International Journal of Advanced and Applied Sciences, 6(8) 2019, Pages: 100-110

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

A review on fault detection and condition monitoring of power transformer

Muhammad Aslam [1, *], Muhammad Naeem Arbab [2], Abdul Basit [1], Tanvir Ahmad [1], Muhammad Aamir [3]

[1]US Pakistan Centre for Advanced Studies in Energy, University of Engineering and Technology, Peshawar, Pakistan
[2]Department of Electrical Engineering, University of Engineering and Technology, Peshawar, Pakistan
[3]Faculty of Electrical Engineering, Bahria University, Islamabad, Pakistan

ARTICLE INFO

Article history:
Received 15 March 2019
Received in revised form
18 June 2019
Accepted 19 June 2019

Keywords:
Transformer
Incipient fault
Condition based monitoring
Insulation deterioration
Electrical fault

ABSTRACT

Real-time monitoring of transformers ensures equipment safety and guarantees the necessary intervention in precise time thereby reducing the risk of non-schedule energy blackouts. Many utilities monitor the condition of the components that make up a power transformer and use this information to minimize interruption and prolong life. Currently, routine and diagnostic tests are used to monitor conditions and assess the aging and defects of the core, windings, bushings and power transformer tape changers. To accurately assess the remaining life and probability of failure, methods have been developed to correlate the results of different routine and diagnostic tests. There are several electrical and chemical (diagnostic) techniques available for condition monitoring of power transformer. This paper reviews real time techniques used for condition-based monitoring of power transformer.

1. Introduction

Power transformer is an important and expensive component in the electrical power system. The reliable operation of power system is dependent on transformer's health. Any fault on transformer not only reduces the reliable operation of power system but also results in financial damages. Special care is taken to ensure that transformers are well protected from all types of faults with greater lifetime and efficiency (Bartley, 2003; Meshkatoddini, 2008; Arshad and Tsai, 2018; Zhao et al., 2019). The insulation made up of oil and cellulose paper plays an important role in safeguarding transformers from electrical breakdown. A thick layer of cellulose paper, wrapped around each part of winding, make it electrically insulated while oil acts as insulation medium and heat dissipater (Azis et al., 2014; Han et al., 2014). The cellulose paper and the oil determine the health of the transformer. Heavy loading on the transformer results in heating that deteriorates the paper quality thus, it reduces transformer lifetime. Likewise, the transformer condition is also affected when oil gets deteriorated by moisture and oxidation (Jan et al., 2015; Mandlik and Ramu, 2014).

Transformer faults are classifying as internal and external faults. The internal faults can be either active or incipient in nature. Active faults are the solid faults that appear on the windings of the transformer. It may be a turn to turn shorts fault, i.e., phase to phase, or turn to earth shorts fault, i.e., phase to ground fault. These faults always result in high currents leading to insulation breakdown and permanent damage to transformer (Bhide et al., 2010; Tuethong et al., 2012; Usha and Usa, 2015; Yao et al., 2014). Incipient faults are not severe at its initial stage but slowly develop into serious faults. Incipient faults are divided into two main categories namely thermal fault and electrical fault. Electrical fault is further classified into over-heating and winding failure, while thermal fault is due to contamination of oil and insulation deterioration. Faults due to insulation deterioration are sub-divided into oil and cellulose paper deterioration faults (Chatterjee et al., 2017; Ciulavu and Helerea, 2008). It is essential to know about conceivable faults that may happen and to know how to prevent them. The degradation cellulose paper and oil contamination insulation in the transformer with time or any abnormal conditions are the primary causes of these incipient faults (Martin et al., 2014; Wang and Butler, 2002).

* Corresponding Author.
Email Address: muhammad.aslam@uetpeshawar.edu.pk (M. Aslam)
https://doi.org/10.21833/ijaas.2019.08.014
Corresponding author's ORCID profile:
https://orcid.org/0000-0003-4787-6598

The high current due to abnormal load conditions or faults result in high temperature that damages the transformer insulation. The break down in insulation releases different types of gases that dissolve into oil instantly and will stay there inconclusively. Certain significant gases are produced by the breakdown of an insulation which are related with particular faults (Gibeault and Kirkup, 1995). These gases are methane (CH_4), ethane(C_2H_6), ethane (C_2H_4), ethyne (C_2H_2), hydrogen (H_2), carbon dioxide (CO_2) and carbon monoxide(CO) (Fofana et al., 2011; Lelekakis et al., 2012; Morais and Rolim, 2006; Su et al., 2000). They are collectively known as the diagnostic gases or key gases. Each fault type evolves a specific characteristic gas. The nature of the fault can be determined from the type as well as the quantity of the gas (Bartley, 2003). The identification of the gases which are generated during abnormal load condition or with an ageing of transformer could be very useful information for any predictive maintenance. Online monitoring is now gaining importance day by day.

There are several electrical and chemical techniques for diagnostic available for monitoring of insulation condition of the power transformers (Abu-Elanien and Salama, 2010, Bengtsson, 1996, Fuhr, 2009, Saha et al., 1997, Tenbohlen et al., 2016, Van Bolhuis et al., 2002, Wang et al., 2002), However, a review of all these techniques in a single paper is rarely available (Abu-Elanien and Salama, 2010; Al-Janabi et al., 2015; Christina et al., 2018; Saha and Purkait, 2004; Sun et al., 2017a; Wang et al., 2002). This paper reviews different types of technique for health monitoring of power transformer which are made up into six sections. In section 2, the paper discusses the chemical techniques for internal incipient faults detection with critical analysis and artificial intelligence-based techniques are briefly discussed in section 3. The Electrical Diagnostic Techniques for incipient faults detection is presented in section 4 while section 5 discusses the furan analysis. Conclusion is presented in last section. The studies presented in below sections are summarized in Fig. 1.

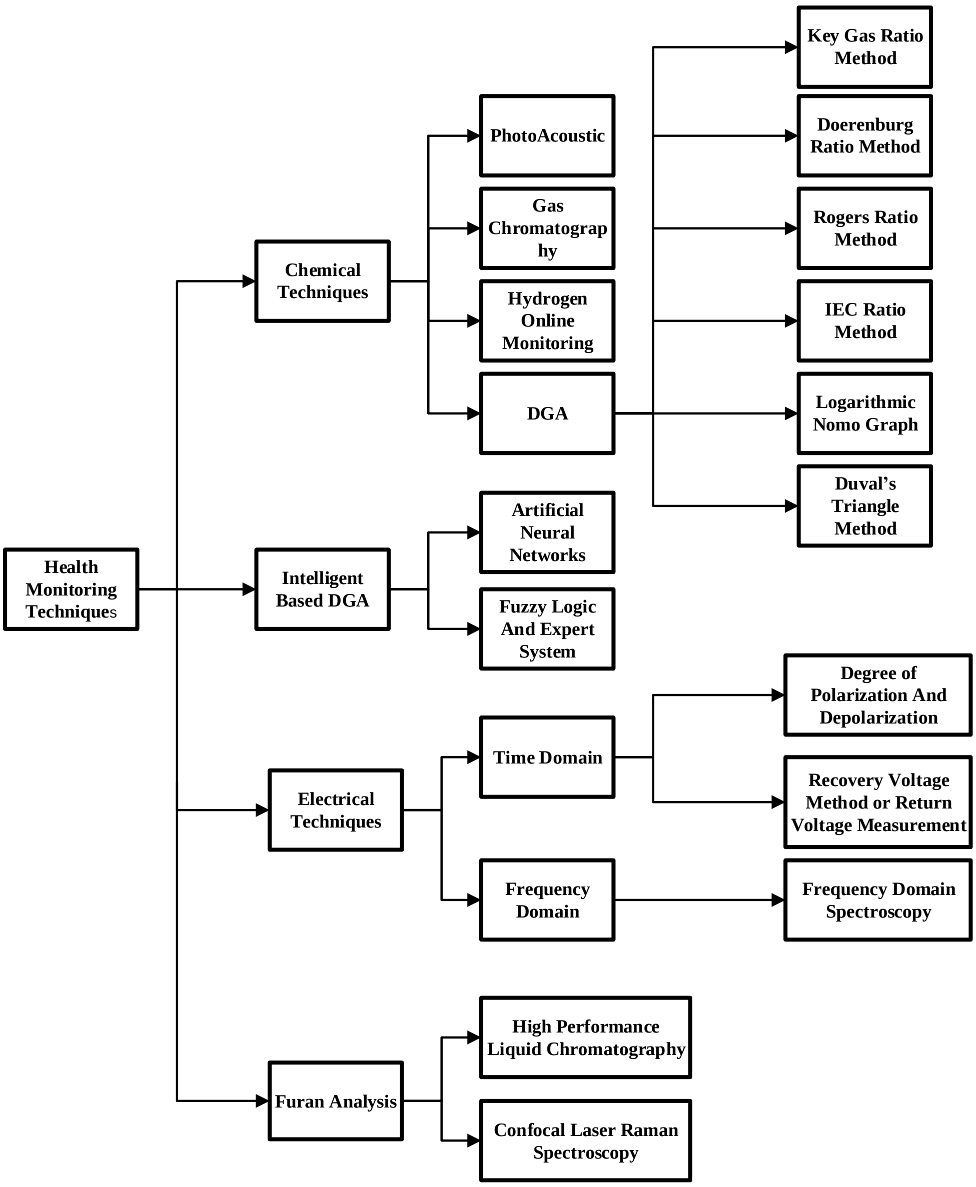

Fig. 1: Health monitoring technique

2. Critical analysis of chemical techniques for detection of incipient faults

Among different chemical techniques for predictive maintenance, the Dissolved Gas Analysis (DGA) has been considered as the single first most powerful techniques for transformer fault detection and still has been used (Duval, 2003; Kelly, 1980; Shintemirov et al., 2009; Sun et al., 2012b; Ashkezari et al., 2011). It has been at the forefront of most progressive utilities monitoring strategy for the last four decades (Saha, 2003; Kim et al., 2012; Gómez, 2014; Kelly, 1980).

Various approaches for analysis of dissolved gas analysis have elaborated e.g. Key gas ratio, Doernenburg ratio, Roger ratio, IEC ratio Logarithmic Nomo graph and Duval triangle methods. Each of these techniques depends on the collection of information or gathered knowledge and linking with various experts alternatively than thorough quantitative technological models and for that reason they delivered different diagnoses for the same oil sample (He and Xu, 2012; Fuhr, 2009). These different techniques are briefly discussed below.

2.1. Key gas ratio method

The main guideline of the key gas ratio technique depends on the quantity of individual fault gases generated from the insulating oil and paper amid the event of a fault. In this method, individual gas is considered rather than the gas ratio for fault detection is calculated. This ratio technique correlates the main gases to faults types and try to identify four different types of faults that also include winding failure (corona) (PD), overheating of oil cellulose paper and arcing. However, key gas ratio method has several drawbacks, the diagnoses are not accurate enough, the diagnoses may be inconclusive if some of gases are not found (Taneja et al., 2016).

2.2. Doernenburg ratio method (DRM)

IEEE C57.104-191 guidelines explains the doernenburg ratio method. The complication of doernenburg ratio method has been led to decrease the use of this method and elaborated into the rogers ratio and key gas ratio perspective (Harlow, 2012). To utilize doernenburg ratio, the concentration of the following main gases should be no less than double the relevant 1 concentration, as appeared in Table 1.

Table 1: Concentration of dissolved gasses

Main gases (key gases)	Concentration (PPM)of Ł1
Ethyne - C_2H_2	35
Ethene-C_2H_2	50
Ethane C_2H_6	65
Methane-CH_4	120
Hydrogen-H_2	100
Carbon dioxide-CO_2	2500
Carbon Monoxide-CO	350

2.3. Rogers ratio

The Rogers ratio technique advanced from the doernenburg method and is utilized the same way, yet as opposed to requiring sufficiently concentrations main key gases, the rogers ratio technique only utilized when the concentrations exceed the same value listed in Table 2 (DiGiorgio, 2005; Muhamad et al., 2007). The values for these three-gas ratios, relating to proposed diagnostic cases is provided below. In this method three ratios are indicated by diagnoses the transformer fault types.

Table 2: Rogers ratio technique

Case	Possible fault diagnoses	$R_1=C_2H_2/C_2H_4$	$R_2=CH_4/H_2$	$R_3=C_2H_4/C_2H_6$
0	Normal	<0.01	<0.1	<1.0
1	Partial discharge of low energy	≥1.0	≥0.1and<0.5	≥1.0
2	Partial discharge of high energy	≥0.6 and <3.0	≥0.1and<1	≥2.0
3	Thermal fault less than 300^{0}C	<0.01	≥1.0	<1.0
4	Thermal fault less than 700^{0}C	<0.1	≥1.0	≥1.0 and <4.0
5	Thermal fault > 700^{0}C	<0.2	≥1.0	≥4.0

Rogers has better accuracy among the key gas, doernenburg and roger's ratio. The only drawback with this method that few bunches of gases don't fit into the predefined range of values when computed and thus the fault type can't be clarified (Kim, 2012).

2.4. IEC ratio method

In this technique fault determination jointly prescribed by the international Electro Technical Commission (IEC). The technique depends on a combine ratio of roger's ratio and gas concentration. Three gas proportions are utilized to decide incipient fault. Three-gas ratios diverse the range of code in correlation with the rogers' ratio technique. Thermal faults, electrical faults, normal ageing, partial discharge of low and high energy are four detected conditions of varying severity, but it does not clarify electrical and thermal faults into precise subtypes (Miranda and Castro, 2005).

2.5. Logarithmic nomo graph

This technique by J. O. Church combines the fault gas ratio concept with the Key Gas threshold limit value providing an incentive to improve the accuracy of fault diagnosis (Arora, 2013). It has been planned to provide graphical introduction of fault-gas information and the method to describe its criticalness. The Nomo graph comprises of a progression of vertical logarithmic scales representing to the concentrations of the individual gases (Gockenbach and Borsi, 2008). Straight lines are drawn by this method between adjoining scales to associate the points representing to the individual gas concentration. Every vertical scale has limited value esteem, marked with an arrow. Through the slope of a line to be viewed as an important, no less than one of the two tie-points should lie above limiting value. However, if neither one of the ties point lies over a threshold value, at that point the fault indication of that slope is not considered as critical (Sica et al., 2015).

2.6. Duval triangle method

Duval Triangle Method (DTM) was presented and illustrated in IEC 60599 and IEEE C57.104. DTM basically depends on the levels of the three gas ratio namely Methane (CH_4), Ethane C_2H_4) and Acetylene (C_2H_2) (Faiz and Soleimani, 2017). Three sides of the triangle are being represented by a, b and c describing relative extent of C_2H_2, C_2H_4 and CH_4 in percentage (%) for each gas. The intersection of all three gases ratios illustrate types of fault in the transformer. In Duval's Triangle Method, the whole area of triangular divided into seven (7) faults area as shown in Fig. 2. They include PD, DT, T3, T2, T1, D2 and D1.

This technique provides better fault diagnosis however there's a misclassification near edges of every adjacent area (Mansour, 2012). However, all triangles have unclassified region thus faults classification will majorly depend on the expert's experience recognized by other techniques (Duval and Lamarre, 2014). There may be chance for mixing the electrical faults with the thermal faults because their boundaries are closed with each other (Alghamdi et al., 2012).

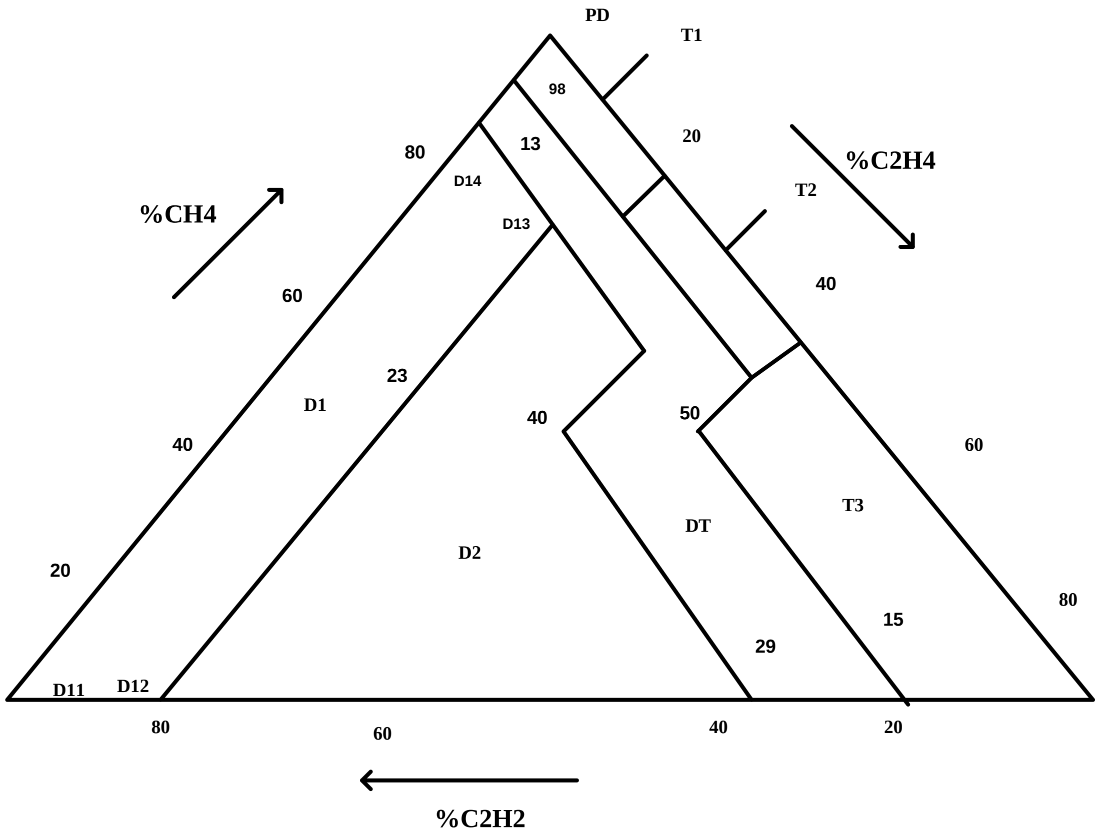

Fig. 2: Duval's triangle

2.7. Gas chromatography

This technique is design to be sensitive to each target gas and in fact use to analyse a huge variety of diverse types of samples from oil and gas to water and air pollution (Adams and Sparkman, 2007). Today, Gas Chromatography Technique is one of the best and most sensitive method for the early sensing and detection of gases in oil of the transformer and thus illustrates an excellent indication for upcoming expected faults inside the transformer (Ferrito, 1990). This technique requires very tight control of gas flow rates, temperatures and carrier gas quality. A sensitive but unstable and therefore has historically been confined to a laboratory environment. This is primarily because Gas Chromatography is sensitive to changing local conditions, e.g., temperature, pressure, movement, continuity of gas flow rates etc. Because of this high degree of sensitivity to environmental factors. Recent attempts to utilize Gas Chromatography in the field environment has met with limited success with the single biggest problem being equipment drift, leading to poor repeatability of results from one sample to the next (McNair and Miller, 2011).

2.8. Hydrogen online monitoring

The hydrogen online monitoring is strong and lower cost technique that is widely used for most of the fault in oil-filled transformer especially for Hydrogen gas. This method detects the main faults such as winding failure, overheating and hot spots. We can easily monitor the units through communication, consumer can access day by day, week after week, and occasional gassing trends and, beneficially uses these results not only to detect active faults but also to predict the development of a fault before it becomes a real service issue. However, hydrogen on line monitoring can detect only the following gases H_2, CO, C_2H_2 and C_2H_4, and not all of them. The level of sensitivity will depend on percentage (%) of the hydrogen monitoring of all individual gases. However, the diagnosis is maximum for Hydrogen and less for the rest of the gases. Moreover, this technique cannot be used for all type of faults detection (Gockenbach and Borsi, 2008).

2.9. Photo acoustic spectroscopy

Photo acoustic Spectroscopy as compare to Gas Chromatography systems are less sensitive to environmental conditions (temperature, humidity, atmospheric pressure, movement associated with vibration or wind buffeting etc.) (Allan, 1980; Chen et al., 2007; Kuster et al., 2005).These conditions are perfectly controlled and checked in a laboratory but in the field it is quite a challenge. The system has to cope with day to night changes, winter to summer changes, weather patterns and local vibration from transformer vibration, road traffic and industrial processes (Mackenzie et al., 2010). High care must be taken by the utility when the manufacturer in instrument specifications often overlooks assessing the guaranteed specification of operating conditions for the Gas Chromatography system in the field as this, in contrast, a photo acoustic spectroscopy system is virtually immune to environmental conditions such as temperature, noise and vibration and remains accurate with a very wide range of operating conditions and long duration (Yun et al., 2008; Harlow, 2012). To summarize the DGA, a comparative analysis is provided in Table 3.

3. Artificial intelligence techniques

Traditionally, various chemical techniques identify the health of power transformers. The human expert experience helps in classifying the transformer state by interpreting data acquired though chemical tests. As it mainly depends on human expert experience, therefore there is always probability of irregularity and uncertainty in interpreting the acquired data. There is need for more advanced techniques based on artificial intelligence (AI) (Taneja et al., 2016; Perez et al., 1994). Fuzzy interface, wavelet network, genetic algorithm, artificial neural network are some of the examples for AI system where the trained data provides quick and accurate result as compare to classical one or conventional methods (Su et al., 2000; Khan et al., 2015; Wang, 2003; Ahmed et al., 2013; Fei and Zhang, 2009; Li et al., 2016; Shintemirov et al., 2009; Sun et al., 2012a).

3.1. Artificial neural networks

The use of Artificial Neural Networks (ANN) in diagnosing the electrical insulation condition has increased over couple of years. The ANN system needs to be trained for differentiating the faulty data from the normal and thereby classify the insulation health. During the training process, an ANN will construct a model to explain dependency between the extracted options and the fault types by adjusting the weights between neurons and the thresholds of activation operate of every neuron. Then the trained ANN model is employ to classify the health of electrical insulation by spotting new samples with the predefined training pattern process.

3.2. An expert system and fuzzy logic

An expert system minimizes human skilled behaviour by providing specific data from concern domain with a machine implementable kind. An expert system implements this information to facilitate decision and justify its reasoning. The expert system initially extracts the intellectual indications from the domain data and so presents the data in several forms and structures, together with production rules, frames and rules, linguistics nets and objects. Electrical device such as transformer has complicated insulation structure and its degradation depends on multiple factors. The insulation health can be diagnosed technically with solid data and skilled expertise (Ahmed et al., 2013). However, the significant constraints of this logic and expert system for the transformer diagnosis are because of the way that the execution of these strategies is profoundly reliant on the result of the predefined information.

4. Electrical diagnostic techniques

Thermal stresses and chemical changes impacts the transformer age. These stresses degrade the paper insulation and thereby the life span of the device decreases.

The degradation of paper insulation depends on the moisture content that are produced by breaking down long chains of glucose into a small molecule (Okabe et al., 2013; Wang et al., 2015; Yunguang et al., 2013). The increase in the moisture level in the oil reduces the breakdown voltage level of the insulation.

Table 3: Overall Comparative Analysis

Types of Method	Distinctive attribute	Strategy	Process
Key Gas Ratio method	Detects four different types of faults (corona (winding failure), arcing, overheating of oil and overheating of cellulose paper) but the diagnoses are not accurate enough. Diagnoses may be inconclusive if some of gases are not found.	Using manual calculations	Assess the quality of oil only. Allows for faults diagnoses only
Doernenburg Ratio	It uses four gas ratios and indicates different types of faults If all the ratios for faults are in the given range then faults can be detected otherwise fault cannot be detected by this method.	Using manual calculations	Assess the quality of oil and paper. Allows for faults diagnoses only
Rogers Ratio	Ratios are identified to diagnose the transformer fault types. Few bunch of gases don't fit into the predefined range of values when computed and the fault type can't be defined.	Using manual calculations	Assess the quality of oil only. Allows for faults diagnoses only
IEC Ratio	It does not clarify thermal and electrical faults into precise subtypes. It indicated a very limited range of decomposition of gas ratios.	Using manual calculations	Assess the quality of oil only. Allows for faults diagnoses only
Logarithmic Nomo graph(LNG)	Improves the accuracy of fault diagnosis by combing fault gas ratio and the concept of key gas threshold. Graphically presenting fault gas data does not concise with actual faults.	Using manual calculations and graphical estimation	Assess the quality of oil only. Allows for faults diagnoses only
Duval Triangle (DTM)	It has more efficient as compare other methods because it clarifies wide range of faults. But It does not explain the normal ageing of transformers. There may be a chance of mixing of electrical and thermal faults	Using a computer program and manual calculations	Assess the quality of oil only. Allows for faults diagnoses only
Gas Chromatography	Offers highest accuracy and repeatability. Ready to identify and analyze each gas dissolved in transformer oil and Results can be utilized to identify the fault. Long time required to finish a test on a transformer. Gas Chromatography is a laboratory-based method due to complexity of the device. A high skill expert is needed to conduct the test an interpret the data. Highly Expensive	Using a computer program and manual calculation	Assess the quality of oil only. Allows for faults diagnoses only and all take the ratios of gases by sending oil samples to external laboratories
Hydrogen online Monitoring	Hydrogen online Monitoring. Detect Hydrogen at low level.	Through communication	Assess the quality of oil and cellulose paper only. Allows for faults diagnoses
Photo Acoustic Spectroscopy	PAS is used for both qualitative and quantitative analysis of the sample	By spectrum analysis	Assess the quality of oil gas and cellulose paper. Allows for faults diagnoses and monitoring human health condition.

There are a few indirect techniques for finding the moisture level in cellulose paper (Sun et al., 2017b). These techniques require accumulation of test sample from basic part, for example, (outside windings, leads) and then analysing them in research lab by Karl-Fischer titration (Suleiman et al., 2017). Similarly, Oommen's technique may be used for computing moisture level in the cellulose papers (Martin et al., 2013). These indirect strategies have a substantially bigger mistake relating to the calculating qualities. Thus, we require frequency or time domain techniques for more exact outcomes (Sarkar et al., 2013). There are three different types of methods for the measurement of dielectric response. Polarization and depolarization current, and recovery voltage method measures the dielectric response through DC voltage test (time domain), while Frequency domain spectroscopy is AC voltage tests in which dielectric response is measured.

4.1. Polarization and depolarization current (PDC)

In this technique a ripple free dc voltage applied for the sample for very long time and the polarization current which is flowing in the test sample is measured. The polarization current involves of different polarization process each one with different time constant and dc conductivity. They relate different insulating material and different condition state (Dutta et al., 2016; Saha et al., 2009; Talib et al., 2015; Kumar et al., 2011). The depolarization current appears as polarization current reaches to zero level.

The polarization processes have different time constants relating to different insulation materials and different ageing conditions for different materials. The value of current is being judged by dc conductivity (σ), Higher the value higher will be the moisture in the insulation and vice versa (Junhao et al., 2009).

4.2. Recovery voltage method

The return voltage is another method in time domain to investigate the moisture level in oil and winding of power transformer. This technique was introduced in 90's and still very effective method (N'cho et al., 2016), with the help of this method we can find the low level of moisture content in the insulation.

When a dielectric is applied DC voltage for a long period and then short circuited for a very short time, the charge movement bounded by the polarization process will change into free charges. As result, voltage builds up across the electrodes on the dielectric material, this phenomenon is known as recovery voltage. The recovery voltage increases with an ageing of transformer and thereby recovery voltage method is useful for evaluating the uniformity of ageing and moisture distribution, not for non-uniformity of ageing (Csepes et al., 1998). However, heat produced inside the transformer container found to be a sensitive parameter for the return voltage (Tamus et al., 2015).

4.3. Frequency domain spectroscopy (FDS)

The objective of the frequency domain spectroscopy is to measure the dielectric dissipation factor or loss factor (tan δ) solid insulation, it is made by calculating the sample impedance at each frequency step by knowing the voltage and measuring the current.

The value of tan δ changes according to different conductivity and moisture in the insulation. The higher the tan δ, more will be the moisture and the lower the conductivity, that is, the more rapid is going into aging. This is currently well accepted that by this techniques of measurement provides good indication for an ageing and moisture content in the transformer insulation. However, it must be emphasized that ageing separating still a part of challenging task in this domain (Ekanayake et al., 2006).

5. Furan analysis

Furan analysis is another method to protect the transformer from catastrophic failure. When a cellulose material de polymerizes into small lengths or chain structures a chemical compound known as a furan is formed. By measurement of these furanics present in transformer oil, the paper insulation with a high degree of confidence can be found. The concentration and types of furans in oil sample indicates degree of degradation (Cheim et al., 2012). There are a number of methods for detecting the furan or furfural concentration in transformer oil but the two primary are explained below

5.1. High performance liquid chromatography (HPLC)

High Performance Liquid Chromatography (HPLC) is a complex analytical technique that can be used to determine the transformer paper degradation by analysing the concentration of furanics within the transformer's oil (Stebbins et al., 2003). When the cellulose chain breaks down during paper degradation, each broken chain releases a glucose monomer unit that undergoes further chemical reaction to become furan compounds and other components such as moisture and other gases.

The concentration or quantity of furans in the mineral oil of a power transformer is the best indication of the cellulose materials such as paper, pressboard and cotton tapes used for insulation. Therefore, direct analysis and quantification of these compounds serves as an indicator of the age and health of the transformer. Since the concentration is directly related to the degradation of paper insulation inside the transformer the analysis might serve as an early warning of a catastrophic failure. Yet, it is critical to monitor the papers tensile strength and degradation or degree of polymerization (DP) to ensure that the paper continues to provide effective insulation for the transformer (Zhang and Macalpine, 2006).

5.2. Confocal laser Raman spectroscopy (CLRS)

Raman spectroscopy has broadly been in use for detection and examination of fluid materials such as transformer oil with the advancement of laser innovation. Laser Raman spectroscopy (LRS) is a technique investigation strategy in light of the Raman impacts, which can have determined material structures and properties by estimating Raman dispersing force specifically. The benefits of LRS over current identification techniques regarding distinguishing the centralization of furfural broke down in transformer oil and different materials can be recognized all at a time the while utilizing a single frequency laser (Wolny et al., 2014; Fu et al., 2012; Pelletier, 2003).

6. Conclusion

Predictive maintenance is recognized as a powerful monitoring technique for the detection of incipient faults within transformer. The transformer is a very important and critical device of electrical power system. It is important to be aware of possible faults that may occur and to know how to prevent them. The degradation of the paper and oil insulation in the transformer with an ageing or any abnormal conditions are the main causes these incipient faults. The purpose of this paper to review different techniques and to develop a prototype that can monitor the health of transformer continuously and ensure the safety of transformers from permanent damages by detecting the fault at its earlier stage.

The literature review shows that the limitation of Chemical and Electrical traditional methods and an artificial intelligence based hybrid system could be the future solution of health monitoring of power transformer.

Acknowledgement

This paper is a part of research project funded by USAID. The research work is carried at USPCAS-E in collaboration with Arizona State University (ASU).

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

References

Abu-Elanien AE and Salama MMA (2010). Asset management techniques for transformers. Electric Power Systems Research, 80(4): 456-464. https://doi.org/10.1016/j.epsr.2009.10.008

Adams RP and Sparkman OD (2007). Review of identification of essential oil components by gas chromatography/mass spectrometry. Journal of the American Society for Mass Spectrometry, 18: 803-806. https://doi.org/10.1016/j.jasms.2007.01.001

Ahmed MR, Geliel MA, and Khalil A (2013). Power transformer fault diagnosis using fuzzy logic technique based on dissolved gas analysis. In the 21st Mediterranean Conference on Control and Automation, IEEE, Chania, Greece: 584-589. https://doi.org/10.1109/MED.2013.6608781

Alghamdi AS, Muhamad NA, and Suleiman AA (2012). DGA interpretation of oil filled transformer condition diagnosis. Transactions on Electrical and Electronic Materials, 13(5): 229-232. https://doi.org/10.4313/TEEM.2012.13.5.229

Al-Janabi S, Rawat S, Patel A, and Al-Shourbaji I (2015). Design and evaluation of a hybrid system for detection and prediction of faults in electrical transformers. International Journal of Electrical Power and Energy Systems, 67: 324-335. https://doi.org/10.1016/j.ijepes.2014.12.005

Allan R (1980). Photoacoustics and photoacoustic spectroscopy. John Wiley and Sons, Hoboken, USA.

Arora RK (2013). Different DGA techniques for monitoring of transformers. International Journal of Electronics and Electrical Engineering, 1(4): 299-303. https://doi.org/10.12720/ijeee.1.4.299-303

Arshad MZ and Tsai C-Y (2018). Performance improvement during grid fault in wind turbines using doubly fed induction generator. Annals of Electrical and Electronic Engineering, 1(1): 5-9. https://doi.org/10.21833/AEEE.2018.01.002

Ashkezari AD, Saha TK, Ekanayake C, and Ma H (2011). Evaluating the accuracy of different DGA techniques for improving the transformer oil quality interpretation. In the 21st Australasian Universities Power Engineering Conference, IEEE, Brisbane, Australia: 1-6.

Azis N, Liu Q, and Wang ZD (2014). Ageing assessment of transformer paper insulation through post mortem analysis. IEEE Transactions on Dielectrics and Electrical Insulation, 21(2): 845-853. https://doi.org/10.1109/TDEI.2013.004118

Bartley WH (2003). Analysis of transformer failures. In the International Association of Engineering Insurers: 36th Annual Conference, Stockholm, Sweden: 1-13.

Bengtsson C (1996). Status and trends in transformer monitoring. IEEE Transactions on Power Delivery, 11(3): 1379-1384. https://doi.org/10.1109/61.517495

Bhide RS, Srinivas MSS, Banerjee A, and Somakumar R (2010). Analysis of winding inter-turn fault in transformer: A review and transformer models. In the 2010 IEEE International Conference on Sustainable Energy Technologies, IEEE, Kandy, Sri Lanka: 1-7. https://doi.org/10.1109/ICSET.2010.5684425

Chatterjee K, Jadoun VK, and Jarial RK (2017). Emerging trends for determining incipient faults by dissolved gas analysis. In the 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems, IEEE, Rupnagar, India: 63-68. https://doi.org/10.1109/CATCON.2017.8280185 **PMCid:PMC5363167**

Cheim L, Platts D, Prevost T, and Xu S (2012). Furan analysis for liquid power transformers. IEEE Electrical Insulation Magazine, 28(2): 8-21. https://doi.org/10.1109/MEI.2012.6159177

Chen W, Yun Y, Pan C, and Sun C (2007). Gas-in-oil analysis in transformers based on photoacoustic spectrometry. Automation of Electric Power Systems, 31(15): 94-98.

Christina AJ, Salam MA, Rahman QM, Wen F, Ang SP, and Voon W (2018). Causes of transformer failures and diagnostic methods: A review. Renewable and Sustainable Energy Reviews, 82: 1442-1456. https://doi.org/10.1016/j.rser.2017.05.165

Ciulavu C and Helerea E (2008). Power transformer incipient faults monitoring. Annals of the University of Craiova, Electrical Engineering Series, 32: 72-77.

Csepes G, Hamos I, Brooks R, and Karius V (1998). Practical foundations of the RVM (recovery voltage method for oil/paper insulation diagnosis). In the 1998 Annual Report Conference on Electrical Insulation and Dielectric Phenomena (Cat. No. 98CH36257), IEEE, Atlanta, USA, 1: 345-355. https://doi.org/10.1109/CEIDP.1998.734015

DiGiorgio JB (2005). Dissolved gas analysis of mineral oil insulating fluids. DGA Expert System: A leader in Quality, Value and Experience, 1: 1-17.

Dutta S, Mukherjee M, Pradhan AK, Baral A, and Chakravorti S (2016). Effect of temperature on condition assessment of oil-paper insulation using polarization-depolarization current. In the 2016 National Power Systems Conference, IEEE, Bhubaneswar, India: 1-5. https://doi.org/10.1109/NPSC.2016.7858910 **PMid:27890676**

Duval M (2003). New techniques for dissolved gas-in-oil analysis. IEEE Electrical Insulation Magazine, 19(2): 6-15. https://doi.org/10.1109/MEI.2003.1192031

Duval M and Lamarre L (2014). The duval pentagon-a new complementary tool for the interpretation of dissolved gas analysis in transformers. IEEE Electrical Insulation Magazine, 30(6): 9-12. https://doi.org/10.1109/MEI.2014.6943428

Ekanayake C, Gubanski SM, Graczkowski A, and Walczak K (2006). Frequency response of oil impregnated pressboard and paper samples for estimating moisture in transformer insulation. IEEE Transactions on Power Delivery, 21(3): 1309-1317. https://doi.org/10.1109/TPWRD.2006.877632

Faiz J and Soleimani M (2017). Dissolved gas analysis evaluation in electric power transformers using conventional methods: A review. IEEE Transactions on Dielectrics and Electrical Insulation, 24(2): 1239-1248. https://doi.org/10.1109/TDEI.2017.005959

Fei SW and Zhang XB (2009). Fault diagnosis of power transformer based on support vector machine with genetic algorithm. Expert Systems with Applications, 36(8): 11352-11357.
https://doi.org/10.1016/j.eswa.2009.03.022

Ferrito SJ (1990). A comparative study of dissolved gas analysis techniques: The vacuum extraction method versus the direct injection method. IEEE Transactions on Power Delivery, 5(1): 20-25.
https://doi.org/10.1109/61.107324

Fofana I, Bouaïcha A, and Farzaneh M (2011). Characterization of aging transformer oil–pressboard insulation using some modern diagnostic techniques. European Transactions on Electrical Power, 21(1): 1110-1127.
https://doi.org/10.1002/etep.499

Fu D, Lu FK, Zhang X, Freudiger C, Pernik DR, Holtom G, and Xie XS (2012). Quantitative chemical imaging with multiplex stimulated Raman scattering microscopy. Journal of the American Chemical Society, 134(8): 3623-3626.
https://doi.org/10.1021/ja210081h
PMid:22316340 PMCid:PMC3396204

Fuhr J (2009). Benefits and limits of advanced methods used for transformer diagnostics. In the 2009 IEEE Electrical Insulation Conference, IEEE, Montreal, Canada: 262-272.
https://doi.org/10.1109/EIC.2009.5166355

Gibeault JP and Kirkup JK (1995). Early detection and continuous monitoring of dissolved key fault gases in transformers and shunt reactors. In the Electrical Electronics Insulation Conference and Electrical Manufacturing and Coil Winding Conference, IEEE, Rosemont, USA: 285-293.
https://doi.org/10.1109/EEIC.1995.482378

Gockenbach E and Borsi H (2008). Condition monitoring and diagnosis of power transformers. In the 2008 International Conference on Condition Monitoring and Diagnosis, IEEE, Beijing, China: 894-897.
https://doi.org/10.1109/CMD.2008.4580427

Gómez JA (2014). Experimental investigations on the dissolved gas analysis method (DGA) through simulation of electrical and thermal faults in transformer oil. Ph.D. Dissertation, Universidad de Duisburg-Essen, Essen, Germany.

Han S, Li Q, Li C, and Yan J (2014). Electrical and mechanical properties of the oil-paper insulation under stress of the hot spot temperature. IEEE Transactions on Dielectrics and Electrical Insulation, 21(1): 179-185.
https://doi.org/10.1109/TDEI.2013.003967

Harlow JH (2012). Electric power transformer engineering. CRC Press, Boca Raton, USA.
https://doi.org/10.1201/b12110

He H and Xu X (2012). Study on transformer oil dissolved gas online monitoring and fault diagnosis method. In the 2012 IEEE International Conference on Condition Monitoring and Diagnosis, IEEE, Bali, Indonesia: 593-596.
https://doi.org/10.1109/CMD.2012.6416214

Jan ST, Afzal R, and Khan AZ (2015). Transformer failures, causes and impact. In the International Conference Data Mining, Civil and Mechanical Engineering, Bali, Indonesia: 49-52.

Junhao L, Wenrong S, Xiu Y, Ming D, and Yanming L (2009). Study of polarization and depolarization current measurements for assessment of aging state of oil-paper insulated transformers. Chinese Journal of Scientific Instrument, 30(12): 2605-2611.

Kelly JJ (1980). Transformer fault diagnosis by dissolved-gas analysis. IEEE Transactions on Industry Applications, (6): 777-782.
https://doi.org/10.1109/TIA.1980.4503871

Khan SA, Equbal MD, and Islam T (2015). A comprehensive comparative study of DGA based transformer fault diagnosis using fuzzy logic and ANFIS models. IEEE Transactions on Dielectrics and Electrical Insulation, 22(1): 590-596.
https://doi.org/10.1109/TDEI.2014.004478

Kim SW (2012). Advanced dissolved gas analysis (DGA) diagostic methods for oil-immersed power transformers. In the International Conference of Doble Client, Chicago, USA.

Kim YM, Lee SJ, Seo HD, Jung JR, and Yang HJ (2012). Development of dissolved gas analysis (DGA) expert system using new diagnostic algorithm for oil-immersed transformers. In the 2012 IEEE International Conference on Condition Monitoring and Diagnosis, IEEE, Bali, Indonesia: 365-369.
https://doi.org/10.1109/CMD.2012.6416455

Kumar A, Rattan J, Sharma RN, and Chauhan S (2011). Investigation of polarization and depolarization current for evaluation of moisture in oil-pressboard insulation. International Journal of Computer and Electrical Engineering, 3(6): 853-856.
https://doi.org/10.7763/IJCEE.2011.V3.432

Kuster WC, Harren FJ, and de Gouw JA (2005). Inter-comparison of laser photoacoustic spectroscopy and gas chromatography techniques for measurements of ethene in the atmosphere. Environmental Science and Technology, 39(12): 4581-4585.
https://doi.org/10.1021/es0504385

Lelekakis N, Martin D, and Wijaya J (2012). Ageing rate of paper insulation used in power transformers part 2: Oil/paper system with medium and high oxygen concentration. IEEE Transactions on Dielectrics and Electrical Insulation, 19(6): 2009-2018.
https://doi.org/10.1109/TDEI.2012.6396960

Li J, Zhang Q, Wang K, Wang J, Zhou T, and Zhang Y (2016). Optimal dissolved gas ratios selected by genetic algorithm for power transformer fault diagnosis based on support vector machine. IEEE Transactions on Dielectrics and Electrical Insulation, 23(2): 1198-1206.
https://doi.org/10.1109/TDEI.2015.005277

Mackenzie EA, Crossey J, de Pablo A, and Ferguson W (2010). On-line monitoring and diagnostics for power transformers. In the IEEE International Symposium on Electrical Insulation, San Diego, USA: 1-5.
https://doi.org/10.1109/ELINSL.2010.5549734

Mandlik M and Ramu TS (2014). Moisture aided degradation of oil impregnated paper insulation in power transformers. IEEE Transactions on Dielectrics and Electrical Insulation, 21(1): 186-193.
https://doi.org/10.1109/TDEI.2013.004186

Mansour DEA (2012). A new graphical technique for the interpretation of dissolved gas analysis in power transformers. In the 2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, Montreal, Canada: 195-198.
https://doi.org/10.1109/CEIDP.2012.6378754

Martin D, Lelekakis N, Wijaya J, Duval M, and Saha T (2014). Investigations into the stray gassing of oils in the fault diagnosis of transformers. IEEE Transactions on Power Delivery, 29(5): 2369-2374.
https://doi.org/10.1109/TPWRD.2014.2316501

Martin D, Perkasa C, and Lelekakis N (2013). Measuring paper water content of transformers: A new approach using cellulose isotherms in nonequilibrium conditions. IEEE Transactions on Power Delivery, 28(3): 1433-1439.
https://doi.org/10.1109/TPWRD.2013.2248396

McNair HM and Miller JM (2011). Basic gas chromatography. John Wiley and Sons, Hoboken, USA.

Meshkatoddini MR (2008). Aging study and lifetime estimation of transformer mineral oil. American Journal of Engineering and Applied sciences, 1(4): 384-388.
https://doi.org/10.3844/ajeassp.2008.384.388

Miranda V and Castro AG (2005). Improving the IEC table for transformer failure diagnosis with knowledge extraction from neural networks. IEEE Transactions on Power Delivery, 20(4): 2509-2516.
https://doi.org/10.1109/TPWRD.2005.855423

Morais DR and Rolim JG (2006). A hybrid tool for detection of incipient faults in transformers based on the dissolved gas analysis of insulating oil. IEEE Transactions on Power Delivery, 21(2): 673-680.
https://doi.org/10.1109/TPWRD.2005.864044

Muhamad NA, Phung BT, and Blackburn TR (2007). Comparative study and analysis of DGA methods for mineral oil using fuzzy logic. In the 2007 International Power Engineering Conference, IEEE, Singapore: 1301-1306.
https://doi.org/10.1109/PCT.2007.4538290

N'cho J, Fofana I, Hadjadj Y, and Beroual A (2016). Review of physicochemical-based diagnostic techniques for assessing insulation condition in aged transformers. Energies, 9(5): 367-395.
https://doi.org/10.3390/en9050367

Okabe S, Ueta G, and Tsuboi T (2013). Investigation of aging degradation status of insulating elements in oil-immersed transformer and its diagnostic method based on field measurement data. IEEE Transactions on Dielectrics and Electrical Insulation, 20(1): 346-355.
https://doi.org/10.1109/TDEI.2013.6451376

Pelletier MJ (2003). Quantitative analysis using Raman spectrometry. Applied Spectroscopy, 57(1): 20A-42A.
https://doi.org/10.1366/000370203321165133
PMid:14610929

Perez LG, Flechsig AJ, Meador JL, and Obradovic Z (1994). Training an artificial neural network to discriminate between magnetizing inrush and internal faults. IEEE Transactions on Power Delivery, 9(1): 434-441.
https://doi.org/10.1109/61.277715

Saha TK (2003). Review of modern diagnostic techniques for assessing insulation condition in aged transformers. IEEE Transactions on Dielectrics and Electrical Insulation, 10(5): 903-917.
https://doi.org/10.1109/TDEI.2003.1237337

Saha TK and Purkait P (2004). Investigation of an expert system for the condition assessment of transformer insulation based on dielectric response measurements. IEEE Transactions on Power Delivery, 19(3): 1127-1134.
https://doi.org/10.1109/TPWRD.2004.829100

Saha TK, Darveniza M, Hill DJT, and Le TT (1997). Electrical and chemical diagnostics of transformers insulation. A. Aged transformer samples. IEEE Transactions on Power Delivery, 12(4): 1547-1554.
https://doi.org/10.1109/61.634174

Saha TK, Middleton R, and Thomas A (2009). Understanding frequency and time domain polarisation methods for the insulation condition assessment of power transformers. In the 2009 IEEE Power and Energy Society General Meeting, IEEE, Calgary, Canada: 1-8.
https://doi.org/10.1109/PES.2009.5275851
PMid:20036577

Sarkar S, Sharma T, Baral A, Chatterjee B, Dey D, and Chakravorti S (2013). A new approach for determination of moisture in paper insulation of in-situ power transformers by combining polarization-depolarization current and return voltage measurement results. IEEE Transactions on Dielectrics and Electrical Insulation, 20(6): 2325-2334.
https://doi.org/10.1109/TDEI.2013.6678886

Shintemirov A, Tang W, and Wu QH (2009). Power transformer fault classification based on dissolved gas analysis by implementing bootstrap and genetic programming. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 39(1): 69-79.
https://doi.org/10.1109/TSMCC.2008.2007253

Sica FC, Guimarães FG, de Oliveira Duarte R, and Reis AJ (2015). A cognitive system for fault prognosis in power transformers. Electric Power Systems Research, 127: 109-117.
https://doi.org/10.1016/j.epsr.2015.05.014

Stebbins RD, Myers DS, and Shkolnik AB (2003). Furanic compounds in dielectric liquid samples: review and update of diagnostic interpretation and estimation of insulation ageing. In the 7th International Conference on Properties and Applications of Dielectric Materials (Cat. No. 03CH37417), IEEE, Nagoya, Japan, 3: 921-926.
https://doi.org/10.1109/ICPADM.2003.1218572

Su Q, Lai LL, and Austin P (2000). A fuzzy dissolved gas analysis method for the diagnosis of multiple incipient faults in a transformer. In the 5th International Conference on Advances in Power System Control, Operation and Management, Hong Kong, China: 344–348.
https://doi.org/10.1049/cp:20000420

Suleiman AA, Muhamad NA, Bashir N, Arief YZ, Rahman MNA, and Phung BT (2017). Moisture effect on conductivity of kraft paper immersed in power transformer vegetable-based insulation oils. IET Generation, Transmission and Distribution, 11(9): 2269-2274.
https://doi.org/10.1049/iet-gtd.2016.1633

Sun C, Ohodnicki PR, and Stewart EM (2017a). Chemical sensing strategies for real-time monitoring of transformer oil: A review. IEEE Sensors Journal, 17(18): 5786-5806.
https://doi.org/10.1109/JSEN.2017.2735193

Sun HC, Huang YC, and Huang CM (2012a). Fault diagnosis of power transformers using computational intelligence: A review. Energy Procedia, 14: 1226-1231.
https://doi.org/10.1016/j.egypro.2011.12.1080

Sun HC, Huang YC, and Huang CM (2012b). A review of dissolved gas analysis in power transformers. Energy Procedia, 14: 1220-1225.
https://doi.org/10.1016/j.egypro.2011.12.1079

Sun J, Zhang S, Xu Z, Wu C, Yu X, Qiu Y, and Gao Z (2017b). Oil-paper insulation characteristic and maintenance measures of oil-immersed transformer in cold environment. In the 19th International Conference on Dielectric Liquids (ICDL), IEEE, Manchester, UK: 1-5.
https://doi.org/10.1109/ICDL.2017.8124667

Talib MA, Muhamad NA, and Malek ZA (2015). Fault classification in power transformer using polarization depolarization current analysis. In the 11th International Conference on the Properties and Applications of Dielectric Materials, IEEE, Sydney, Australia: 983-986.
https://doi.org/10.1109/ICPADM.2015.7295439

Tamus ZA, Szirmai A, and Nemeth B (2015). Comparison of voltage response and return voltage measurements of a transformer insulation model. In the 19th International Sympsium on High Voltage Engineering, ISH, Pilsen, Czech Republic: 1-5.

Taneja MS, Pandey K, and Sehrawat S (2016). A review on prognosis and diagnosis of transformer oil quality using intelligent techniques based on dissolved gas analysis. In the 7th India International Conference on Power Electronics, IEEE, Patiala, India: 1-6.
https://doi.org/10.1109/IICPE.2016.8079419

Tenbohlen S, Coenen S, Djamali M, Müller A, Samimi M, and Siegel M (2016). Diagnostic measurements for power transformers. Energies, 9(5): 347-371.
https://doi.org/10.3390/en9050347

Tuethong P, Yutthagowith P, Kunakorn A, and Potivejkul S (2012). Internal failure analysis of transformer windings. In the 2012 International Conference on High Voltage Engineering and Application, IEEE, Shanghai, China: 100-104.
https://doi.org/10.1109/ICHVE.2012.6357063

Usha K and Usa S (2015). Inter disc fault location in transformer windings using SFRA. IEEE Transactions on Dielectrics and Electrical Insulation, 22(6): 3567-3573.
https://doi.org/10.1109/TDEI.2015.005060

Van Bolhuis JP, Gulski E, and Smit JJ (2002). Monitoring and diagnostic of transformer solid insulation. IEEE Transactions on Power Delivery, 17(2): 528-536. https://doi.org/10.1109/61.997930

Wang H and Butler KL (2002). Modeling transformers with internal incipient faults. IEEE Transactions on Power Delivery, 17(2): 500-509. https://doi.org/10.1109/61.997926

Wang M, Vandermaar AJ, and Srivastava KD (2002). Review of condition assessment of power transformers in service. IEEE Electrical Insulation Magazine, 18(6): 12-25. https://doi.org/10.1109/MEI.2002.1161455

Wang MH (2003). A novel extension method for transformer fault diagnosis. IEEE Transactions on Power Delivery, 18(1): 164-169. https://doi.org/10.1109/TPWRD.2002.803838

Wang X, Li Q, Yang R, Li C, and Zhang Y (2015). Diagnosis of solid insulation deterioration for power transformers with dissolved gas analysis-based time series correlation. IET Science, Measurement and Technology, 9(4): 393-399. https://doi.org/10.1049/iet-smt.2014.0074

Wolny S, Adamowicz A, and Lepich M (2014). Influence of temperature and moisture level in paper-oil insulation on the parameters of the Cole-Cole model. IEEE Transactions on Power Delivery, 29(1): 246-250. https://doi.org/10.1109/TPWRD.2013.2270917

Yao C, Zhao Z, Chen Y, Chen X, Li C, Li W, and Wang J (2014). Detection of internal winding faults in power transformers based on graphical characteristics of voltage and current. In the 2014 ICHVE International Conference on High Voltage Engineering and Application, IEEE, Poznan, Poland: 1-4. https://doi.org/10.1109/ICHVE.2014.7035475

Yun Y, Chen W, Wang Y, and Pan C (2008). Photoacoustic detection of dissolved gases in transformer oil. European Transactions on Electrical Power, 18(6): 562-576. https://doi.org/10.1002/etep.191

Yunguang C, Guangning W, Xiaojian W, Qian P, Ling C, and Bo G (2013). The influence of organic acid on thermal aging of power transformer oil-paper insulation. In the 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, Shenzhen, China: 116-119. https://doi.org/10.1109/CEIDP.2013.6748119

Zhang CH and Macalpine JMK (2006). Furfural concentration in transformer oil as an indicator of paper ageing, part 1: A review. In the 2006 IEEE PES Power Systems Conference and Exposition, IEEE, Atlanta, USA: 1088-1091. https://doi.org/10.1109/PSCE.2006.296461

Zhao L, Zhang P, and Huang J (2019). Utilizing analytical hierarchy process and smart techniques in fault detection in electrical power networks. Annals of Electrical and Electronic Engineering, 2(5): 19-25. https://doi.org/10.21833/AEEE.2019.05.004