A REVIEW ON TRANSFORMER DIAGNOSTICS

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Abstract: This paper deals with the practical importance of the transformer diagnostic in the Electrical Engineering field. A review has been made on the modern development of this practical technology. Some empirical relation has been established by utilizing several practical data of the different transformers.

1. Introduction: A man becomes ill and then he goes to the doctor to get him cured. But, if he makes up check up of his health regularly, may be he can avoid many times the illness at which he suffers. Is it only true to human being? No, it is also true for equipments used in our technology. Transformers is a device on which cost effective supply of electricity mostly depends. Hence, to manage the life of transformers, to reduce failures and to extend the life of transformer, some measures are being adopted. This is in nut shell termed the transformer diagnostic. New diagnostic and monitoring techniques have already been developed for this. The life measurement of the transformer is made considering the following aspects:
a). Improvements over traditional time-based maintenance, e. g. condition based or reliability centered maintenance.
b). Maintaining a transformer in service.
c). Continuity of supply.
d). Priority of in-field repair and on line processing.
e). Minimizing the remedy actions and making the most effective remedial actions.
f). Comprehensive life assessment and/or extension program.

2.1. Classification in terms of condition: The transformers are in general classified into categories from the condition point of view.
a). Normal
b). Aged and normal
c). Defective
d). Faulty
e). Failed

When the transformer is normal, no remedial action is justified since there is no evidence of degradation. Normal aged transformer can not be totally defect free but it is usually taken acceptable. Defective transformer gradually deteriorates more unless remedial action is carried out. Faulty transformer may or may not be possible to improve condition by remedial action. Failed transformer can not be kept in service. Remedial action is required before the transformer can be returned to service.

2.2. Causes of Failure: Many failure occurs due to aging phenomenon:
a). Shortened life due to accelerated deterioration of components particularly bushing and OLTCS.
b). overheating of the HV winding coils due to poor cooling excessive circulating current.
c). Change in the condition due to ingress of water, particle contamination, aging of oil, loosening of contacts and clamping forces, vibration, unusual stresses etc.
d). Latent defects of design or defects during manufacture. These may require some other factors such as aging of insulation or increase in fault level to lead to a failure.
e). Water, oxygen, oil aging products and particles of different origin are agents of degradation, that can shorten transformer life. Significantly under impact of thermal, electric, electromagnetic field and electrodynamic stresses.
f). Three sources of excessive water may be developed in transformer insulation (i) Residual moisture in thick structural components not removed during dry out. (ii). Ingress from the atmosphere. (iii). Aging decomposition of cellulose and oil.
g). Cellulose, fibers, iron, aluminum, copper and other particles resulting from the manufacturing process are normally present in the transformer oil. These form sludge particles slowly during normal and overload operating temperature. The most dangerous particles are conductive mode particles, e. g. metals, carbon, wet fibers.
h). The present of bubbles may cause critical partial discharge (PD) to occur even at rated voltage. Bubble evaluation is a problem of a “hot transformer”
i). Dissolved water is also a problem of a cold transformer. The sudden ingress of free water may cause failure of the transformer immediately.

Temperature, water and oxygen are the main agents of cellulose degradation as well as oxidation of oil insulation decomposition is a chemical phenomenon. The three mechanisms of degradation hydrolysis, pyrolysis and oxidation act simultaneously. Hydrolysis is the decomposition of a chemical compound by reaction with water, pyrolysis is the decomposition or transformation of a compound caused by heat. Oxidation is the combination of the substance with oxygen.

In addition to the description of failure, it is to be identified what deficiency of condition allowed the failure to occur and whether condition monitoring or diagnostic tests enabled a prior fault to be detected.

3.1. Condition based diagnosis: The medical doctor studied the symptoms of the patient and then makes the diagnosis to cure him. Similarly, in case of transformer, diagnosis is to be made analyzing the condition of the transformer. Only the difference with the human cure can be described as follow. A human being is able to recognize when he or she is ill and then the doctor is consulted. But in case of transformer health it is essential to employ some form of monitoring to provide an idea of when to initiate the above process. In case of transformer monitoring, the following questions are to be answered.

a). Is it normal?
b). Is there a fault?
c). Is the fault serious?
d). Is it fit for service?
e). What is its reliability?

The first two questions are answered effectively by
i). Dissolved Gas Analyzer (DGA).
ii). Power factor/ Tan delta testing.

The last three questions actually makes the condition assessment. Examples of transformer tests, that might be used, include magnetizing currents, winding resistance, frequency response analyzer test (FRA), partial discharge (PD) and polarization spectrum (recovery voltage) measurements. The following main features of the transformer are mainly responsible for smooth running of transformer.

i). Electromagnetic circuit.
ii). Current carrying circuit.
iii). Dielectric system.
iv). Mechanical structure.
v). Cooling system.
vi). Bushing.
vii). OLTC.
viii). Oil preservation and expansion system.
ix). Protection and monitoring.

3.2. Condition assessment: The condition assessment is based on the following questions:

a). What is the level of contamination with water and particles? Shall we expect a substantial reduction in the dielectric margin at operating temperature?
b). What is the level of water contents in solid insulation? Shall we expect bubble evolution at over loading?
c). Shall we expect a substantial insulation surface contamination?

For answering the question (a) the following tests are required:
i). Measurement of oil relative saturation.
ii). Water heat run test considering change of water content and breakdown voltage with temperature.
iii). Conventional water in oil test.
iv). Particles in oil counting, metals in oil.
v). DGA in oil.
vi). Oil aging degree.
vii). PD- parameters- apparent change magnitude, pulse repetition rate, discharge power.

For answering the question (b), the following tests are adopted:
i). Water heat run test at on-line.
ii). Interpretation through oil relative saturation values at on-line.
iii). Estimation of water content using temperature response of power factor/tan delta and insulation resistance at off-line.
iv). Estimation of water content using polarization spectrum/ dielectric frequency response tests at off-line.
v). Oil interfacial tension test at off-line.

For replying to the query made in (c), the on-line tests are following:
i). PD measurement
ii). Particles counting.
iii). Oil aging by products.

Similarly, in the off-line the tests are made:
i). Temperature response of power factor/tan delta.
ii). Particles identification and oil tests.
iii). Dielectric frequency response tests.

4. Dissolved Gas Analysis: Dissolved gas analysis is the most important test in determining the condition of a transformer. It is the first indicator of a problem and can identify deteriorating insulation and oil, over heating hot spots, partial discharge and arcing. Dissolved gas analysis is made on the basis of the standard IEC60599 [3] and IEEEC 57-104^{TM} [4] standards. A four condition DGA guide to classify risks to transformers with no previous problems has been published in the standard IEEE C57-104^{TM}.

Table 2: Action Based on dissolved combustible gas

Condition	**TDCG level or highest individual gas**	**TDCG generation rates (ppm per day)**	**Sampling intervals and operating action for gas generation rates**	
			Sampling Intervals	**Operating Procedure**
Condition 1	<720 of TDCG of highest condition based on individual combustible gas from table 1	< 10	Annually- 6 months for extra high voltage transformer	Continue normal operation
		10-30	Quarterly	
		> 30	Monthly	Exercise caution. Analyze individual gases to find cause. Determine load dependence
Condition 2	721-1920 ppm of TDCG or highest condition based on individual combustible gas from table 1	< 10	Quarterly	Exercise caution. Analyze individual gases to find cause. Determine load dependence
		10-30	Monthly	
		> 30	Monthly	
Condition 3	1941-2630 ppm of TDCG or highest condition based on individual combustible gas from table 1	< 10	Monthly	Exercise extreme caution. Analyze individual gases to find cause. Plan outage. Call manufacturer and other consultant for advice.
		10-30	Weekly	
		>30	Weekly	
Condition 4	>4639 ppm of TDCG or highest condition based on individual combustible gas from table 1	< 10	Weekly	Exercise extreme caution. Analyze individual gases to find cause. Plan outage. Call manufacturer and other consultants for advice.
		10-30	Daily	
		> 30	Daily	Consider removal from service. Call manufacturer and other consultant for advice

4.1. Diagnosing transformer problems utilizing dissolved gas analysis and the Duval triangle: Michael Duval of Hydro Quebec developed Duval triangle utilizing a data base of thousands of DGAS and transformers problem diagnosis. This method has proved to be accurate and dependable over many years and is now gaining popularity. The following faults can easily be assessed by Duval triangle.

PD – Partial discharge.
T1 – Thermal fault less than 300^o C.
T2 – Thermal fault between 300^o and 700^o C.
T3 – Thermal fault greater than 700^o C.
D1 – Low energy discharge (Sparking)
D2 – High energy discharge (Arcing)
DT – Mix of thermal and electrical faults.

According to the percentage of CH_4, C_2H_4 and C_2H_2, the nature of faults can be diagnosed by Duval triangle.

4.2. Estimate of paper deterioration (On-line): When cellulose insulation decomposes due to overheating, chemicals in addition to CO_2 and CO are released and dissolved in the oil. These chemical compounds are known as furanic compounds or furans. The most important one is 2–furfuraldehyde. When furans become greater than 250 parts per billion (ppb), the oil should be reclaimed. In healthy transformers there are no detectable furans in the oil or they are less than 100ppb. In cases where significant damage to paper insulation from heat has occurred, furan levels have been found to be at least 1000ppb and up to 70,000 ppb.

4.3. Estimate of paper deterioration (Off-line): One of the most dependable means of determining paper deterioration and the remaining life is the DP test of the cellulose.. The cellulose molecule is made up of a long chain of glucose rings which form the mechanical strength of the molecule and the paper. DP is the average number of these rings in the molecule. As paper ages or deteriorates from heat, acids, oxygen and water, the number of these rings decrease. When the insulation is new, the DP is typically between 1000 and 1400. As paper deteriorates, bonds between the rings begin to break. When the DP reaches around 200, the insulation has reached the end of life. That means the transformer must be replaced.

4.4. Correlation between amounts of furans (in ppb) and estimated degree of polymerization (DP): From the practical data, some empirical relation can be established in connection with furans and estimated percentage f remaining life using systat software, the following correlation between furan and DP can be established.

$$y = 1303.5863 - 123.97843\lambda_n x_1$$ **(Logarithm of x)**

$$y = 1387.1026 - 149.26419\lambda_n x_2$$ **(Logarithm of x)**

The above logarithmic expression is found error free.

x_1 – 55^o C rise transformer 2FAL (in ppb)

x_2 – 65^o C rise transformer total furans (in ppb).

y – estimated degree of polymerization.

The empirical relation between the estimated percentage of remaining life (RL) and degree of polymerization (DP) is found

$$RL = -381.91574 + 72.053012\lambda_n DP$$ --------

(Logarithm of x)

The empirical relation between the estimated percentage of remaining life (RL) and concentration of furfuraldehyde is found

$$(RL)^{0.5} = a + bx_1^{0.5}$$

$$a = 10.598376$$

$$b = -0.092978923$$

$$(RL)^{0.5} = a_1 + b_1 x_2^{0.5}$$

$$a_1 = 11.10373$$

$$b_1 = -0.15201543$$

5. Detection of fault of transformers: For proper diagnostic of transformer, the most important is to develop the data bank of the same. The following data are essential.

1). Population of transformers (make wise).
2). Age of all the transformers.
3). Voltage wise transformer population.
4). Number of transformer problems in percentage form in relation to:

a). winding &core related.
b). DGA violation.
c). component related.
d). bushing related.
e). oil leakages.
f). age wise bushing related problems in percentage form.

Suppose, there is DGA problem, usually following repairs are required.

a). Fusion may be noticed at one location between OLTC head lower part and OLTC support bracket.

b). problem may be due to the provision of insulating washer against the conductive washer used for clamping the frame and the base foot near the HV terminal. As a result capacitive charging and discharging occur and that develops considerable heating of the order of more than 300^o C.

c). Presence of acetylene gradually increases. DGA data indicates a thermal fault more than 700^o C.

d). Top frame of core on the cooler side at LV bushing end of the tank had inadequate clearance with internal edge of the top location bolt housing.

e). If C_2H_2 is increased suddenly within fortnight, there is definite indication of arcing inside the transformer.

To draw full advantages of DGA proper sampling methods and regular sampling should be adopted. More importance is to be given to the trend of gas generation rather than the violation limits, levels of fault gases etc. DGA monitoring can save equipments from disastrous failure. Limitation of DGA is that, it can not point to the exact location of fault, it only indicates the probable components affected.

Frequency response analysis (FRA) is another way of detection of fault. FRA is primarily used for detection of deformation / movements of winding. FRA is carried out periodically for detection of deformation of smaller magnitude, when transformer experiences several short circuit forces. It helps in monitoring health and condition assessment of transformers. Impulse signal is applied and the corresponding winding responses are recorded using a performance digitizer. The results are transformed into frequency domain by Fast Fourier transform calculation.

A response function is obtained which is dependent almost entirely on the test object and is independent of applied signal and test circuit. The techniques now for FRA analysis is a sweep frequency technique which is suitable for site use and has a superior signal to noise performance at high frequencies. Sinusoidal signal output of approximately 2v rms from the frequency response analyzer is applied. One measuring input (R1) are connected to the end of a winding and the other measuring input (T1) is connected to the other end of the winding making tank earthed. The voltage transfer functionT1/R1 is measured for each winding for five standard frequency scans from 5Hz to 10MHz.

Recovery voltage measurement (RVM) is also another test method for assessing the moisture content in the transformer winding. HV bushings (400 KV & 220 KV) and neutral bushings are shorted and grounded. LV bushings (33KV) are also shorted separately and test voltage is applied at LV bushings. RVM test is conducted between LV and HV.

Partial discharge measurement is carried out with the help of M/s Scope using PD test kit of DDI, USA. Usually no PD actively is recorded inside the transformer except some PD activity at one point between OLTC and HV. The partial discharges are not generally taking place inside the transformer tank. Based on the evaluation of various test results health of the various components is summarized as follows:

Component	**Test Result**	**Condition assessment**	**Remarks & action required**
1. Winding paper insulation	a). Tan-delta value b). RVM (Moisture content) c). DGA (Violation of standard value of different gases) d). IR value. e). Furan content	It is to be assessed whether paper insulation is wet or dry.	Dry out is required or not. Internal inspection is required or not.
2. Oil	a). DGA test. b). Moisture content in oil. c). Colour	Oil quality is good or not	If it is not good, then replacement is required.
3. Winding Mechanical Integrity	FRA test vibration to be assessed.	Winding mechanical integrity is good or not. Winding clamping pressure & core tightness is normal or not.	Any repair is possible or not.
4. Transformer Core	DGA test, FRA test, Vibration assessment ratio test.	Transformer core, core insulation & core tightness are good or not.	Any repair or replacement is required or not.
5. Bushings	HV bushing tan delta value. LV bushing tan delta value	Whether the bushing are healthy or not.	If it is not healthy, capacitance & tan delta test is to be repeated using automatic tan delta test kit.
6. OLTC	Winding resistance at each tap, Ratio test. Oil colour check . Operation check.	Whether it is healthy or not.	This is to be taken up for rectification if it is found unhealthy.
7. Other components	PRD- healthy, Buchholz- healthy, OTI/WTI- calibration OK, Radiator Banks- Multiple point leakages, no blocking. Values- healthy, no leakages, Main gasket- healthy, Gasket of MBS- worn out, Turrets- healthy, Cabling- some cables cracked	All are healthy or not	If radiator bank is not healthy, it is better to replace the same. If PRD is found not healthy, modified kit is to be installed on PRD to avoid possible spurious tripping due to ingress of moisture. Cracked cables &damaged gaskets are generally replaced.
8. General appearance	Painting- whether repainting requires or not, Oil leakages- whether there are multiple leakages, Terminal Connection- It is to be checked by thermo- vision scanning. All foundations are OK or not, whether the oil pit needs cleaning.	Whether the general appearance is good or not.	The cases which are not found good are to carefully looked into.

A new technology has been developed for internal transformer inspections using a specifically designed borescope. The borescope can be utilized with oil inside the transformer, core, windings, connections etc. can be examined and photographed. If it is essential to go inside the transformer for repairs, technicians should know exactly what is the defect and what is to be done. This technology actually saves generating time and saves money. Instrument Technology, in a (ITI) has developed two inspection kits termed inspection Borescope kits. This is suitable to the unique needs of HV AC professional. The HV AC Borescope kit (model 131050) has been designed specially to view, photograph & recondition HV AC system.

Conclusions: An attempt has been made in this paper to review modern chemical and electrical diagnostic methods for proper transformer maintenance. DGA is the most widely used method for investigating incipient faults. A number of interpretation techniques are available to analyze fault types. Already there are IEEE and IEC standards for interpretation schemes. Furan and DP measurement are widely used for monitoring cellulose mechanical strength. Power Grid Corporation, India has already performed transformer study with the help of modern diagnostic technique of furan analysis. Main problem of DP estimation is that the cellulose samples are to be collected from operating transformers. The separation of aging and moisture impacts on the recovery voltage parameters is the most important problem which is yet to be solved. It is very difficult to consider any single method as the best method of transformer diagnostic. Still it can be claimed that DGA and furan analysis and at the same time FRA give much better idea about the condition of the transformer. Borescope technology is now in the stage of contracting service, but plans are being made by the developing company to make the instrument available for sale.

References:

1. Tapan K. Saha – "Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers" – IEEE, Transaction on dielectrics & Electrical Insulation, vol. 10, no. 5, October, 2003.
2. "M. Duval, Hydro Quebec (IREQ)" – "Dissolved Gas Analysis: It can save your transformer", - IEEE, Electrical Insulation Magazines, vol. 5, no. 6, November, December, 1989.
3. Mukund Hazeeb, S. K. Chand, B. N. De Bhowmick, M. M. Goswami, - "Dissolved Gas Analysis – Some case studies", Power Grid Corporation of India Limited.
4. CIGRE WG A2.18 – "Guide for Life Management Techniques for Power Transformers", 20th January, 2003.
5. United states Department of the interior Bureau of Reclamation – Transformer Diagnostics (Facilities Instructions, standards and techniques, vol. 3-31, June, 2003).
6. M. M. Goswami, Power Grid – Power Grid Data Bank of transformers and case studies.
7. Ramesh Bahri, N. S. Sudha & M. M. Goswami – Report on residual Life Assessment (RLA) of 315 MVA, 400/220/33 KV, BHEL make ICT at Durgapur substation.
8. SYSTAT 10.2 (www.systat.com) - SYSTAT Software Inc.