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Condition Assessment Techniques for Insulation Diagnosis of Oil Filled Power Transformers

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Abstract

Power transformers are key components in the substation/switchyard and failure of transformer can have an enormous impact on reliability and availability of power supply and has financial implications. As there is ever increase in demand of power, the reliability of power equipment assumes high importance. Economic factors are the main consideration and in order to minimize capital expenditure on new equipment, it is a common policy among utilities to maximize the use of existing power transformers by operating at their design capability. This can be achieved by periodic diagnostic testing and adopting condition based maintenance practices. In this paper various condition assessment techniques for oil filled transformers are discussed and few case studies are presented.

Keywords: Condition Assessment, Generator Transformer, Insulation Diagnosis, SFRA

1. Introduction

The transformer insulation system in service is subjected to a combination of electrical, mechanical, thermal and environmental stress. Neither all the factors those affect the life expectancy of transformers are known, nor are properly understood. However, in general, the following facts are significant.

(a) The initial thermal, electrical and mechanical properties of insulating materials used affect life expectancy. Various materials lose their properties at different rate and during the aging process the same material may lose different properties at different rates.
(b) Thermal, electrical and mechanical stresses also affect life of transformer. Thermal stress arises due to overload currents, local overheating, leakage fluxes as well as well as malfunctioning of cooling system.
(c) Electrical stresses are caused by system as well as transient over-voltages, winding resonances etc.
(d) Mechanical stress between leads, conductors and windings are produced by short-circuit inrush currents.
(e) Normal load cycle along with environmental factors like ambient temperature and humidity affect life expectancy. Both mechanical and dielectric withstand strength of the transformer is reduced by aging of its insulation. During the service life of transformer, it is subjected to faults that result in high radial and compressive forces. With system growth the operating stress on transformer increases as the load increases. In an aged transformer, typically the conductor insulation is weakened to the point where it can no longer sustain mechanical stresses of the fault. Then dielectric failure of turn to turn insulation occurs or loosening of winding clamping pressure takes place, which reduces the transformer's ability to withstand future short circuit forces[1].

Central Power Research Institute (CPRI), Bengaluru, a premier institute for Indian Power Sector has been conducting diagnostic testing on power transformers in service to assess the condition and their useful life.

2. Causes of Insulation Failure

Notable defects in the transformer major insulation are (a) moisture in cellulose insulation, (b) contamination of oil with water, particles and insulation aging product, (c) Insulation surface contamination, which occurs mainly due to absorption of aging by products on a cellulose

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surface or due to deposition of conducting particles and insoluble aging products and (d) Partial Discharges in weaker parts of insulation. The presence of moisture and impurities changes dielectric parameters of deteriorated components, viz. their conductivity, permittivity and dissipation factor, particularly with temperature. This in turn results in related changes in dielectric characteristics of the whole transformer. Defects related to excessive moisture, oil contamination or surface contaminations are reversible defects, while damage created by partial discharge activities is usually irreversible in nature[1].

3. Evaluation Techniques

The various techniques for condition assessment of transformers are Detection of PD, detection of distortion of winding geometry, detection of aging by products by chemical methods, and detection of changes in dielectric characteristics by time domain and frequency domain method. The following are the diagnostic testing techniques frequently used in the field for power transformers.

3.1 Insulation Resistance (IR) and Polarisation Index (PI) Test

The IR indicates whether the transformer insulation is moist (contaminated) or not. The IR values will be usually high (several hundred mega ohms) for a dry insulation system. PI is used as an index of dryness and represents cleanliness of the winding. The test parameters identified are IR after one-minute voltage application and IR after 10 minutes voltage application at 2500 Volts DC. PI is the ratio of 10 minutes to the one-minute value[2].

3.2 Dielectric Loss Angle (Tan Delta) and Capacitance Measurement

The dissipation factor (tan delta) represents the gross defects and overall dielectric losses in the insulation. In order to, assess the state and quality of the entire mass of the transformer insulation, following four test schemes are used during the measurement of the tan delta.

C_H : Capacitance and Dissipation Factor of the insulation between the HV windings and the tank.
C_{HL}: Capacitance and Dissipation Factor of the insulation between the HV windings and the LV windings.

C_L : Capacitance and Dissipation Factor of the insulation between the LV windings and the tank.

Capacitance and Dissipation Factor of HV Bushing Insulation between the bushing conductor and test tap[2].

3.3 Dielectric Response Measurement

There are three main types of dielectric response measurement techniques: Polarization and Depolarization Current Measurement (PDC), (b) Recovery or Return Voltage Measurement (RVM) and Frequency Domain Spectroscopy (FDS). PDC and RVM are DC voltage tests in which the dielectric response is measured as a function of time. FDS is an AC voltage test and in FDS dielectric response parameters are measured as function of frequency.

In PDC, a step voltage of constant magnitude is applied to the test object for a longer period of time and the resulting polarization current through the test object is measured. The measurement of polarization current is stopped when the polarization current become either stable or very low. Subsequently the test object is short circuited for a longer period of time and consequent depolarization current is measured.

The initial part of the polarization and depolarization currents measured for transformer insulation system are greatly influenced by higher mobility of charge carriers in the insulating oil and hence are sensitive to condition of transformer oil. The steady state part at longer times of polarization current measurement is due to the not so mobile charge carriers in the paper or the press board insulation. Hence steady state part of the polarization current is a good indicator of the condition of the solid insulation.

In RVM the test object is subjected to a step dc voltage for a certain period of time and then short circuited for lesser period of time. Subsequently, the test object is open-circuited. Since the depolarization of all the polarization processes having different time constants will not be complete during the inadequate depolarization duration, the charges present in the incomplete depolarization process starts charging the geometric capacitance in open circuit condition and a voltage appear across the terminals of the test object, which is known as return or recovery voltage. The initial slope of the recovery voltage is determined by the dc conductivity. A lower value of the time required to attain the peak value of the recovery voltage, indicate poor condition of the transformer insulation. RVM is useful for assessing the un-uniformity of the insulation aging and/or moisture distribution.

FDS is an extended version of commonly used method of dielectric dissipation factor measurement at power frequency. But measurement of dielectric dissipation factor at power frequency is insufficient to detect changes that take place in complex insulation system such as in transformers. Moisture content, contamination and other impurities affect the dielectric properties of transformer insulation system at different and specific frequency ranges[1,2].

3.4 Partial Discharge (PD) Measurement

Partial discharge test is a significant diagnostic test for power transformer it is capable of revealing incipient faults in the transformer insulation system. The partial discharges are known to be detrimental to the insulation and leads to gradual deterioration of the insulation in the course of service. Any PD activity that indicates harmful insulation defects must be detected. After detecting and recording the PD analysis of the PD data is carried out to identify the defect in the transformer. The identification of the defect can be done by finding the location of the insulation defect from a reference database. Finally, risk management for an insulation failure of the transformer is to be done[1,2].

3.5 Sweep Frequency Response Analysis Test (SFRA)

Sweep Frequency Response Analysis (SFRA) is a reliable tool for mechanical condition assessment of the windings. Transformers are subjected to mechanical stresses during transportation, short circuit faults near the transformer, Transient over voltages such as switching, lightening etc. Mechanical Stresses Cause Winding displacement or deformation, winding collapse in extreme cases, such mechanical defects eventually lead to dielectric faults in the winding.

SFRA is capable of detecting Core movement, winding deformation and displacement, Faulty core grounds, Partial winding collapse, Broken or loosened clamping structures, Shorted turns and open windings[1–3].

3.6 Winding Resistance Measurements

The transformer Winding resistances are measured in the field in order to check for abnormalities due to loose connection, broken strands and high contact resistance in tap-changers. Interpretation of results is usually based on a comparison of measurements made separately on each winding. Comparison may also be made with original data measured in the factory. Winding resistance test is capable of indicating short circuited turns, poor joints or bad contacts in the windings. This reading should be comparable to the factory test data[2].

3.7 Transformer Turns Ratio Measurement

In service, the insulation around windings can become damaged or deteriorated, from an array of causes including spikes, surges, contamination, faults, shipping damage, and others. Insulation damage can result in shorts between turns, effectively reducing the number of turns and altering turns ratio to some value deviating from nameplate rating. The extent of deviation from nameplate ratio is a direct indication of winding deterioration. A transformer will tolerate a limited amount of such deterioration[2].

3.8 Short Circuit Impedance Measurement

The short-circuit impedance ($\%Z$) of power transformers is measured on site and it can be compared to the nameplate or factory test values. It is used to detect winding movement that may have occurred since the factory tests were performed. Winding movement usually occurs due to heavy fault current or mechanical damage during transportation or installation. The measurements are usually performed on one phase at a time. Changes of more than ±3% of the short-circuit impedance should be considered significant[2].

3.9 Chemical Methods for Condition Assessment

The chemical reactions that occur within transformer insulation due to aging are caused by pyrolysis oxidation and hydrolysis. The factors that accelerate aging are temperature, oxygen and moisture. These age related chemical reactions cause reduction of mechanical strength of cellulose insulation.

Over the years, chemical methods are being used extensively for assessment of overall condition of transformer. Traditional chemical tests are measurement of dielectric strength of insulating oil, neutralization value and interfacial tension. A reduction in dielectric strength of insulating oil indicates presence of moisture sediment such as sludge and conducting particle in oil. Acid in the insulating oil originate primarily from decomposition/oxidation of oil. These organic acids are detrimental to the entire oil paper insulation system.

A sensitive and reliable technique for assessing the condition of oil filled transformer is Dissolved Gas Analysis (DGA). Small quantities of gasses are liberated due to decomposition of oil and cellulose insulation under electrical and thermal stress. The quantitative of decomposition of the liberated gas is dependent upon the type of fault.

Depolymerization of cellulose takes place due to various aging mechanisms of paper insulation during its service life. An effective method of evaluation of remaining life of paper insulation is measurement of degree of polymerization. DP measurement is an invasive test. Specific furan compounds are generated due to paper degradation that remains dissolved in oil. Measurement of furanic concentration by oil testing is a non-invasive and convenient diagnostic technique[1,2].

4. Condition Assessment Methodology

Though there are several criteria proposed by the researchers over the years there is no unanimity in the global technical community about the best criterion for remaining life assessment or End of Life prediction. Residual Life Assessment[4,5] in true sense involves following steps:

1. Collection of O&M history of the equipment.
2. Visual inspection & examination of the equipment.
3. Conducting appropriate diagnostic tests to assess the present status of the equipment.
4. Analysis of the data to detect extent of deterioration or to detect defective components.
5. Recommendation of appropriate remedial measures to

a. avoid forced outages
b. extend residual life

The diagnostic tests need to be conducted periodically [every (2 / 3 / 4 years)] to monitor the trend in the parameters. Data logged over the years and trend analysis provides useful information to initiate appropriate remedial measures to extend life of the equipment.

CPRI has carried out extensive condition assessment studies of power transformers. No quantitative assessment of life in terms of years is possible with the data generated. However, on the basis of analysis of the data, appropriate remedial measures such as run, repair or replacement to extend the remaining life of the equipment is recommended.

5. Case Studies

CPRI has been conducting diagnostic testing on power transformers for utilities, process industries and power plants for condition assessment of their insulation system by conducting appropriate diagnostic tests. Analysis of the diagnostic test data has helped the plant managers in asset management. Few case studies are discussed as given below.

Case 1. 11/33kV, 25MVA, 3-Φ, 50Hz, Generator Transformer, 58 Years Old.

History: The transformer was overhauled in May/June 2016. Winding insulation system and Core were cleaned by oil jet. Gaskets were changed and transformer was dried out by applying vacuum and nitrogen cycle during. New hot circulated transformer oil was filled under vacuum diagnostic testing.

CPRI had conducted FDS and DP test for condition assessment. The furan analysis conducted before overhauling by third party indicated hugh furan content as high as 2380ppb. The diagnostic test results are tabulated in Table 1.

The Tan delta values are normal and lie in the normal permissible range. The estimated moisture content in the HV winding insulation, barrier insulation and LV winding insulation sections are 4.2 %, 4.1% and 4.1% respectively. These moisture levels are slightly higher than the maximum permissible level of 4.0% for an in-service 33kV class transformer.

The DP values obtained on the subject transformer (HV Winding-562.5, LV Winding-562.3) indicate moderate deterioration of the paper insulation. The mechanical strength of the paper insulation is good.

Table 1. 11/3 kV, 25 MVA Generator Transformer

Insulation Section	10 kV Equivalent Power Frequency Value		DP Value
	Tan d (%)	Moisture Content (%)	
CH+CHL	2.586	4.2	HV Winding-562.5
CHL	3.836	4.1	--
CL+CHL	3.029	4.1	LV Winding-562.3

From the diagnostic test data, it can be inferred that the transformer is generally healthy. As condition monitoring is a continuous process and condition monitoring is based on trend analysis, it is recommended to conduct diagnostic testing after one year.

Case 2. 99 MVA, 11/220kV, 3- Φ, 50 Hz Generator Transformer, 42Years Old

History: The transformer was under shutdown since fifteen days prior to testing. Oil leakage was observed at HV side Y phase bushing bottom flange, near OTI pockets and inspection window near OTI pocket. Transformer is running under 10% overload (Considering Generator rating 103.5 MW and Transformer rating 99MVA at 0.9 power factor). The diagnostic test results are tabulated in Table 2.

The IR, PI and tan delta values are normal and lie in the normal permissible range.

The estimated moisture content for all the three insulation sections was less than 1.74%. TTR, winding resistance and short circuit impedance were comparable to name plate value.

The oil test results were normal indicating healthy condition of the transformer oil. D.G.A results were normal indicating healthy internal condition of the transformer. Furan analysis shows higher level (1260 ppb) of furan content indicating deterioration of solid insulation.

From the diagnostic test data, it can be inferred that the transformer is generally healthy. However, in view of high furan content, it is recommended to repeat the oil testing after 06 months to monitor the trend.

As diagnostic testing is a continuous process and condition assessment is based on trend analysis, it is recommended to repeat the tests after Three years.

Case 3. 99MVA, 11/220kV, 3- Φ, 50 Hz Generator Transformer, 42Years Old History:

Transformer was in operation prior to testing. Transformer is running under 10% overload (Considering Generator rating 103.5 MW and Transformer rating 99MVA at 0.9 power factor). The diagnostic test results are tabulated in Table-3.

The IR values are low and tan delta values are high for a 220kV class transformer.

The estimated moisture content in the insulation system is 4.69%. TTR, winding resistance and short circuit impedance were comparable to name plate value.

The oil test results show higher concentration (114ppm) of ethylene gas even after recent filtration. The presence of the key gases methane, ethane and ethylene is an indication of probable overheating in the insulation. Furan analysis shows higher level (1510ppb) of furan content indicating deterioration of solid insulation. The diagnostic test data indicate that the transformer is not healthy. The dielectric losses and the moisture content are high in the transformer insulation system. The transformer oil indicates symptom of overheating. The furan analysis indicates deterioration of the solid insulation.

In view of this, it is recommended to withdraw the transformer from service and subject for thorough internal inspection. It is also recommended to extract three paper samples from the HV windings for conducting Degree of Polymerization test which is the confirmatory test to take decision to replace the transformer or not.

Table 2. 11/22 kV, 99 MVA Generator Transformer

Insulation section	IR (GW)	PI	Tan d (%)	Cap. (pF)
CH+CHL	2.00	1.64	0.747	19280.03
CH	--	--	1.029	3706.43
CHL	3.03	1.41	0.682	15576.29
CL+CHL	1.20	1.81	0.802	28693.45
CL	--	--	0.941	13118.74

Table 3. 11/220 kV, 99 MVA Generator Transformer

Insulation section	IR (MW)	PI	Tan d (%)	Cap. (pF)
CH+CHL	76.8	1.17	2.527	20258.52
CH	--	--	2.975	3886.08
CHL	111	1.26	2.424	16370.16
CL+CHL	53.3	1.21	2.891	30819.93
CL	--	--	3.419	14447.28

6. Conclusions

Based on field experiences the following conclusions are drawn.

Though there are various diagnostic tests for diagnosis of power transformer, one single diagnostic test does not give complete information about the condition of the transformer.

For meaningful analysis a comprehensive diagnostic program to be evolved and appropriate diagnostic tests to be conducted to assess the condition of the transformers.

Diagnostic testing and condition monitoring is a continuous process and based on trend analysis. The diagnostic tests need to be conducted periodically to monitor the trend in the parameters.

Diagnostic test results can be used for asset management decision support for different maintenance activities, repair, replacement and condition assessment steps.

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8. References

1. Chakravorti S, Dey D, Chatterjee B. Recent trends in the condition monitoring of transformers-theory, implementation and analysis.
2. IEEE Std. 62-1995 IEEE guide for diagnostic field testing of electric power apparatus-Part1 oil filled transformers, regulators and reactors. IEEE Xplore Digital Library; 1995 Dec 1.
3. IEC Std. 60076-18, power transformer Part-18: Measurement of frequency response. International Electrotechnical Commission (IEC); 2012 Jul.
4. Lifetime Evaluation of transformers. CIGRE Working Group 12.09; 1993.
5. Pradhan MK, Ramu TS. On estimation of elapsed life of oil-immeresed power transformers. IEEE Transactions on Power Delivery. 2005; 20(3):1962–9.