International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

# Transformer Condition Monitoring and Digitally Enabled Lifecycle Management: A Utility-Based Perspective

**Imtiyaz Barkatali Surani**

Sr. Transformer Professional – Electrical Engineer, Transmission Substation Commissioning, Dubai Electricity & Water Authority – UAE
Emai: *surani_imtiyaz5[at]yahoo.co.in*

**Abstract:** ***Power transformers are key components in electrical network (Generation, Transmission and Distribution). Failure of power transformers can cause outages, costly repairs, and significant economic and time losses. Moreover, the interconnected grid sub-station suffers the challenges of handling the increased power demand complexity aiming towards the system agility & reliability. Hence, it is worth detecting incipient insulation defects inside the transformers at the earliest possible stage and then taking appropriate potential remedial action to avert a more serious failure. Power transformers are critical to power systems, and their unexpected failure can lead to costly outages. This paper presents an in-depth analysis of online transformer condition monitoring techniques and their integration with digital technologies across the transformer lifecycle. By examining electrical, thermal, mechanical, and chemical diagnostic tools, including Dissolved Gas Analysis (DGA), partial discharge detection, and vibration analysis, this study highlights how artificial intelligence, and smart sensors can enhance fault prediction and maintenance efficiency. Furthermore, the paper discusses digital system architecture, including analog-to-digital conversion and SCADA integration, offering a utility-based perspective on implementing proactive maintenance strategies. These insights underscore the transformative potential of digital monitoring systems in reducing operational risk and extending transformer life. This is possible by using the latest state of the art technologies, various technical tools and industry leading innovative practices. The electrical system is going through a fundamental transition as the utilities shift from conventional analog methods to digitization. To effectively monitor transformer assets, we need to monitor parameters by using modern intelligent sensors to which we have access. These parameters can then be converted into a probability of failure through the use of a digital transformer engineering model based on IEEE and IEC standards. This type of transformer embedded with digital sensors and supported by intelligent network is termed as "SMART TRANSFORMER". Smart transformers are becoming an integral part of the new electricity grid, which provides all the digital inputs & control parameters at the SCADA (Supervisory Control & Data Acquisition) system through HMI (Human Machine Interface) screen for pro-active action towards proper regulation of voltage and other important parameters. The use of these transformers is gaining popularity both at the transmission and distribution level. These transformers are equipped with intelligent electronic devices, smart monitoring and automated diagnostics features.***

**Keywords:** transformer monitoring, smart transformer, asset management, condition diagnostics, digital system

## 1. Introduction

The reliability of the power transformer insulation system is a major concern point for electric power utilities. The aging process of the impregnated insulation system (insulation paper, press board, wood & oil) may take place accompanied with degradation in the insulating characteristics. This degradation may lead to a complete failure in the transformer insulation system and consequently, a serious problem can take place which can lead to more than simple monetary damage. The ability to predict the ageing behavior/state of power transformer is therefore a key feature for safe operation over decades. This paper aims to examine current practices in online transformer condition monitoring and explore how digital technologies can be effectively integrated across the transformer lifecycle to enhance reliability, operational efficiency, and decision-making in utility networks.

Condition assessment, monitoring and diagnostic techniques provide accurate health conditions of the transformer and help users to reduce the risk of in-service failures and forced outages. These processes are often above and beyond routine maintenance work completed on a regular basis to keep the transformer operational. IEC standard 60076-1 [1], CIGRÉ Technical Brochure 323& 343 [2] & [3] and IEEE Standard C57.104 [4] provide recommendation on supply and provision of various condition assessment, monitoring and diagnostic tools along with new transformers.

Further, the electrical network is embracing major disruptive changes. The substantial growth in all categories is making the situation a bit complex due to the huge approach of RE and its integration with the ever-increasing load demands. Electrical production has been shifting towards renewables, and the trend is now accelerating with pressure mounting on decarbonization to fight climate change. The latest data from the international energy agency indicates that renewables accounted for 25% of the world's electrical production in 2018.

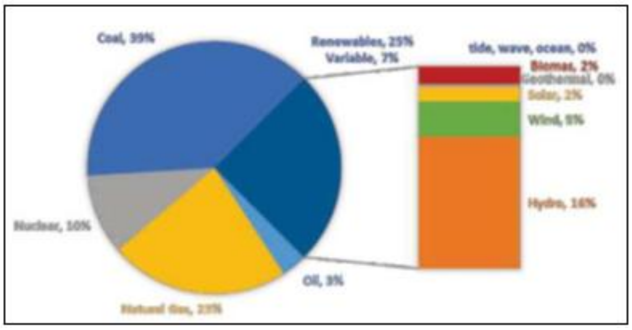


**Figure 1:** World electricity production from 2018

The interconnected GSS (Grid Sub-Station) suffers the challenge of handling this complex power that flows in different directions aiming towards the system availability for 24×7 with multiple and multipattern generators, modern concept of prosumers with DER (Distributed Energy Resources). The other multi-bound practical issues make the situation still critical, like running the system with existing old-ageing infrastructures, reluctant approach of end users on the acceptance to the advanced technologies, their over-conscious approach to the techno economical aspects.

Over the years, we have come across many of the technological adoptions on transformers, like use of low loss amorphous core, use of bio-degradable oil, use of modern and improved conductors for highly efficient applications. But the need of the time is to improve the system's availability based on quality and reliable power to the end user. These all depend upon in-time data handling of the system parameters to get actionable information for automated decision making towards operation and maintenance of the assets under control.

Moreover, in the present era towards adaptation to smart grids, the data availability and communication link from all the available primary devices need to be integrated to the automated system. Transformers, the vital primary device among all, must be inter-connected to the smart system loop for greater visibility and best control in terms of monitoring, supervision and operation. The basis behind the best concept of handling of this device depends upon the management of AI (Analog Inputs) and conversion of the same to scalable DI (Digital Inputs) for SCADA system. So, in totality, the transformer, equipped with sensors for the preparation of AI and subsequent DI, shall be termed as smart digital Transformers.

The transformer condition is monitored continuously and evaluated for appropriate asset management decisions. Asset management needs to be both cost effective and reliable, sensing solutions that provide asset managers with actionable intelligent data. The focus shall be on the development of an electrical system with monitoring and supervising of the electrical parameters that can control the maximum availability of electrical power to consumers with quality, reliability, safety and security.

The significance of this study lies in its holistic approach, combining traditional monitoring techniques with digital intelligence to enable proactive maintenance and asset optimization, which are essential for modern utilities facing evolving energy demands and infrastructure challenges.

## 2. Online Condition Monitoring

Various diagnostic and condition monitoring techniques have been in existence for many years and are being practiced by utilities. Condition monitoring techniques like Dissolved Gas Analysis (DGA), Capacitance and Tan Delta measurement of Bushing & Winding, Winding Resistance measurement, Turns Ratio Test, magnetization/ Excitation current test, Frequency Response Analysis (FRA), PD measurement based on Acoustic principle or UHF Technique, On-line dissipation factor monitoring of Bushings, Polarization Spectrum or Recovery voltage (RVM) measurement, On-line hydrogen monitors, On-line moisture content measurement and Online temperature monitoring- direct measurement through fiber optic sensors for continuous monitoring of hot spot temperature are some of the latest state of the art Condition monitoring and diagnostic techniques being practiced by some of power utilities to assess the health of Power transformers.

But many of these tests shall be performed during transformer in offline condition; However, this paper focuses on the monitoring of the condition by various thermal, electrical, mechanical and chemical parameters of transformer during online.

### 2.1 Thermal Properties

Thermal analysis of the transformers can provide useful information about its condition and can be used to detect the inception of any fault. Most of the faults cause change in the thermal behavior of the transformer. Abnormal conditions can be detected by analyzing the hot spot temperature. The life of a transformer significantly decreases when the hotspot temperature continuously exceeds 110 degree C [5]. Predicting the HST can be done by two techniques. The first technique uses the artificial intelligence techniques such as Artificial Neural Network (ANN) to predict the HST [6]. The second technique develops a thermal model to predict the thermal behavior of the transformer [7–9].

#### 2.1.1 Online Temperature Monitoring

As shown in figure-2 using following temperature measurements, we can determine many operational parameters and detect incipient faults before they lead to outages.

- Transformer main tank top and bottom oil
- Windings and core using fiber optic probes
- Radiator inlets and outlets
- Ambient temperature
- OLTC compartment oil temperature

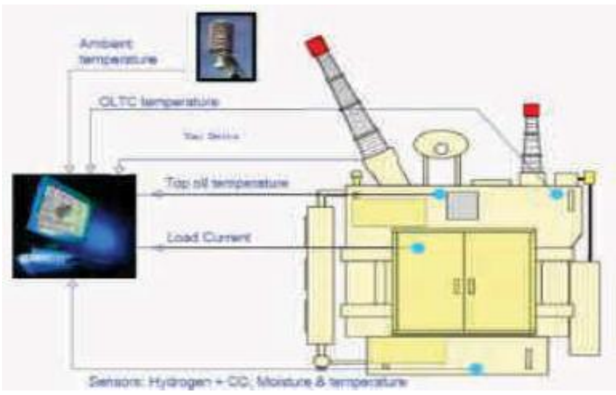


**Figure 2:** On-line sensor module for temp. monitor

From the measurement of the oil temperatures and load, one can determine by digital simulation how hot the windings will get given the factory data for the transformer. The winding temperature in turn determines the aging rate of the paper insulation inside the transformer; the hotter it gets the faster it ages. A fiber optic temperature sensor can be used to monitoring the temperature directly in the windings in order to provide a more accurate picture and serves to confirm that the calculations are correct.

Based on the measurement of the oil inlet and outlet temperatures one can determine the efficiency of the cooling system and detect any degradation that may occur over time. This can happen for example if there is buildup of sludge in the radiator that is restricting oil circulation.

The ambient temperature can be used to determine the maximum load the transformer can support without exceeding its design temperature and suffering premature aging due to overheating.

By monitoring the temperature of the tap changer tank relative to the main tank we can determine if there is a malfunction of the diverter switch; indeed if it gets much hotter than the main tank we have a clear indication that the tap changer is bleeding energy while switching tap positions. This should not occur and the tap changer should be overhauled before the transformer fails catastrophically.

### 2.1.2 Infrared Temperature Analysis

Infrared analysis should be conducted annually while equipment is energized and under full load, if possible. IR analysis should also be conducted after any maintenance or testing to verify the connections are proper. IR results performed during factory heat run test, can be used as a baseline for comparison at site for Transformer Main Tank, Bushings, Radiators and Cooling Systems.

Unusually high external temperatures or unusual thermal patterns indicate problems inside the transformer such as low oil level, circulating stray currents, blocked cooling, loose shields, tap changer problems, etc. Thermal patterns of transformer tanks and radiators should be cooler at the bottom and gradually warmer ascending to the top. The IR image in below figure-3 shows that the cold left radiator section is blocked or valve in off position.

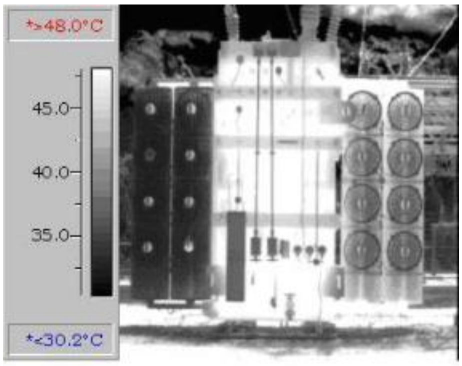


**Figure 3:** IR image showing blocked radiator

## 2.2 Electrical Properties

### 2.2.1 Partial Discharge analysis

PDs occur when the electric field strength exceeds dielectric breakdown strength of a certain localized area, in which an electrical discharge or discharges partially bridge the insulation between conductors. The dielectric properties of the insulation may be severely affected if subjected to consistent PD activity over long periods of time. This may lead to complete failure if the PD activity remains untreated [12]. PD can be detected and measured using piezo-electric sensors, optical fiber sensors [13], and Ultra High Frequency (UHF) sensors [12, 14, 15]. On site PD measurement is often affected by strong coupled electromagnetic interference that increases the difficulty of extracting PD signals without noise. The most common methods for PD de-noising are the usage of the Wavelet Transform [16, 17], the gating method, the directional sensing [19], Fast-Fourier-Transform (FFT), Low-pass filtering, notch-filtering, T-F Map, 3PARD etc. PD measurement was used extensively for the condition assessment of the transformer insulation due to the fact that large numbers of insulation problems start with PD activity [14, 18, 19].

Partial discharges can also occur in the winding insulation layers and lead to the same type of failures in the core of the transformer. One of the challenges with detecting partial discharges is to determine their origin and distinguish them for high frequency perturbations coming from the network outside the transformer. The analysis of partial discharge data lends itself well to smart machine learning algorithms that can interpret the data based on previously observed patterns. The analysis of partial discharge data is a relatively new aspect of transformer monitoring.

PDs in transformers can be measured offline, online, and/or a continuous monitoring system can be installed to monitor PD's time-trend pattern. When PD activities are initiated, the resulting energy is transformed into mechanical, electrical, thermal, and chemical energy. Different detection methods like electrical, UHF, chemical and acoustic can detect PD in transformers.

#### 2.2.1.1 Conventional method (used during FAT):

The conventional method gives the value of apparent charge in pico-Coulomb (pC), where calibration is performed at bushing terminals. This serves as the acceptance criteria in routine testing of transformers as PD's value (in pC) is an insulation quality indicator.

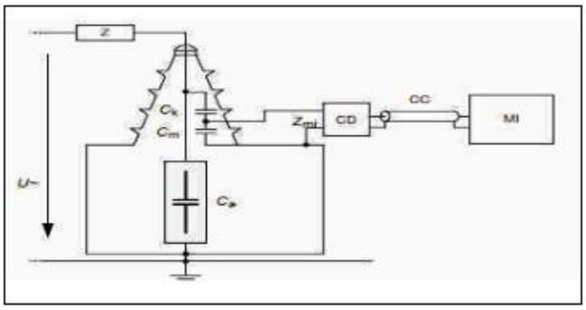


**Figure 4:** Test circuit for measurement at bushing tapping

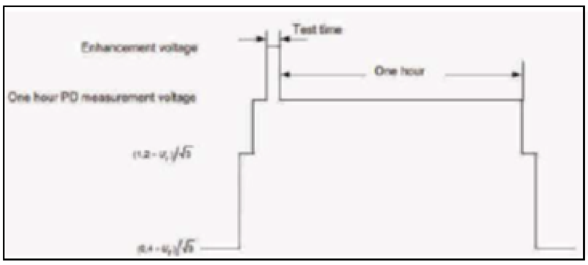


**Figure 5:** IVPD test sequence

Acceptance criteria for the IVPD test as per clause no. 11.3.5 of IEC 60076-3 are as under:

- No collapse of test voltage occurs


Paper ID: SR25705185124 DOI: https://dx.doi.org/10.21275/SR25705185124

- PD ≤ 250pC during the 1-hr period
- no rising PD-trend during the 1-hr and no increase by more than 50pC
- no sudden sustained increase during the last 20 min of the test
- PD ≤ 100 pC at 1,2Ur/√3 after the 1-hr period

Below actions are recommended during the investigation of external PD sources:
- Conducting particles on the bushing surface
- Non-shielded sharp points on the transformer or in the test circuit
- Bad connections on shielding electrodes
- Unearthed metallic objects close to the transformer
- Noise or internal PD from the voltage source
- Electric discharges in the air (corona) generated by sharp electrodes by using a portable ultra-sonic detector.

PD pattern characteristics that to be analyzed are:
- Phase position of the PD signal
- The symmetry of the PD signals during the positive and negative sine wave
- Number of PD signals per cycle
- Reproducibility of the PD pattern

Interpretation and screening of the correct PD pattern from the real PD pattern results require experience and a strong interpolation capability. PD patterns are based on physical electric discharge processes in the weakness or defects. They can be detected in any insulating system. Few typical PD sources and PD pattern are described in reference [20].

**2.2.1.2 Ultra High Frequency (UHF) Method:**
The UHF method is advantageous for onsite/online monitoring of transformers because UHF sensors do not require high-voltage coupling capacitors or bushing-tap measurement. They are less affected by external PD sources (e.g., corona at bushing outdoor connection) due to different shielding effects and filtering methods available [21]. Electromagnetic signals travel directly through the transformer oil towards the tank. Faraday shielding of the transformer tank and low-pass filters provided by HV bushings shield the UHF PD measurements against external disturbances [22].

This method uses the ultra-high frequency range (300MHz – 3GHz) for the detection of PD. Such a large bandwidth enables this method to have distinctive PD pulses and easy rejection of low-frequency noise and/or external disturbances.

Sensors can either be placed at existing drain-valves (DN50/DN80 drain-valves) using UHF drain-valve sensors or retrofitted on dielectric-windows in new transformers in the factory, using UHF disk/plate type sensors [21]. CIGRE Working Group WG A2-27 recommends in brochure 343 to provide DN50 valves at all transformers for later fitting of UHF probes [3]. The CIGRE Technical Brochure 662 [23] recommends installing dielectric windows in newly manufactured transformers for mounting UHF sensors; however, it does not mention where to position them. A UHF disk/plate sensor on the dielectric window is shown in Figure - 6.

**Figure 6:** UHF disk sensor on the transformer tank

PD sources can be localized by using this method. The optimal configuration requires four sensors in cross diagonal arrangement to triangulate PD source, as shown in Figure - 7 [24].

PD measured by this method can't be expressed in pico-Coulomb (pC) as calibration of charge to pC is not possible in the UHF detection method. Also, UHF sensors are limited by the availability of dielectric windows or drain-valves in a transformer.

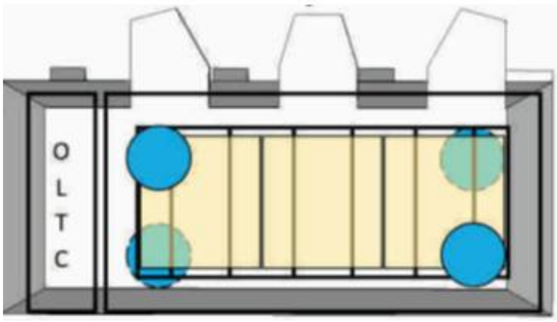


**Figure 7:** Optimal UHF sensor positions to locate PD

**2.2.1.3 Chemical Method (DGA):**
This method involves the dissolve-gas analysis of transformer oil, which is an indirect detection of PD in transformers. PD activity is usually indicated by increasing concentrations of its characteristic failure gases, H2, and CH4. Although this method doesn't quantify and identify the PD occurring inside the transformer, it indicates possible PD in transformers. The response time for DGA is usually slow when compared to PD detection. The localization of the PD source is not possible by this method.
A combined monitoring system involving PD and DGA (single gas to multi-gases) can be highly advantageous for asset management.

**2.2.1.4 Ultrasonic Acoustic Method:**
This test should be applied when fault gases are increasing markedly in the DGA. When PD occurs in insulation, acoustic waves are also generated. These waves travel through transformer oil and strike its tank. These acoustic waves can be decoupled using acoustic sensors. Acoustic sensors are are immune to external electrical and electromagnetic

interferences. On the other hand, the acoustic sensor can be sensitive to external mechanical noises [25].

In the transformers, the propagation of acoustic waves is largely affected by the complex structure of the insulating system (windings, core, and tank walls). In a complex structure, both the amplitude and the shape of the acoustic signal emitted by a PD source change along its propagation path. The acoustic method is very helpful in the localization of PD. At least three sensors at different locations must triangulate the PD source by time difference of arrival (TDOA) method. However, PD defects in the transformer's main insulation are the most difficult to detect due to the transformer board barriers and outer winding. Acoustic waves caused by PD defects in the core are very difficult to analyze and may, at times, give misleading results [20].

Ultrasonic contact (in contact with the tank), fault detection can detect partial discharge (corona) and full discharge (arcing) inside the transformer. This test can also detect loose parts inside the transformer. Partial discharges emit energy in the order of 20 kHz to 200 kHz. These frequencies are above levels that can be detected audibly. The test equipment receives the signals and converts them electronically into audible signals. Headphones are provided to eliminate spurious noise from other sources. A baseline test should be conducted and compared with future test data. This test method has some limitations; if a partial discharge is located deep within the windings, external detectors may not be sensitive enough to detect and locate the problem. However, partial discharges most often occur near the top of the transformer in areas of high voltage stress which can readily be located by this method. These defects can sometimes be easily remedied extending transformer service life.

It can be summarized that for continuous online monitoring, the UHF method proves to be more successful than the acoustic method, as it is more sensitive to PD occurring in the main insulation or core of the transformer.

#### 2.2.2 Corona Scope Scan

With the transformer energized, scan the bushings and surge arresters and all high voltage connections for unusual corona patterns. Corona should be visible only at the top of bushings, surge arresters and at connection joints, should be similar in nature to sister units. As a bushing deteriorates due to physical defects, the corona pattern will grow progressively larger. When the corona pattern reaches a grounded surface (i.e., the tank or structure) a flashover will occur destroying the bushing or surge arrester and perhaps the transformer. The corona scope will reveal this problem long before a flashover.

#### 2.2.3 Sweep frequency response analysis

When a transformer is subjected to high through fault currents, the windings are subjected to severe mechanical stresses causing winding movement, deformations, and in some cases severe damage. Deformation results in relative changes to the internal inductance and capacitance of the winding which can be detected externally by frequency response analysis (FRA) method [26]. Winding damage detection can be accomplished by comparing the fingerprints of a healthy winding (or the calculated response using a transformer equivalent circuit) with the fingerprints of a damaged winding. Changes in fingerprints can be used to estimate the degree of winding damage and its location [27].

Online FRA has the potential to be an integral part of a smart grid asset management strategy. Cost minimization drivers in utility company's make desirable the replacement of time based routine maintenance with condition based monitoring using automated monitoring and interpretation. Online FRA has been a research topic over the past decade. In the early stages, development of online FRA focused on Impulse FRA (IFRA) with uncontrolled signals, which occur in nature like lightning or produced by switching in the power system. Since the frequency content of these signals is not controlled, it typically requires a significant time and effort to capture enough useful data for analysis. Some of the researchers [28] favor the IFRA method using transients from the network or injected signals. To obtain the response curve from the signals the common signal processing tools of Fast Fourier Transform (FFT) and Wavelet Transform (WT) are typically used.

A review of online FRA literature shows that in this application there has been little interest in using Sweep Frequency Response Analysis (SFRA) for in-service monitoring [29]. SFRA has the benefit of facilitating a better signal to noise ratio and can produce almost constant accuracy across the wide frequency range and there is a reduced need for complex signal processing. Therefore, development of SFRA for an online application could be of significant benefit to industry. Sweep frequency response measurement through high frequency CTs using the bushing DDF points as shown in figure-8, have the potential to be used for an online FRA measurement system.

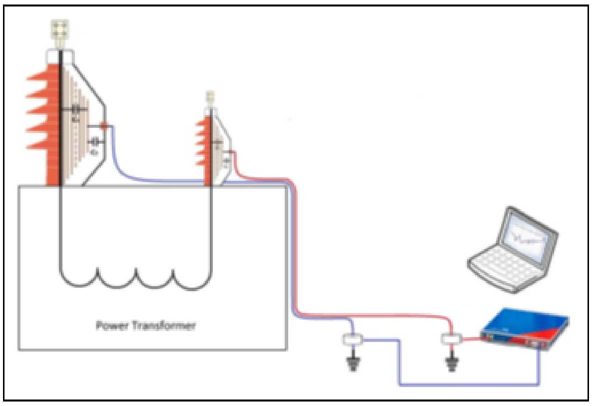


**Figure 8:** FRA measured through CTs & bushing taps

#### 2.2.4 Bushing Monitoring

Bushing failure contributes to a significant percentage when it comes to the reasons for transformers' failure. Hence, monitoring leakage current of bushings is, in any way, much better than not monitoring at all.

The leakage current from the bushings can be measured through the diagnostic taps at the base of each bushing. The vector sum of the three phases should equal 0 if the bushings are all identical in terms of capacitance and power factor. Any change in the capacitance or power factor of one of the bushings will unbalance the system and lead to a nonzero vector sum of currents. This provides a clear indication of impending bushing failure. This deterioration of the bushing can also precipitate partial discharge events, whereby we get a short term momentary discharge across one of the insulation layers. These discharges will tend to degrade the insulator rapidly and can lead to a cascade failure. It is possible to provide early evidence of partial discharge activity by monitoring the bushing tap at high frequency and looking for patterns of high speed transients.

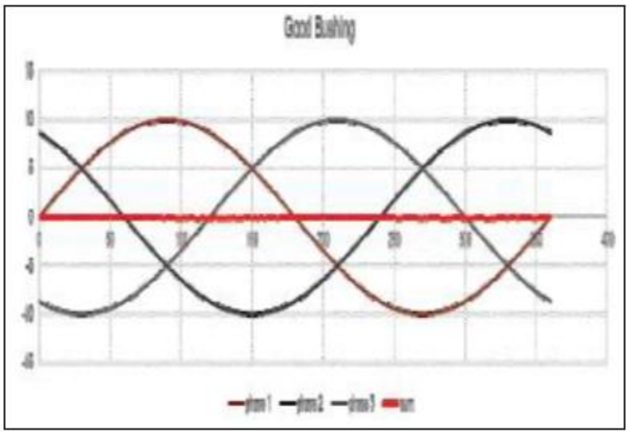


**Figure 9:** Zero sum of currents for system with three good bushings

Finally, we can measure the strength of the magnetic field around the transformer. Any change in this magnetic field is indicative of a change in the mechanical configuration of the windings and can be used to predict incipient faults.

### 2.3 Mechanical Parameters

The types of mechanical parameters that can be measured are visual inspection, sounds, vibrations, torques and monitoring of new developed sensors technology and communication systems.

#### 2.3.1 Visual Inspection

Visual inspection of the transformer exterior and various electro-mechanical protection devices reveals important condition information. For example, valves positioned incorrectly, plugged radiators, stuck temperature indicators and level gauges, and noisy oil pumps or fans. Oil leaks can often be seen which indicate a potential for oil contamination, loss of insulation, or environmental problems. Also, the torque required to change tap changer positions or to start a cooling fan can be used to predict impending failures. Physical inspection requires staff experienced in these techniques.

#### 2.3.2 Vibration Analysis

The usage of the vibration signals in assessing the transformer health is a relatively new technique compared with other methods. Vibration analysis by itself cannot predict many faults associated with transformers, but it is another useful tool to help determine transformer condition. Vibration can result from loose transformer core segments, loose windings, shield problems, loose parts, or bad bearings on oil cooling pumps or fans, and on load tap changer vibrations. Extreme care must be exercised in evaluating the source of vibration. Many times, a loose panel cover, door, or bolts/screws lying in control panels, or loose on the outside have been misdiagnosed as problems inside the tank. There are several instruments available from various OEMs and the technology is advancing quickly. Every transformer is different; therefore, to detect this, baseline vibration tests should be run and data recorded for comparison with future tests. For a normal transformer in good condition, vibration data is normally 2 times line frequency (120 Hz) and also appears as multiples of 2 times line frequency; that is, 4 times 60 (240 Hz), 6 times 60 (360 Hz), etc. The 120 Hz is always the largest and has an amplitude of less than 0.5 inch per second (ips) and greater than 0.1 ips. The next peak of interest is the 4 times line frequency or 240 Hz. The amplitude of this peak should not exceed 0.5 ips. None of the remaining harmonic peaks should exceed 0.15 ips in amplitude [30].

#### 2.3.3 New developments in online condition monitoring and assessment

With the development of sensors technology and communication systems, more than one parameter can be monitored in the same time. New online systems that monitor more than one parameter in the transformer are commercially available.

Many parameters can be monitored online using these new systems such as HST, dissolved gases, and oil temperature. Advanced technology sensors are used for parameter measurements in these new CM systems. All data measured are then collected using data acquisition subsystem to be analyzed and to provide interpretation for the operator. These new CM systems provide fast and accurate interpretation to any problem in the transformer.

### 2.4 Chemical Analysis

Chemical analysis mainly deals with the composition of the transformer oil in terms of dissolved gases and moisture. If a hot spot develops inside the main tank of a transformer, it will locally heat up the long chain molecules that make up standard transformer mineral oil. Heat it up enough and the chemical bonds will start to break, leading to the release of small fragments made of carbon and hydrogen atoms. These are species like hydrogen, methane, acetylene, ethylene and ethane as shown in figure-10. In the same manner if the paper insulator is overheated and breaks down oxygenated species will be released because paper has oxygen atoms in its makeup as shown in figure-11. The relative quantities of these gases in dissolved state in transformer oil is related to the temperature of the hot spot and the mechanism of its formation.


Paper ID: SR25705185124 DOI: https://dx.doi.org/10.21275/SR25705185124

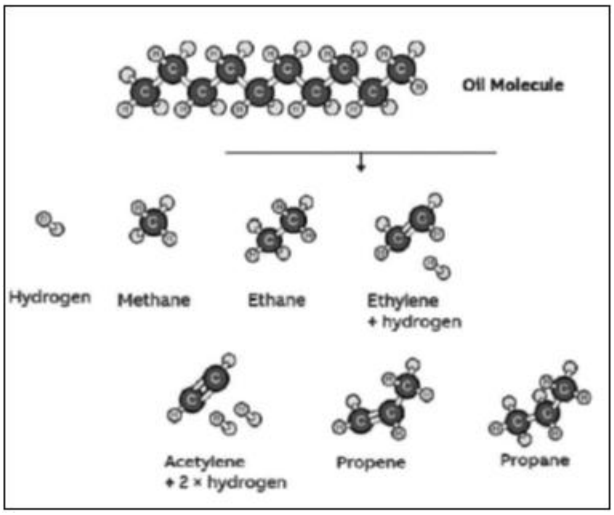


**Figure 10:** Oil breakdown products when overheated

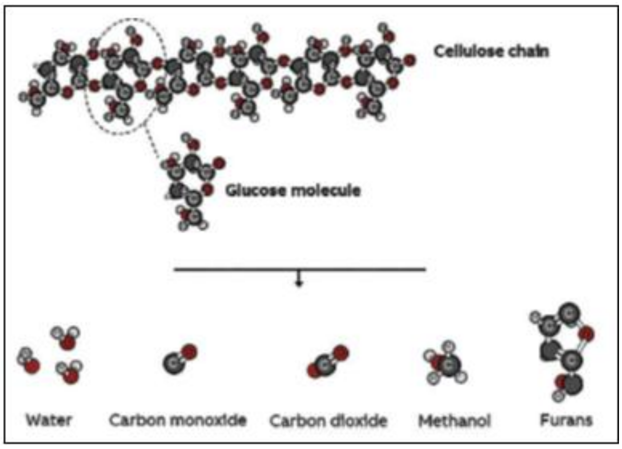


**Figure 11:** Paper breakdown products

Water and oxygen are not fault indicators but will act to accelerate paper degradation and therefore should be monitored and kept as low as possible to maximize the life expectancy of the transformer. Moisture is also monitored to ensure low enough levels to avoid generating free water and/or bubbles in the transformer which could lead to partial discharges and significantly damage an operating transformer. All transformers generate different gases at normal operating temperatures. Nevertheless, the concentration of these gases increases in the presence of an abnormality (fault) such as thermal, partial discharge, and arcing faults. During internal faults, oil produces gases such as hydrogen (H2), methane (CH4), acetylene (C2H2), ethylene (C2H4), and ethane (C2H6), while cellulose produces methane (CH4), hydrogen (H2), carbon monoxide (CO), and carbon dioxide (CO2).

Dissolved gas analysis (DGA) is the most important tool in determining the condition of a transformer. The health of the oil is reflective of the health of the transformer itself. The most important indicators are the individual and total dissolved combustible gas (TDCG) generation rates [31, 4]. Analyzing transformer oil for these key gases by chromatography helps to know the fault type, and location. Also, laboratories may rely upon defined critical levels of gases, rates of increase in gas level (on a year-by-year basis), or one of the ratio methodologies such as Rogers or Dorn Enberg ratios and Duval triangle to assess the condition of oil. However, interpretation by the individual gases can become difficult when there is more than one fault in the transformer. [4, 32]

The ratio of CO2/CO is sometimes used as an indicator of the thermal decomposition of cellulose. The degradation of the paper insulation can be detected using the ratio of CO2/CO dissolved in transformer oil, which represents the tensile strength of the paper insulation. When cellulose insulation decomposes due to overheating, chemicals, in addition to CO2 and CO, are released and dissolved in the oil. These chemical compounds are known as furanic compounds or furans. In healthy transformers, there are no detectable furans in the oil, or they are less than 100 ppb.

## 3. Digital Philosophy Concept

The better system operation always demands the quick availability of signals at the interface point for detail processing and subsequent real time action execution. The quick availability of signals depends upon the medium/communication channel through which it is transmitted. Moreover, the risk of signal loss or breakage is also another important reason of delay or failure of the work execution. In broad sense, this medium is considered as hardware type or software type. For example, transfer of signal in the form of energy pocket by the use copper wire is termed as the hardware signal. Transfer of signal by the wireless form or by use of fiber optics is termed as software type. The faster availability can be attained by software form and the possibility of loss or breakage of the signal is also less. So, continuation of the signal availability can help us for perfect actuation of the work management.

We have the following advantages for digitization of the process.

- Extensive self-diagnosis through sensors used in the system ensures the maximum uptime.
- Sequential seamless control and operation with interlocks for safety of equipment and personnel.
- Increased system Reliability, Safety, Security, and Efficiency.
- Optimization of Transformer operation that the operational and maintenance cost.
- Easy Data recording helps for improved measurement accuracy and subsequent Analysis for corrective action towards repair and maintenance.
- Reduction of Copper wire and possibility of signal loss due to looseness, breakage or short-circuit.
- Improved Communication capabilities like data exchange between intelligent devices intra and inter-substation.
- Better EMC performance and quick isolation of circuits as per requirement.
- Less or nil error & dependence on human beings.

### 3.1 Basic Working Action

Digital transformer system network largely contains three important areas (Hardware, Software and Process Application).

a) The hardware part is the primary device that used in the transformer to collect the system parameters for the application process. These basically are called sensors, transducers, converters, instruments etc. fitted inside or outside of the transformer at a suitable region. In digital system we call it AI (Analog Input).

b) Software part is the intermittent device that manages to convert the hardware signal to the scalable digital signal for readiness to the application purposes at SCADA/HMI. These include the device called A to D converter (Analog to Digital), Opto-couplers etc… The output of this software part reports directly to the process bus for the integration to the automation network. Now for perfect system operability a common communication is chosen and presently IEC 61850-9-2 is the protocol that interconnects all soft logics for seamless deliver towards reliability and efficiency of the device. In this digital system we call as BI or DI (Binary or Digital Input). [33]

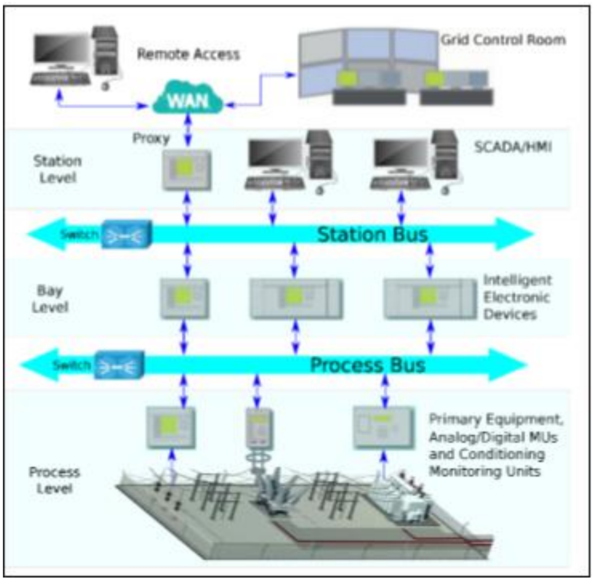


**Figure 12:** Digitally optimized S/S_Utilities perspective

c) Application Process is the final process bus part of the system for real time action towards supervision, control and monitoring of the system. Built-in components like digital sensors, dissolved gas analyzers and digital safety devices collect data for monitoring, diagnostics and control at the common house. The action of suitable control is extended by the signal called BO or DO (Binary or Digital Output).

### 3.2 Typical Application Note

This application note has been described from utilities perspective. All utilities are concerned about the Power system availability with Quality, Reliability, Safety and Security. Transformers are subjected to electrical, chemical, and mechanical stress due to environmental and operational variations. Among all the parameters, temperature plays an important role that affects the transformer materials quicker in comparison. So, it requires continuous monitoring of the temperature profile on the transformer. Moreover, the loading pattern in the system is always un-certain that needs to be monitored and controlled based on temperature recording with respect to the load pattern. In present practice we use fiber optics directly with the transformer winding, core, oil immersion etc. that provides accurate temperature rise and its analysis at the SCADA can decide about the operational control of the transformer helping the device for higher efficiency and life span. (Refer Fig.12)

### 3.3 Modern Applications

Digital technologies are also being embedded by technology providers in different types of transformers, be it oil type or dry type. In digitally enabled transformers, smart sensors collect data and combine them to provide powerful analytics. These sensors embedded with digital response transformers could also be the best solution to monitor for proactive action towards its control and necessary action.

Digital technologies embedded robots now have reached the field application for submersible transformer inspection which performs fast, safe and cost-effective internal inspection, reducing personnel risk and less down time with cost effective solution. Another advantage is that this could also be controlled wireless from remote center, maintaining point to point security control. Many other applications include RTCC bank controller, Cooler Kiosk Controller by MCU (Motor Controller Unit), Online DGA, Piezoelectric camera controller, Online condition monitoring etc...

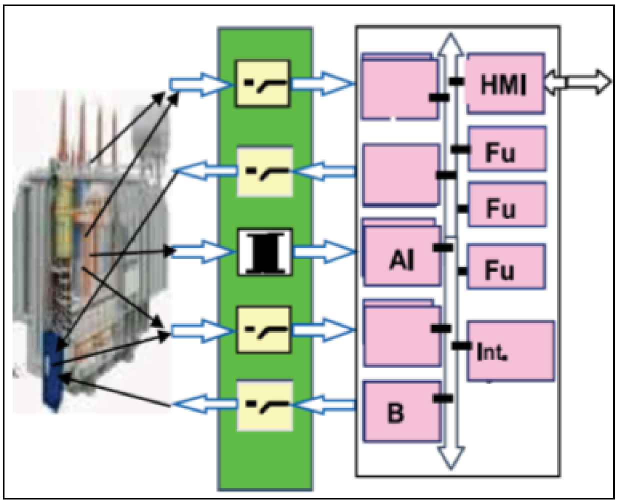


**Figure 13:** Basic digital system

## 4. Role of Digital System for Transformer Application

Transformers, being the most vital and valuable equipment in the T&D system, the technical specification is prepared by utilities with utmost care and caution considering the techno commercial aspects. In the era of competitive bidding the manufacturers are also bound to continuously innovate and optimize their design processes, to meet the expectations of the customers. Even after the system is in service, preventive maintenance and condition monitoring activities are judiciously followed to improve the life expectancy of the transformers. However, human errors and process deficiencies are bound to occur, which hence leads to meteoric results than expected. Therefore, the critical analysis and systematic observation of the events and happenings during the lifecycle of the transformer shall be helpful in improving the domain expertise and diagnostic capabilities of various stake holders at all fronts. The digital system and its application can judiciously guide us to land upon the corrective action at each level of life cycle starting from its inception stage to after math death for postmortem analysis.

The detailed life cycle points are enunciated below.

**a)** The inception and planning for giving birth of this equipment. (Preparation of GTP & specifications, tendering and award of contract)

**b)** From embryonic stage to infancy

Every utility has certain pre-recorded guidelines, procedures and referrals for the checking, testing and inspection of the transformers. The inspection process includes different stages starting from the preliminary point of design review, technical data comparison, stage inspection with raw materials and assembly inspection and final inspection etc... Each time few of the predefined tests are conducted. The following are the role of digital systems during these stages:

- Preference has been considered for the preparation of digital set up with the available guidelines, procedures and referrals for easy scrutiny of the documents.
- Regarding different stage inspections, updated and innovative micro-sensors could be utilized for obtaining accurate data and conclusion regarding the use of correct materials.
- 3rd Eye high resolution camera could be integrated to the customer premises for easy, quick and economical inspection. Moreover, this audio-video coverage could be kept for future record reference and quotation for the similar job.
- Digital testing equipment with facility of data storage, retrieval and data analysis is another choice for accurate testing during the inspection. e updated SCREEN SHARE concept is also gaining popularity for the remote control on the testing of the job with satisfaction and quick access to the result preparation.
- Most important point of developing DATA BANK for the equipment/manufacturer wise observations on digital base helps in improving quality and minimize the time for future reference.

**c)** The methods for adoption of the same, at the utility's premises. (Dispatch, delivery & transportation)

**d)** Care with immunization and preparatory acceptance for the new society during infancy

Maximum cases, the issues develop on the availability of OEM representative due to scarcity
of sufficient manpower, that results in delaying of the commissioning process. Hence, the following are the role of digital systems during installation & erection, pre-commissioning test & energization as a improvements:

- Use of Audio-video system, the expert's advice could be obtained for correct and successful erection of the job at site, instead managing by the novice representative at site.
- The digital instruments are the next option for correct testing and comparison of the same with the factory results.
- Due to use of Digital result sheet, the site and factory value could be analyzed for taking final decision during charging of the transformer.

**e) Successful Operating and Maintenance**

This is the prime functional area that needs utmost care for successful running of the transformer in the network to maintain a stable and reliable power system. Every developing nation is now in the search of clean electricity, encouraging energy harvest through Renewable sources. This situation demands new technical challenges regarding the integration of the RE with a conventional system. Smart system is the only option for early detection of the system parameters and corrective action towards control of the system. In the era of Smart Grid evolution, the assets in the system should also be smart enough to pace with the system. So Smart Transformer is the option for successful Operation Control and in subsequent for Maintenance feature also.

For this section Digital system helps to satisfy the successful operation in many of the aspects such as:

- Modern innovative LMS- Loading Management Schedule with CBM- Condition Based Maintenance
- Use of Digital Bays equipped with modern NXIT (Nonconventional Instrument Transformers), MU (Merger Units) and SCU (Switching Control Unit)
- Use of Digital RTCC (Remote Tap Changer Control Cubicle) and MCU (Motor Controller Unit) based DM
- Preparation of TCC (Transformer Condition Code) for CBM (Condition Based Maintenance)

By implementing the above, smooth, accurate and confirmed operation can be achieved, which in turn have the following advantages:

- Energy conservation results due to a reduction of transformation loss.
- Life span of the transformer increases, because of proper loading on them.
- Life span of other equipment increases.
- Maintenance becomes easy with no interruption of the system loads.

**f)** Condition monitoring practices during young and dynamic stage. (Online & offline condition monitoring & testing).

**g)** Health monitoring, testing and care during old age. (RLA study, overhauling process etc.)

**h)** Postmortem analysis (upon accidental or natural death).

## 5. Utility Perspectives

The wish list of every utility is to have PQRS in the system network (Power with Quality Reliability, Safety and Security). In the complex network system, sooner the adaptation to digital system by the utility shall enhance credibility and its efficient response to the consumers in the system. Some study reveals the advantages and extract from CIGRE study supplements the same with strong fact, "Guide on Economics of Transformer Management (Technical Brochure 248)", the digitalization of transformers will provide the benefits of 75% reduction in repair costs due to early detection, 60% reduction in revenue loss due to unanticipated problems/outages, 50% reduction in the risk of catastrophic failures and 2% annual cost savings, which is approximately equivalent to the replacement cost of a new transformer. [34]

## 6. Conclusion

Monitoring thermal, electrical, mechanical, and chemical parameters allow for early detection of transformer faults. By integrating smart sensors with cloud-based monitoring and AI, utilities can manage transformer fleets more efficiently, reduce operational costs, and avoid unplanned outages. Embedding digital intelligence into the transformer lifecycle offers significant advantages in asset management, making smart transformers a cornerstone of modern power systems.

Total Life cycle management module of the transformer can be tagged with digital system, which can help the utility to reduce investment cost, running cost and maintenance cost at large. This can also manage the judicious operation of all rating transformers in the system. The digital approaches with smart sensors on condition monitoring system enable the maintenance crew to take corrective action to prevent unplanned downtime. Hence, sooner the better, utilities should adopt this Digital System for Transformer to make it smart and intelligent enough.

## References

[1] IEC standard 60076-1, Edition 3.0-2011, Power Transformers - General.
[2] CIGRE TB 323, Ageing of cellulose in mineral-oil insulated Transformers.
[3] CIGRE TB 343, Recommendations for condition monitoring and condition assessment facilities for Transformers.
[4] Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers, IEEE C57.104 Standard, 2019
[5] Guide for Loading Mineral-Oil-Immersed Transformers, IEEE C57.104 Standard, 2019
[6] J.K. Pylvänäinen, K. Nousiainen, P. Verho, Studies to utilize loading guides and ANN for oil-immersed distribution transformer condition monitoring, IEEE Trans. Power Deliv. 22 (2007) 201–207.
[7] W.H. Tang, Q.H. Wu, Z.J. Richardson, Equivalent heat circuit based power transformer thermal model, IEE Proc. Electr. Power Appl. 149 (2002) 87–92.
[8] J.Q. Feng, P. Sun, W.H. Tang, D.P. Buse, Q.H. Wu, Z. Richardson, J. Fitch, Implementation of a power transformer temperature monitoring system, in: Proc. Int. Conf. on Power Syst. Technol., PowerCon, 2002.
[9] O. Roizman, V. Davydov, Neuro-fuzzy algorithms for power transformers diagnostic, in: Proc. Int. Conf. on Power Syst. Technol., PowerCon, 2000.
[10] J. Shengchang, S. Ping, L. Yanming, X. Dake, C. Junling, The vibration measuring system for monitoring core and winding condition of power transformer, in: Proc. 2001 Int. Symp. on Electr. Insulating Mater, ISEIM, 2001.
[11] P. Kang, D. Birtwhistle, Condition assessment of power transformer on-load tap-changers using wavelet analysis, IEEE Trans. Power Deliv. 16 (2001) 394–400.
[12] S.M. Strachan, S.D.J. McArthur, M.D. Judd, J.R. McDonald, Incremental knowledge-based partial discharge diagnosis in oil-filled power transformers, in: Proc. 13th Int. Conf. on Intell. Syst. Appl. to Power Syst, 2005.
[13] A. Zargari, T.R. Blackbum, Acoustic detection of partial discharges using nonintrusive optical fiber sensors, in: Proc. IEEE Int. Conf. on Conduct. And Breakdown in Solid Dielectr., Vasteras, Sweden, 1998.
[14] S.D.J. McArthur, S.M. Strachan, G. Jahn, The design of a multi-agent transformer condition monitoring system, IEEE Trans. Power Deliv. 19 (2004) 1845–1852.
[15] M.D. Judd, S.D.J. McArthur, J.R. McDonald, O. Farish, Intelligent condition monitoring and asset management: partial discharge monitoring for power transformers, IEE Power Eng. J. 16 (2002) 297–304.
[16] H. Zhang, T.R. Blackburn, B.T. Phung, D. Sen, A novel wavelet de-noising method for on-site PD measurements on HV cables, in: Proc. 2005 Int. Symp. on Electrical Insulating Mater, Kitakyushu, Japan, 2005
[17] H. Mingyou, H. Xie, T.B. Tiong, X. Wu, Study on a spatially selective noise filtration technique for suppressing noises in partial discharge on-line monitoring, in: Proc. the 6th Int. Conf. on Prop. and Appl. of Dielectr. Mater., 2000.
[18] P. Werle, A. Akbari, H. Borsi, E. Gockenbach, Partial discharge localization on power transformers using neural networks combined with sectional winding transfer function as knowledge base, in: Proc. Int. Symp. on Electr. Insulating Mater., 2001.
[19] J.S. Foo, P.S. Gosh, Artificial neural network modeling of partial discharge parameters for transformer oil diagnosis, in: Proc. Annual Rep. Conf. on Electr. Insulation and Dielectr. Phenom., 2002.
[20] ABB, "Testing of Power Transformers – Routine tests, Type tests, and Special tests," 1st Edition, Pro Print GmbH, Düsseldorf, 2003.
[21] S. Tenbohlen, M. Beltle, and M. Siegel, "PD monitoring of power transformers by UHF sensors", International Symposium on Electrical Insulating Materials (ISEIM), Toyohashi, Nov. 2017 - Sep. 2017, pp. 303–306.
[22] M. Judd, "Partial Discharge Monitoring for Power Transformers Using UHF Sensors Part 2: Field Experience," IEEE Electrical Insulation Magazine, Vol. 21, No. 3 May/June 2005
[23] Gulski E., Koltunowicz W., and Tenbohlen S., "Guidelines for partial discharge detection using conventional (IEC 60270) and unconventional methods," Cigre Technical Brochure 662, 2016.
[24] C. P. Beura, M. Beltle and S. Tenbohlen, "Positioning of UHF PD Sensors on Power Transformers Based on the A_enuation of UHF Signals," IEEE Transactions on Power Delivery, Volume: 34, Issue: 4, pp. 1520 – 1529, Aug. 2019
[25] M. Harbaji et al., "Classi□cation of Common Partial Discharge Types in Oil-paper Insulation System Using Acoustic Signals," IEEE Trans. Dielectr. Electr. Insul. Vol. 22, No. 3; pp. 1674-1683, June 2015.
[26] IEC standard 60076-18, Edition 1.0-2012, Power Transformers – Measurement of frequency response.
[27] S. Birlasekaran, F. Fetherston, Off/on-line FRA condition monitoring technique for power transformer, IEEE Power Eng. Rev. 18 (1999) 54–56.
[28] C. Yao, Z. Zhao, Y. Chen, X. Zhao, Z. Li, Y. Wang, Z. Zhou and G. Wei, "Transformer Winding Deformation Diagnostic System Using Online High Frequency



Paper ID: SR25705185124 DOI: https://dx.doi.org/10.21275/SR25705185124 

Signal Injection by Capacitive Coupling," IEEE Transactions
[29] T. De Rybel, A. Singh, A. J. Vandermaar, M. Wang, J. R. Marti, and K. D. Srivastava, "Apparatus for Online Power Transformer Winding Monitoring Using Bushing Tap Injection," IEEE Trans. Power Del., Vol. 24, pp. 996-1003, 2009.
[30] Proceedings: Substation Equipment Diagnostics, Conference IX, Electric Power Research Institute
[31] IEC standard 60599, Edition 1.0-2015, Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis.
[32] Y.C. Huang, C.M. Huang, Evolving wavelet networks for power transformer condition monitoring, IEEE Trans. Power Deliv. 17 (2002) 412–416.
[33] IEC standard 61850, Edition 1.0-2021, Communication networks and system for power utility automation.
[34] CIGRE Technical Brochure 248 - Guide on Economics of Transformer Management.

## Author Profile

**Imtiyaz Barkatali Surani** received the bachelor's degrees in electrical engineering from Charotar Institute of Technology, Changa (Gujarat University) in June 2006. He is a senior professional with over 19 years of experience in Power Transformer and Reactor rated up to 500 MVA, 765kV class with strong skills in installation, site commissioning and testing – Type, Special & Routine inspections as per related IEC/IS/BS/NEMA/ANSI standards. Attending factory acceptance test inspection, failure investigation, leading design review meetings, technical specification committee, drawing standardization and substation digitization team, specialist committee member for review & optimization of technical specification, losses optimization and condition monitoring.