

A Review of the Monitoring & Diagnostic Methods of Oil Immersed Transformers

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Abstract— Transformer is vital equipment in a power system and to ensure reliable service and to plan for timely preventive maintenance suitable monitoring & diagnostic methods are required. This paper gives a review of the on-line monitoring & diagnostic and off-line diagnostic methods used for oil immersed transformers.

Keywords—Distribution Transformer; Dissolved gas Analysis (DGA); Furan analysis; Degree of polymerization of transformers; Sweep frequency response analysis

I. INTRODUCTION

The modern power system is mandated to provide reliable uninterrupted power supply and therefore, it is important to ensure the health and longevity of the transformer. There are several effective on-line and off-line diagnostic tools available today for the diagnostic the condition of the transformer which can identify incipient faults, estimate the remaining life, and ascertain maintenance strategy or to schedule the retirement & replacement of the transformer. This paper lists out the diagnostic / monitoring methods and reviews some of the commonly used techniques.

II. ON-LINE AN OFF-LINE DIGNOSTIC METHODS

The online monitoring / diagnostic methods measure the inputs continuously without affecting the operation of the transformer whereas the off-line methods need the planned shutdown of the transformer. Maintaining the Integrity of the Specifications

I. On Line monitoring

Table I shows the commonly used on line data monitoring methods. The measurement applicable for a particular transformer is selected based on the design, the application, the rating etc.

TABLE I ON-LINE MONITORING METHODS

Sl. No.	Transformer Subsystem	On Line Data Monitored
1.	Core & Coil Assembly	- Load current of Transformer -Terminal Voltage of Transformer -Winding Temperature -Top oil Temperature -Peak Voltage of surge (if any) -Short circuit current / surge current (if any) -Search coil based monitoring of internal faults -Dissolved gases in oil (DGA) -Core to ground current -Tank to ground current -Moisture in oil

		-Operating Noise -Partial discharge measurement
2.	Oil Preservation System	- Oil level in Tank/conservator -Nitrogen / gas pressure level -Moisture in oil
3.	Cooling System	-Ambient Temperature -Cooling system supply -Cooling fan status (ON/OFF) -Fan motor current -Status of oil pump (ON/OFF) -Oil pump motor current -Oil flow through the pump
4.	Bushings	-Capacitance & Tan delta -Leakage current -Bushing voltage through capacitive coupler
5.	On Load Tap Changer	-OLTC oil level -Dissolved gas in OLTC oil -Moisture content in OLTC oil -Current through OLTC (winding current) -Oil temperature of OLTC Diverter switch

II. Off-Line Diagnostic Methods

Off-line measurements are taken when a transformer is disconnected from service. The major techniques are given below. Most of the on-line monitoring parameters in 2.1 can be measured and analyzed off-line also, depending on the criticality of the installation and the type of diagnostic system envisaged.

- Insulation resistance and polarization index
- Capacitance & Tan delta measurement
- Oil break down voltage
- Polarization, Depolarization current (PDC)
- Recovery voltage method
- Optical spectroscopy
- Sweep Frequency Response Analysis (SFRA)
- Dielectric Frequency Response Analysis (DFRA)
- Impulse Frequency Response Analysis
- Transformer Impedance circle characteristics
- Frequency Domain Spectroscopy

III. MAJOR MONITORING AND FAULT DETECTION DIAGNOSTIC METHODS

The predictive maintenance and reliability centered techniques used frequently are reviewed here.

A. Dissolved Gas Analysis

Dissolved Gas Analysis (DGA) detects incipient fault conditions leading to future faults of transformer. Oil is a hydrocarbon molecule containing hydrogen and carbon atoms forming chemical bonds. Decomposition of Electrical insulation materials in transformer (paper & oil) generates gases. Table II, shows the various gases developed in the transformer oil.

TABLE II VARIOUS GASES DISSOLVED IN THE TRANSFORMER OIL

Gas	Formula	Temperature at which gas forms	Source of Gases
Hydrogen	H ₂	<150°C – Corona in oil >250°C – Thermal & Electrical faults	Partial Discharge Thermal faults Power Discharges
Methane	CH ₄	<150°C -300°C	Corona partial discharge low & medium temperature faults
Ethane	C ₂ H ₆	200°C – 400°C	Low and medium temperature faults
Ethylene	C ₂ H ₄	300°C – 700°C	High temperature Thermal faults
Acetylene	C ₂ H ₂	>700°C	High Hot Spot. Low Energy discharge.
Carbon Monoxide	CO	105°C – 300°C > 300°C complete decomposition	Thermal faults involving paper press board, wood etc.
Carbon Dioxide	CO ₂	100oC – 300oC	Normal aging Thermal fault involving cellulose
Oxygen	O ₂	Vacuum when temperature drops	Exposure to air, Leaky gasket Air breathing through Conservator

Gases dissolved in oil are analyzed by gas chromatography which separates each gas form other and directly measures their concentrations individually. The interpretation is carried out by the guidelines given in IEC 60599-2007-5 “mineral oil Impregnated Electrical Equipment in service: guide to the interpretation of Dissolved and Free gas Analysis” or IEEE C57.104.2008 – “IEEE guide for the Interpretation of gases generated in Oil Immersed Transformer”. or CIGRE guidelines or Dual triangle or a combination.

The concentration of various gases and the ratios of the concentration give conclusion regarding the type of fault/condition existing in the transformer.

TABLE III IEC 60 599-2007-5 METHOD

C ₂ H ₂ / C ₂ H ₄	CH ₄ / H ₂	C ₂ H ₄ / C ₂ H ₆	Fault Type
Not significant	< 0.1	< 0.2	Partial Discharge
> 1.0	0.1 – 0.5	> 1.0	Discharge of Low Energy (D ₁)
0.6 – 2.5	0.1 – 1.0	> 2.0	Discharge of High Energy (D ₂)

Not Significant	>1.0	< 1.0	Thermal Fault < 300°C
< 0.1	>1.0	1.0 – 4.0	Thermal Fault <300°C to 200°C (T ₂)
< 0.2	> 1.0	> 4.0	Thermal Fault > 700°C (T ₃)

When the values of CO > 500 PPM and CO₂ > 5000 PPM CO₂/CO Ratio of <3 indicates thermal cellulosic Degradation. (However, this ratio is not reliable for sealed type Transformers). A ratio 3 to 11 is considered healthy cellulose insulation.

• Interpretation by CIGRE SC15

The guidelines for interpretation of DGA in oil filled transformers as per CIGRE SC-15 is given in Table IV

TABLE IV DGA IN OIL FILLED TRANSFORMER AS PER CIGRE SC -15

Name	Ratio	Significant Value	Interpretation
Key Ratio 1	C ₂ H ₂ / C ₂ H ₆	>1	Discharge
Key Ratio 2	H ₂ / CH ₄	>10	Partial Discharge
Key Ratio 3	C ₂ H ₄ / C ₂ H ₆	>1	Thermal fault in oil
Key Ratio 4	CO ₂ / CO	>10 indicate over heating of cellulose <3 indicates degradation of cellulose by Electrical	Cellulose Degradation
Key Ratio 5	C ₂ H ₂ / H ₂	>2 (>30 PPM) Diffusion from OLTC or through common conservator	Applicable for in Tank OLTC

Evaluation of Faults by Rogers Ratio Method (IEEE C57.104.2008) Table VI gives the 6 different cases as per IEEE C57.104.2008

TABLE V DIFFERENT CASES AS PER IEEE C57.104.2008

Case	R ₁ CH ₄ / H ₂	R ₂ C ₂ H ₂ / C ₂ H ₄	R ₃ C ₂ H ₄ / C ₂ H ₆	Diagnosis
0	>0.1 to 1.0	<0.1	<1.0	Normal unit
1	<0.1	<0.1	<1.0	Low Energy Arcing – PD
2	0.1 to 1.0	0.1 to 3.0	>3	Arcing – High Energy Discharge
3	>0.1 to <1.0	<0.1	1.0 to 3.0	Low Temperature Thermal
4	>1.0	<0.1	1.0 to 3.0	Thermal <700°C
5	>1.0	<0.1	>3.0	Thermal <700°C

• Duval Triangle

Duval Triangle method plots the relative percentage of CH₄, C₂H₄ and C₂H₂ on each side of a triangle from 0 to 100%. 6 zones of faults are indicated in the triangle and a zone indicating mixture of thermal and Electrical faults (DT zone)

This graphical method follows the evolution of faults with time. Several software packages are available for DGA interpretations using triangle method. In an oil filled transformer the dielectric including cellulose and oil is continuously under electrical stress. The minor voids or

imperfections, conductive particles etc create localized stresses leading to partial breakdown of the dielectric. These discharges are very fast electrical processes and radiate electromagnetic waves of high frequency and ultra High frequency range. If such partial discharges are continuously increasing, it is a sure sign of a weak insulation, high stress concentration etc. These are signs of incipient faults. A healthy oil filled transformer can have PD magnitude of 10-50 PC or lower at operating voltage. The increasing PD levels signify the following:

TABLE VI SIGNIFICANCE OF VARYING PD LEVELS

100 – 300 PC	Presence of particles with small air bubbles. (This is typical after filling oil)
Up to 500 PC	This level in an oil barrier space may be considered as normal deterioration. (This does not affect the dielectric withstand level)
>1000PC	This can be caused by different degradation process a. 2000-4000 PC level generally signifies increasing moisture level. (PD inception level is reduced in the case) b. 1000-2000PC – indicates poor impregnation c. >2500pC is cellulose – will cause destructive ionization if prolonged d. >10,000 PC in oil- will cause destructive ionization if prolonged

The different methods of PD detection are shown in Table VII

TABLE VII METHODS OF DETECTION OF PD

No.	Type of Sensor	Advantages	Disadvantages
1.	Electric Direct Connection to the Test Tap of bushing or through high frequency CT on ground wires	Good Sensitivity	Sensor installation is possible only when transformer is de energized
2.	Electromagnetic Antenna	Easy to use	High disturbance of ambient
3.	Acoustic {Pie30 Accelerometer placed on Tank}	<ul style="list-style-type: none"> Easy to use Can detect acoustic Emission magnitude Approximate location of PP can be identified 	Low sensitivity (can detect PD>10,000 PC)
4.	UHF PD Probes (UHF Couplers)	Can be installed in drain valve or special flanges installed at factory on tank.	Less affected by ambient PD as the measurement is at UHF

B. Furan Analysis and Degree of Polymerization (DP) of Transformers

When the transformer operates the insulation ages (becomes weak) and it would ultimately lead to a breakdown causing the failure of the transformer. The number of glucose rings in the

cellulose is reduced when the kraft paper ages and this is called Degree of Polymerization (DP).

New Cellulose will have 1000-1200 glucose rings when a transformer is manufactured, what it is processed under drying some of the rings are broken down and hence the DP value of new transformer is about 950.

A DP value of 250 is considered as the end point of insulation life and at this point the insulation becomes highly brittle and the tensile strength of the cellulose becomes very low. [If left without disturbance some transformers may give extended useful service after reaching this point].

Measuring the DP value of the insulation paper can be done by taking sample from the transformer. However, this has several drawbacks like

- (a) The transformer will have to be switched off and opened to take a sample and
- (b) The sample collected may not be from the area of maximum aging i.e. the hot spot

The disintegration of the cellulose inside the transformer generates Furan Compounds which are dissolved in the transformer oil. Hence, it is convenient to analyze the transformer oil sample for Furan content to determine the aging (DP) of the insulation. This can be done without switching off the transformer. The Furan compounds generated by various types of reactions are different. The concentration of Furaldehyde (2FAL) in the oil is due to the overheating of the paper and the maximum aging is at the location of hot spot. The drawback of this method is that the measurement gives an average of the Furan Concentration and therefore, the same at the hot spot may be much higher. The concentration of Furans is measured by High Pressure Liquid Chromatography. The concentration of various Furans indicate different types of stresses as shown in Table VIII

TABLE VIII CONCENTRATION OF FURAN WHICH INDICATES DIFFERENT TYPES OF STRESSES

Sl. No.	Type of Furan	Symbol	Nature of Stress
1	5 – Hydroxymethyl 2 Furfuraldehyde	5 H ₂ F	Oxidation
2	Furfural Alcohol	2 FOL	High moisture
3	2 Furaldehyde	2 FAL	Overheating
4	2 Furyl Methyl Ketone	2 ACF	Lightning
5	5 Methyl – 2 – Furaldehyde	2 M ₂ F	Local Severe Overheating

The concentration of 2 FAL value is used by different authors to estimate the DP value and the results of DP values corresponding to the concentration of 2 FAL values as per “chengdong” are given in Table IX

TABLE IX CORRESPONDING TO THE CONCENTRATION OF 2FAL VALUES AS PER “CHENG DONG”

Sl. No.	FURAN (2 FAL) PPM	Estimate DP Value
1	0.01	1003
2	0.10	717
3	0.50	517
4	1.0	431
5	2.5	318
6	5	232
7	10	146
8	15	95

C. Sweep Frequency Analysis (SFRA)

The transformer is a complex RLC network and any form of damage, inconsistency or deformation anywhere in the active

part results in change of this RLC circuit. When different frequencies are applied to the transformer, the RLC network offers different impedance path and the transfer function at each frequency is a measure of the effective impedance of the network. Any geometrical change alters the RLC network which in turn changes the transfer function at different frequencies thereby highlighting the area of concern.

When a new transformer is manufactured and passes the tests, the SFRA of the transformer can be taken for using as a reference (signature). This can be compared with SFRA measurement in future, for example, after transportation to site, after installation, after an incident like a tripping, earthquake etc.

If SFRA of a transformer is not available, detection of abnormalities can be tired in any one of the following methods.

- Checking the SFRA of another transformer of the same design from the same batch of production, if available.
- Comparing SFRA of other phases of the transformer

SFRA test is done typically between 20 Hz to 1 MHz
 The number of tests for various types of transformers is as per Table 10

TABLE X NUMBER OF TESTS FOR VARIOUS TYPES OF TRANSFORMERS

Sl. No.	Type of Transformer	Number of Tests
1	2 Winding Transformer	15
2	Auto Transformer without tertiary	18
3	Auto Transformer with tertiary	33
4	3 Winding Transformer	36

The response of SFRA for different range of frequencies can pin-point the region / component of concern / problem. A guideline for the interpretation of probable reasons is given in Table XI.

TABLE XI GUIDELINE FOR THE INTERPRETATION OF PROBABLE REASONS

Sl. No.	Frequency Range	Component	Probable reasons for deviation of SFRA
1	≤ 2000 Hz	Main Core Main Winding Inductance	Core deformation, core joints becoming loose, open circuit of winding, shorted turns, Residual Magnetism
2	2 KHz – 20 KHz	Shunt Inductance	<ul style="list-style-type: none"> • Movement between winding and clamping structure • Loose clamping
3	20 KHz – 400 K Hz	Main Windings	Deformation within the main or tap windings
4	400 KHz – 1 M Hz	Main windings Tap windings Internal leads	<ul style="list-style-type: none"> • Movement of the main & Tap winding • Ground Impedance variation

B. Dielectric Frequency Response Analysis

The traditional method of measuring the moisture content of the oil in the transformer does not give the oil absorbed in the cellulose insulation. This is because when the transformer is loaded, and the winding temperature rises, the moisture comes out from the cellulose and absorbs in oil. When the load comes down the temperature comes down and the moisture returns back to the cellulose. Though the moisture equilibrium curves can be used to determine the moisture in cellulose, the results are highly dependent on temperature of the oil and it may give inaccurate results.

The dielectric frequency response is an advanced technique to ascertain the insulation of moisture. The frequency response of a dielectric is a unique characteristic of a particular insulation system. The increased moisture content changes the dielectric model and the frequency response.

By measuring the dielectric response over a wide frequency range, the moisture content of the insulation can be determined and the condition assessed.

The test is normally done between the High Voltage and Low Voltage winding of a transformer by applying frequencies from 0.001 Hz to 1000 Hz to measure the dissipation factor. The voltage used for testing is up to 200 volts. The moisture content and aging is revealed at higher frequencies. The shape of the curve shows the relative moisture levels and a typical response pattern is shown in Figure-1

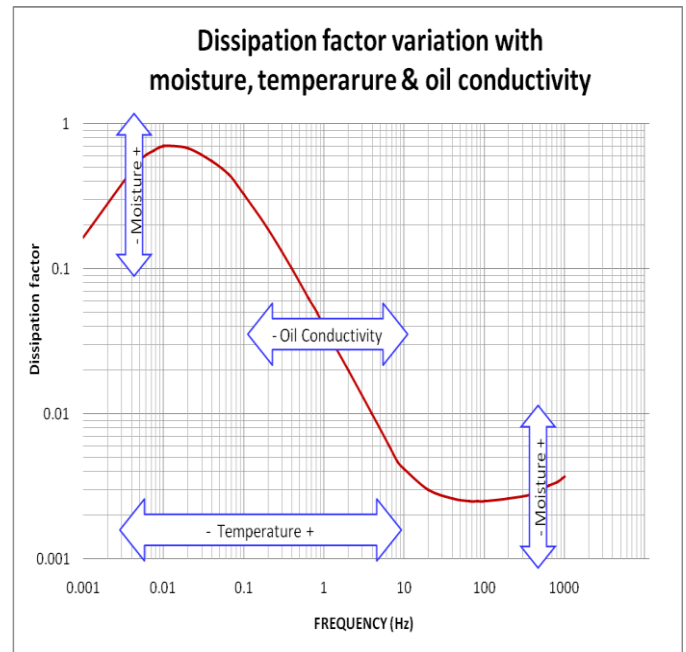


Figure I Dielectric Frequency Response Pattern

C. Recovery Voltage Measurement (RVM)

A step voltage is applied to the transformer and a charging current flow. Then it is short circuited during the discharge time and then it is open circuited. A recovery voltage appears across the terminals. This is caused by the unfinished polarization.

The recovery voltage is measured by changing the charging time. The discharging time is kept as 2 times charging time for all measurements. These measurements at different charging times give the polarization spectra.

D. Optical Spectroscopy

The absorbance of ultra violet (UV) light of fresh oil is low. When the oil ages, the absorption of UV light goes up. The absorption is the highest between the wavelengths of 200-380 nm. Figure 2 shows the pattern of absorbance of UV light in fresh oil and service aged oil.

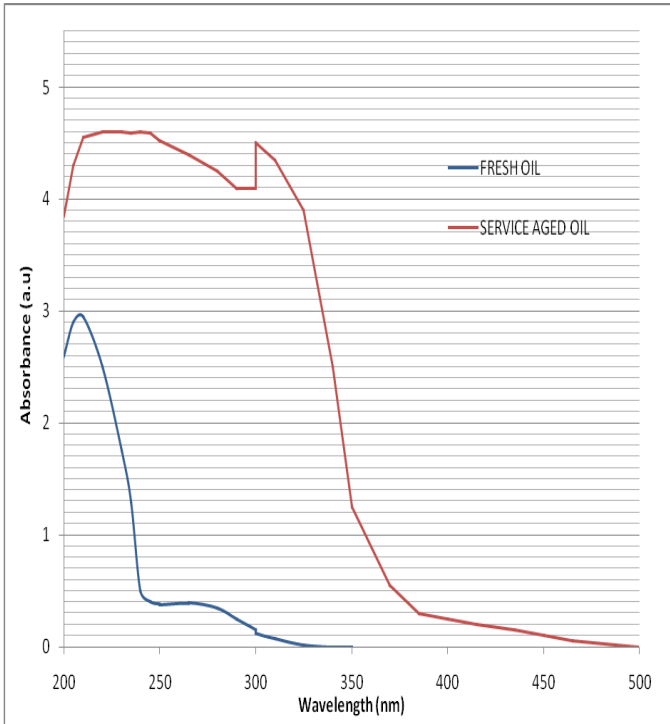


Figure II Absorbance Of Ultra Violet (Uv) Light In Fresh Oil And Aged Oil

E. Search Coil based on-line diagnostics of transformer internal faults

Internal faults related to transformer windings such as inter turn faults and winding displacement changes the inductance of the winding when compared to the inductance at healthy conditions. If search coils are installed during manufacture, the induced voltages in the search coils can be analyzed to monitor the changes of the inductance. The faulty winding and location of the defect can be detected.

F. Polarization and Depolarization Current Test (PDC)

The polarization current of a transformer winding is a function of the geometry, oil properties & aging. Initial value of polarization current is determined by the oil conductivity. The depolarization current comes down with the elapse of time when compared to polarization current depending on the moisture. A typical pattern of the polarization and depolarization current is shown in Figure 3

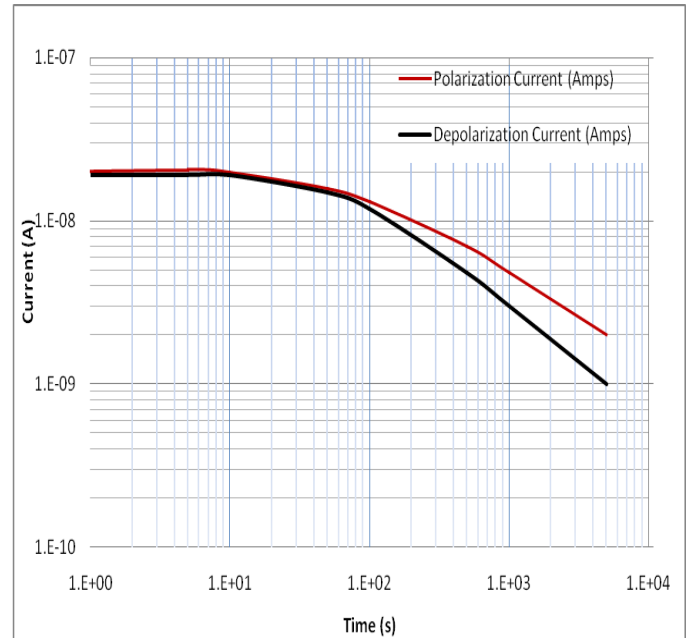


FIGURE III POLARIZATION & DEPOLARIZATION CURRENT WITH HIGH MOISTURE IN CELLULOSE ($\approx 1\%$)

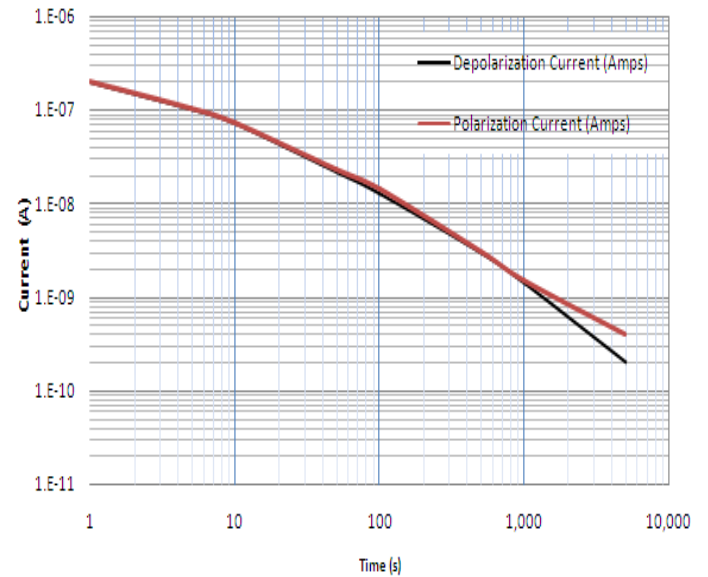


Figure IV Polarization & Depolarization Current With High Moisture In Cellulose ($\approx 5\%$)

G. Embedded wireless monitoring and Fault diagnostic system

On line monitoring is possible for diagnostic methods including dissolved gases in oil, oil temperature, winding temperature, oil level, core temperature, cooler operation etc. Embedded system is used and the data is transmitted by RF transmitter to the control room. Schematic diagram of a typical wireless monitoring system is shown in figure 5

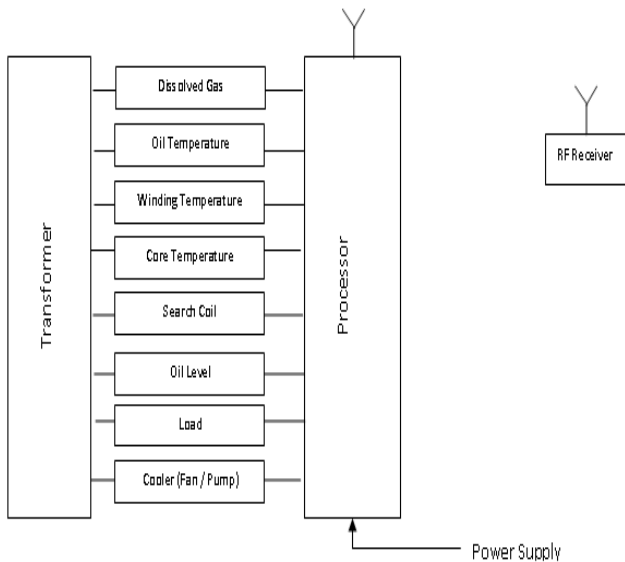


Figure V Schematic Of Embedded Wireless Monitoring System

H. Frequency Domain Spectroscopy (FDS)

When a dielectric material is subjected to an Electric field, the electrical dipoles are oriented in the direction of the field. This orientation has a time delay which depends on the material, the moisture content and the geometry of the insulation. The frequency range used for analysis is normally 0.001 Hz to 1000 Hz.

I. Monitoring of temperature

Monitoring of the ambient, winding, oil and tank body temperatures can identify any excessive temperature above the permissible values. If the temperature exceeds the designed value applicable for the class of insulation, the aging becomes rapid and also this can be an indication of defects / faults leading to failure.

The top oil temperature and winding temperature can be monitored on-line and tools are available for remaining life estimation & load management.

On-line thermograph can monitor and detect temperature gradients on tank surface. The gradients can be compared to the tested values under defined operating conditions to take suitable action.

J. Load Monitoring

The loads of each phase of the primary, secondary, and other windings (if applicable) is monitored for load management by including the data of ambient temperature, oil temperature and winding temperature. Where Fans and pumps are used for transformer cooling, the input currents to these devices and the operation can be monitored.

K. Vibration Monitoring

Excessive vibration is often an indication of abnormal operation of fan, pump, loose coils, loose clamping, shorted turns etc. which can lead to a failure.

For comparison, vibration measurement results of new transformer after installation is necessary.

L. Monitoring of the functioning of bushings & on Load Tap Changer

The operation of condenser bushing is monitored by measuring the current through the test tap in operation. Change in tan delta and the charging current are monitored to detect the abnormality / fault of the bushing.

- In oil insulated on-load tap changer, (OLTC) the contact temperature can be indirectly monitored by measuring the temperature of the oil in the OLTC compartment. This temperature is compared with the oil temperature of the main tank.

III. FUZZY INFORMATION APPROACH TO INTEGRATE RESULTS OF DIFFERENT DIAGNOSTIC METHODS

Good experience is essential to interpret the results of many of the diagnostic techniques with accuracy. Artificial Intelligence (AI) tools can be applied to arrive at the most probable interpretation using the Fuzzy information approach. Information about the relationship between different fault types and diagnostic results is made into a fault tree.

- This approach consists of the following:
- Select the diagnostic method.
- Initiate the probability of all conclusions showing probabilities between 1 and zero
- The measurement results are then applied to the fault tree
- Perform conflict resolution
- Calculate the basic assignment for all nodes of the fault tree
- Repeat the procedure for all measurement method and aggregate the results

IV. CONCLUSION

A review of the important monitoring and diagnostic methods used for oil filled transformers is presented in this paper. Guideline values of Dissolved gases, partial Discharge and Furan (2FAL) levels for interpretation of results are presented. The paper further presents the principles of techniques like SFRA, DFRA, RVM optical spectroscopy, PDC, Frequency Domain spectroscopy etc.

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