Transformer Diagnostic and Assessment Methodology

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Abstract: In this paper a methodology has been developed to use information derived from condition monitoring and diagnostics for rehabilitation purposes of transformers. The interpretation and understanding of the test data are obtained from the International Standards. In particular, the standardization of diagnostic and analysis techniques are being improved that will enable regular staff to more easily use the test results and will reduce the need for interpretation by experts.

I. INTRODUCTION

Under the deregulation policy of electric systems, each utility is trying to cut its cost, and the prevention of accidental loss is much more important than before. The capital loss of an accidental outage is often counted in million dollars for transformers. To meet the growing demand of the electric power grid and to maintain system reliable, significant changes may be required in the way an owner operates and cares for its transformers. It is usually not economically feasible to subject every aging transformer to a rigorous inspection and extensive testing. A promising industry strategy for a life-cycle management is to set monitoring priorities and to provide strategic direction for all transformers.

This is the reason why monitoring, analyzing or diagnostic systems became a fixed part for the supervision of transformers. With the help of the measuring techniques the technical diagnosis permits a standard evaluation, which goes beyond to summary the obvious signs of defects. Different monitoring methods, which cover the multiplicity of physical effects, are used from the measurement of the parameters over to the analysis of data and diagnostics of failure and at last to electrical, thermal, mechanical and optical techniques. Therefore the aim of the diagnostic methods is the evaluation of condition, the finding of the ageing causes, the recommendation of measures to improve the quality and the assessment of lifetime.

With these methods of technical diagnostics it is possible to record typical values, from which conclusions can be drawn about the future operational behavior of transformers. The conditions of transformers are the important inputs to the technical and economic models used to determine the most cost-effective alternative for operation, refurbishment or replacement.

II. CONDITION MONITORING AND DIAGNOSTIC

Once the FMEA process (failure mode and effect analysis) has established a priority list, diagnostic testing and condition assessment can establish a detailed asset management strategy. The importance of diagnostic methods can recognize which diagnostic parameters affect the transformer condition to a greater or lesser degree than other parameters. Transformer diagnostics is somewhat subjective, relying on (1) analysis of oil and paper; (2) power factor, capacitance and excitation current tests; (3) turns ratio, leakage reactance, winding resistance, frequency response, core insulation resistance, ultrasonic/sonic and vibration analysis. Fig. 1 shows the importance of different diagnostic methods for the estimation of transformer conditions.

![Fig. 1. Importance of different diagnostic methods for the estimation of transformer conditions](diagram)

There are some basic procedures by which an electric distribution utility can better judge the condition of its transformers: monitoring, diagnostics and maintenance. These basic evaluation steps in condition assessment provide the data for analysis and prioritization methods of maintenance. To be effective maintenance, testing and diagnostics must be applied in a careful coordinated way that uses the results from
International Standards to identify overall transformer condition and performance. To assess the overall condition of a transformer reliably, several monitoring techniques are used and are under investigation. Besides those traditional routine tests, there are some special tests including partial discharge measurement, frequency response analysis, infrared examination, vibration analysis, and degree of polymerization. These monitoring tests may detect problems such as local partial discharge, winding looseness and displacement, and mechanical faults, hot spot on connection, moisture in paper and aging of paper, as well as insulation degradation.

Interpretive discussions are also included to provide guidance on acceptance criteria. These activities may help to identify existing weaknesses or faults and also give some indication of expected service reliability and remaining life. Only the careful recording and plotting of the test results makes it possible to get the full information out of a test and to compare the values with those of previously accomplished tests and International Standards.

A. Dissolved Gas Analysis (DGA)

DGA has proven to be a valuable and reliable diagnostic technique for the detection of incipient fault conditions within liquid-immersed transformers. Insulating oils under abnormal electrical or thermal stresses break down to liberate small quantities of gases. The composition of these gases is dependent upon the type of fault. The most important diagnostic parameters are the individual and total dissolved combustible gas concentrations (TDCG) and their generation rates [1] - [5]. By means of dissolved gas analysis (DGA), it is possible to distinguish faults such as internal arcing, bad electrical contacts, hot spots, partial discharge, or overheating in oil, cellulose paper, tank, or conductors, etc.

The first step is to establish whether or not a fault exists by using the IEEE® method. Only when these levels exceed some threshold value, a fault is suspected. The second step is to determine the type of fault. Three methods are most commonly used: Duval Triangle, Roger Ratio Criteria and Doernenberg Ratio. Interpretation of fault conditions associated with gas concentration and combinations of these gases are also provided in [4]. The analysis can be made on line and is therefore a very important diagnosis tool.

B. Physical and Chemical Tests of Oil

An important part of the life extension of a transformer is the restoration of the insulating fluid quality. Physical and chemical tests [5] such as moisture test, interfacial tension test, oxygen test, acidity test, power factor test and dielectric strength test usually indicate oil conditions and operational characteristics.

Moisture in the transformer reduces the insulation strength by decreasing the dielectric strength of the transformer’s insulation system. The combination of moisture, heat, and oxygen is the key factor that affects the rate of cellulose degradation. High fluid acidity and high particle levels increase the capacity of the fluid to absorb moisture. The interfacial tension between insulating fluids and water is a measure of the molecular attractive force between unlike molecules at the interface. This test provides a means of detecting soluble polar contaminants and products of deterioration. The oil conditions can be remedied through various reclamation processes. Therefore, they are not indicative of overall transformer conditions, which would lead to replacement.

Additional tests [6] such as color, visual appearance, flash point, pour point, specific gravity and viscosity to detect the presence of deleterious products of oxidation or contamination in service-aged oils also seem appropriate. These tests and their significance are recommended for classification purposes and to determine the suitability for use of reclaimed oils. The analysis can be made off line.

C. Insulation Tests of Cellulose Paper

Furanic analysis, degree of polymerization [7] and CO₂/CO ratio tests [1] - [3] may indicate a problem with the paper insulation, if the transformer is overheated, overloaded, aged, or after changing or processing the oil.

As paper degrades, a number of specific furanic compounds are produced and dissolved in the oil. Furanic compounds are a family of molecules based on a furan ring structure. The most stable of these compounds is 2-furfuraldehyde, or 2-FAL. Thermal degradation of paper insulation could be monitored by furan analysis, especially under overheating conditions.

The presence of these compounds is related to the strength of the paper as measured by its degree of polymerization (DP). DP is the average number of glucose molecules making the cellulose chains. Cellulose (i.e., the main constituent of paper and wood) is a large linear polymeric molecule constituted of several hundreds of glucose units. The DP value decreases with time as the cellulose molecules break and fragment. The paper is assumed to age at a more rapid rate where the temperature of the paper and exposure to oxygen are the highest. Attempts have been made to relate the furanic content (2-FAL) of oil to the degree of polymerization (DP) of paper. When the DP test reveals a value of 200 or less, the paper is considered to have lost almost all mechanical strength, and the transformer has reached its end of life. The analysis can be made off line.

D. Infrared Thermograph Test

The monitoring of the temperature is usually no problem and is very important to evaluate and to assess the influence of many other parameters, e.g. the humidity content in oil or paper. An increase in the temperature can indicate cooling problems or higher losses in winding, core, bushing, arrester, tank, LTC, radiator, cooling system and oil pump and this can accelerate the ageing of the insulation system. An increase of about 6 to 8 K correlates with a doubling of the ageing processes [8], [9].

Thermography is a noncontact means of identifying thermal anomalies relating to electrical and mechanical components that are exhibiting an excessive heat loss. The self-emitted radiation in the infrared portion of the electromagnetic spectrum is measured at the target surface and converted to electrical signals. It is useful for detecting thermal problems in
a transformer, such as cooling system blockages, locating electrical connection problems, and for locating hot spots. The analysis can be made on line.

E. Power Factor Test

Power factor test is important to determine the insulation condition of transformers because it can detect the insulation integrity in winding, bushing, arrester, tank and oil. The condition of bushings can also be determined by measurement of capacitance [2]. Increased power factor may be the result of moisture or polar and ionic compounds in the oil. The ageing of bushings is caused by cracking of the resin bonded paper and inhomogeneous impregnation with insulating oil. The analysis can be made off line.

F. Capacitance Test

As the transformer ages and events occur such as nearby lightning strikes or through faults, changes in these measured capacitances indicate winding deformation and structural problems such as displaced wedging and support in winding and core. The insulation condition of bushings can also be determined by measurement of capacitance [8]. About 90% of bushing failures may be attributed to moisture ingress. The analysis can be made off line.

G. Excitation Current Test

The purpose of this test is to detect short-circuited turns, poor electrical connections, core de-laminations, core lamination shorts, on load tap changer (OLTC) problems, and other possible core and winding problems. Excitation current test [8] measures the single-phase voltage, current, and phase angle between them, typically on the high-voltage side with the terminals of the other winding left floating (with the exception of a grounded neutral). On three-phase transformers, results are also compared between phases. This test measures current needed to magnetize the core and generate the magnetic fields in the windings. The analysis can be made off line.

H. Frequency Response Analysis (FRA)

FRA [10] is used to help identify possible deformations and movements in the transformer’s core and coil assembly as well as other internal faults. This test is also helpful if a protective relay has tripped or a through fault, short circuit, or ground fault has occurred.

The basis of the FRA technique is that the impedance of the transformer is related to the construction and geometry of the windings. Deformations and movements have an effect on both inductance and capacitance that may be reflected on the resulting frequency response. Therefore, a change in the mechanical arrangement results in a change of the resonance frequencies. A change in the electrical performance due to partial discharges also results in a larger damping of the resonance frequencies.

Different aging mechanisms can be detected and identified at their respective frequency ranges. At the lower frequency range, shorted turns, open circuits or core grounds determines the dielectric loss; at medium frequency range, core movement or damage is the dominant contributor; and at the higher frequency range, winding displacement or damage is the mechanical defect. The analysis can be made off line.

I. Vibration Test

Vibration can result from loose core and coil segments, shield problems, loose parts, or bad bearings on oil cooling pumps or fans [2] of transformers. If wedging has been displaced due to paper deterioration or through faults, vibration will increase markedly. It may also show if an internal inspection is necessary for transformers. Information gained from the vibration test supplements ultrasonic and sonic (acoustic) detection and DGA tests. The analysis can be made on line.

J. Turn Ratio Test

The turn ratio (TTR) test detects shorts or open circuits between turns of the same coil, which indicates insulation failure between the turns [8]. All tap positions and all phases should be measured and may show the necessity for a further internal inspection or removal from service. The analysis can be made off line.

K. Leakage Reactance Test

Sometime it is called percent impedance test [8]. The test is performed in the field and compared to nameplate information, previous tests, and similar units to detect deformation of the core or windings due to shipping damage, through faults, or ground faults. The analysis can be made off line.

L. Core-to-Ground Test

The core-to-ground resistance test [8] can detect the default of a loose connection or can indicate if a spurious, unintentional core ground is the problem. It can also supplement DGA test that shows the generation of hot metal gases. To check for unintentional core grounds, remove the intentional ground between the core and the grounded transformer tank. If the intentional core ground is intact, the resultant resistance should be very low. Experience can help to locate the source of the problem. The analysis can be made off line.

M. Winding Resistance Test

Careful measurement of winding resistance can detect broken conductor strands, loose connections, and bad contacts in OLTC [8]. Results from these measurements may indicate the need for an internal inspection. This information supplements DGA if DGA shows the generation of heat gases. When comparing to factory tests, a temperature correction must be employed. The analysis can be made off line.

N. Ultrasonic and Sonic Fault Detection Tests

Partial discharge occurs in an insulation system when a local breakdown of the insulation medium causes a redistribution of charge within the system [8]. The impulse behavior due to partial discharges is influenced by the insulation medium. It comes further to a change of the original impulse (electrical, mechanical, acoustical, and optical) due to the propagation characteristics in the medium. The PD measurement systems
principally differ upon the bandwidth (narrow-, limited-wide or a wide-band system). With the knowledge of the impulse characteristic (spectrum and waveform of the PD impulse) different measurement methods for the apparent charge and localization of the PD source are possible [11]. A technique consists of electrical measurements in picocoulomb or in some countries in microvolt of radio frequency. The other method consists of acoustical measurements with an ultrasonic transducer.

This test can detect partial discharge (corona) and full discharge (arcing) inside the transformer. These devices also can detect loose parts inside the transformer that cause corona, sparking and arcing. Sonic testing can detect increased core and coil noise (looseness) and vibration, failing bearings in oil pumps and fans, and nitrogen leaks in nitrogen blanketed transformers. Information gained from these measurements supplements DGA test, and provides additional support information for de-energized tests such as core ground and winding resistance tests. The analysis can be made on line.

O. Visible Inspection and Internal Inspection

If an internal inspection is absolutely necessary, it must be completed by an experienced person who knows exactly what to look for and where to look. The analysis can be made off line. There are very few reasons for a visible inspection or an internal inspection as shown below:
- corona in bushings, arresters and all high voltage connections
- mechanical connections in conservator, bladder, breather, etc.
- increasing C2H2, C2H4 and C2H6 in DGA tests
- an additional core ground
- loose windings
- low CO2/CO ratio
- high Furans

III. CONCLUSION

The aim of asset management can be defined in this way that a maximum of information by a minimum of expenditure can be gathered from selected measuring and test methods by corresponding acquisition of International Standards. Standardization will make it easier to integrate data from sophisticated monitoring systems on transformers into asset management of transformers.

The use of the diagnostic model can improve the reliability and repeatability of the analysis of test data. It can also be used to extract information that is not available from the data directly. This systematic approach can not only help maintenance managers and inspectors, but also general managers to generate sound business cases for investments, to prioritize projects for O&M budgeting and to manage risks for the future.

REFERENCES