findings revealed that there were large, sudden increases in variations in the internal winding capacitance values ranges from 2954 to 9638 measured after failure at 40℃; while the tan δ values ranges from 0.9976 % to 1.241% tan δ when compared with the base value of capacitance ranges from 2569 to 8381 and tan δ values from 0.344 % to 0.428% measured at 30 ℃ before failure of the transformer. These higher values change in the tan δ over time, capacitance power factor, and excess leakage current revealed deteriorating solid insulating material conditions, contaminations, insulation losses in the dielectric and degradation in the overall insulating materials.

Assessment of the solid insulation degradation further revealed major aging factors responsible to include mechanical, electrical, environmental, and thermal stresses.

Results revealed that mechanical stress caused by power frequency transient currents when switching on power transformer and give rise to transient power frequency currents; the insulation can be damaged by mechanical vibration imposed on its supporting structure, differential thermal expansion and contraction at power frequency operation. Finding showed that electrical stresses create significant high-voltage equipment exposure to voltage transients. These stresses were due to operating voltage and transient over voltages causing ageing under dielectric stress as a result of partial discharges (PD). Similarly, environmental stresses had serious impact on the presence of moisture, dirt, chemicals, radiation, or other contaminants. Results indicate that moisture penetrates the cracks and pores of the insulation, and provides low resistance paths for creepage currents and potential sources of dielectric failure. Chemical fumes like acids and alkalis in the industrial environment directly attack insulation and permanently lower its insulation resistance. In addition, dirt and dust in combination with moisture become conductive and thus caused creepage currents and insulation degradation.

While thermal stresses were due to the environmental conditions such as high ambient, loading, and ability to dissipate heat in the transformer. The temperature at which insulation operates determines its useful life. Operating transformer at hottest-spot temperatures above 140 ℃ caused gassing in the solid insulation and transformer oil. Gassing produces potential risk to the dielectric strength integrity of the transformer. Physical deterioration of insulation under thermal aging increases rapidly with increase in temperature. Thus, thermal stress caused gradual mechanical deterioration with time at an elevated temperature and eventual insulation degradation. Finding revealed that, electrical, mechanical, environmental, and thermal stresses were contributing factors to transformer insulating materials degradation**.**

CONCLUSIONS

Condition monitoring of power transformers solid insulating materials degradation due to various operating stresses were analyzed. This article analytically evaluates the causes of insulating materials degradation based on condition monitoring of power transformer in an energized / de-energized condition. Dielectric theories of insulating materials were assessed and formulations presented. Measurement of the three-phase two-winding insulations dissipation factors (DF) or power factor (PF) based on guard–to-ground-to-shield test (GST) method was conducted using the delta-3000 Megger instrument to measure the capacitance, leakage currents and Tan δ of the winding's insulation degradation conditions. Electrical characteristics of the insulating materials, such as capacitances, alternating current (AC) dielectric loss, and PF conditions were evaluated and presented. The proposed power transformers condition monitoring technique applications characteristics and its advantages were highlighted and presented. By on-line condition monitoring the transformer's performance can help utilities to provide early detection of faults; optimized maintenance; avoids catastrophic events and improves efficiency and reliability of the overall power grid.

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Conflict of Interest

The authors declare no conflict of interest on the article.

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