Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 5, May 2024

A Comprehensive Review of Methods and Tools Used for Condition Monitoring of Transformers-Progress and Scope for Future Research

Drake Fulton
Student, Department of Electrical and Computer Engineering, University of West Florida
Pensacola, FL, USA 32514

Dr. Bhuvana Ramachandran
Professor, Department of Electrical and Computer Engineering, University of West Florida Pensacola, FL, USA 32514

Abstract— **Transformers are critical electrical equipment in power systems. They are also expensive devices while factoring in the initial investment in designing and building an electric power system. Several different types of condition monitoring approaches and diagnostic methods have been researched in the past few decades with a crucial objective of increasing the transformer's operating life and decreasing the chances of catastrophic damages to the transformers. However, with the growing challenges of the electric grid's aging infrastructure, ever increasing load capacity demands, and the impact of extremely severe weather conditions, the stress on the utility power grid to operate at near zero downtime is possible only by proper planning and by implementing new, efficient, accurate monitoring and diagnostic methods. This paper provides an overview of the methods used in condition monitoring of transformers by reviewing the existing literature, analyzing the latest techniques used for monitoring and diagnostics while also emphasizing the advantages and disadvantages of current methodologies. In the end, some future directions for research in this critical topic are suggested.**

Keywords— **Condition monitoring of transformers, transformer faults, machine learning based monitoring methods, computational intelligence, asset management**

I. INTRODUCTION

Transformers are an integral part of the electric grid. Unlike most of the equipment connected in the interconnected electric grid, the transformers are reliable equipment and can be in service for 5 or 6 decades. The repercussions of failure of these machines could lead to extensive financial losses to both consumers and utilities. Moreover, repairing or replacing a transformer would take several weeks to months and in some situations, even more than a year. As a result, condition monitoring (CM) and asset management should be used to keep transformers in good working condition to avoid any major losses and outages. Since the 1930's, CM of power transformers have been performed. Throughout the past decades, new methods have been developed and others have been continuously studied for monitoring and diagnosis of transformers [1][2] [3]. The traditional CM methods are the Dissolved Gas Analysis (DGA) method and Partial Discharge (PD) method. Transformers contain oil that surrounds their core. Oil contained inside the tank of the transformer is used as a coolant to reduce the intense heat produced when a transformer is in use for an extended period of time or overloaded. DGA method of testing is performed to determine the levels of gas dissolved in the oil. PD occurs due to human error, contamination, poor installation, or manufacturing defects. Some causes are environmental such as temperature and humidity. Over time, PD can also occur due to aging of the insulation. PD method acts as a primary indicator in monitoring the weakness of insulation in transformers.

In this paper, the authors have focused on the progress of state-of-the-art research on CM of transformers over the past couple of decades. A mixture of traditional CM methods as well as Computational Intelligence (CI) based methods are presented in this literature review. In the past, many methods of CM were implemented to adhere to specific transformers' structure and to adapt to their external surroundings [4]. A systematic review of literature that includes the application of CI methods (such as artificial intelligence and machine learning) and mathematical techniques in DGA based diagnosis has also been performed [5]. The level of PD must be continuously monitored to assess the lifespan of electrical insulation in transformers to avoid any unexpected breakdowns. The occurrence of PD can directly relate to a damaged transformer [6]. The use of frequency response, temperature measurement, current measurement, and vibration monitoring have been used as forms of CM. With newer and recent developments in computers and expert systems, Artificial Intelligence (AI) algorithms and Machine learning (ML) based methods have become more studied forms of CM in recent years. AI algorithms take pre-existing data and use a mathematical model to determine if there is a fault, or even predict if there could be a fault based on the data [7]. Additionally, advancements in data collecting mechanisms are providing faster ways of detecting faults and relaying them to the control centers to take corrective actions. These mechanisms include automated diagnostic systems that are capable of issuing a fast alert when a fault occurs. The new online real time diagnosis tools create user friendly interfaces that simplify CM as shown by researchers [8]. A detailed description of online CM of transformers can be found in [9]. Fig. 1 [10] shows the different types of faults occurring in transformers.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Published by :
http://www.ijert.org

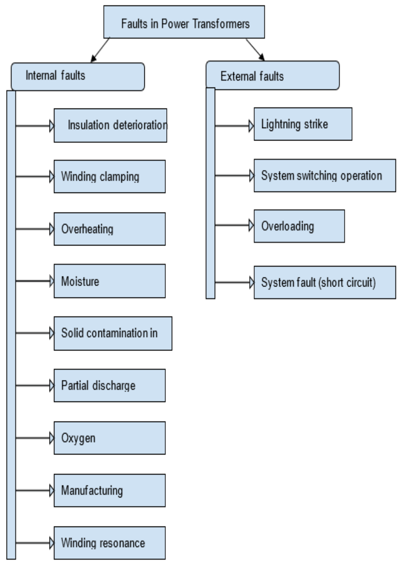

Figure 1. Classification of Transformer faults

Given the importance of CM, there is a large volume of published research studies describing the role of methods regarding both conventional methods and newer CI based methods. In this regard, state of the art CM using both traditional and newer methods will be comprehensively presented in this review paper. The authors have categorized the research articles in this topic into 4 sub sections, DGA and its variants-based research articles, PD and its variants-based research papers, CI based papers and miscellaneous papers that were based on a combination of one or two of the above-mentioned methods. The paper is organized as follows. Section II sheds light on the fundamental concepts of different traditional methodologies that have been used for CM of power transformers. Section III discusses the research in CM of power transformers that has been carried out over the past two decades. Section IV provides an overview of the future scope and extension of this research work based on the gaps in existing research providing technical solutions to some of the problems mentioned in literature. Section V summarizes the findings and provides concluding remarks for research on CM of power transformers.

II. FUNDEMENTAL CONCEPTS

A. DGA and its variants

Dissolved Gas Analysis (DGA) is a heavily researched and well-developed method for CM. DGA is used by analyzing the oil in a power transformer for specific chemical gas compounds that are produced as a result of the high intensity heat inside the power transformer's tank. Gases such as H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2 are all gases that may occur due to dissolved gas. These gases pollute the oil as a result of which oil shows signs of aging. The concentrations of these compounds inform the researchers about the health of the transformer and allows them to better understand the power transformer's life expectancy and health [11]. DGA is a non-invasive method that produces high accuracy results compared to other CM methods [12].

B. PD and its variants

Partial Discharge (PD) occurs when a higher voltage than normally expected occurs at a location inside a power transformer. When a high voltage is present, high amounts of energy are produced in that location. PD allows for a specific location of a fault to be determined and analyzed. PD's occurrence is a sign of other problems occurring in the transformer. Typically, sensors are used to detect PD occurrences in the power transformer and are being continuously monitored [6]. Fig.2 [13] shows the experimental setup of PD applied to CM of transformers.

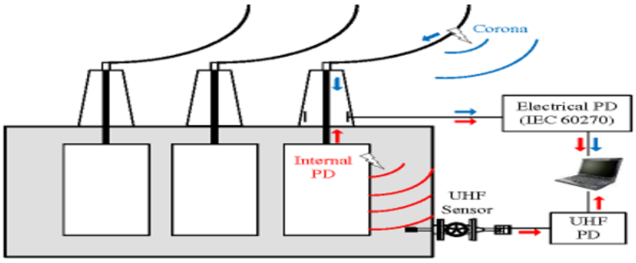

Figure 2. PD applied to CM of Transformers

C. Computational Intellegence Based Methods

In recent years, integration of AI, ML and web-based CM methods are being researched by many researchers. These methods include AI based CM, sensor-based detection, ML based approaches and internet-based detection interfaces. Though not always connected, these methods can be used together to build an accurate and efficient CM method. AI techniques involve methods like statistical machine learning, deep learning etc. that are not only core areas in the field of artificial intelligence, but also one of the hot research directions in electrical engineering today.

CI based methods also attempt to improve the existing intelligent methods by adjusting a certain parameter in the algorithm or combining multiple techniques to enhance the robustness of the transformer fault diagnosis methods. Intelligent computational techniques have been used by the researchers to mine gas data information and to find the correlation between gas data and faults, so that early faults in transformers can be detected more accurately. Expert system-based methods like Fuzzy Logic were used to evaluate the probability of failure and detect specific defects in transformers. Human expertise and the parameters obtained from fuzzy logic implementation were used for CM of transformers [14]. Sensor based fault detection uses sensors to detect, and relay data from the transformer sensor to an online CM system. Sensors can be used for a wide variety of purposes. Fig.3 [15] shows the subsystems of a power transformer and Fig.4 [16] shows a multi sensor monitoring system composed of sensors, transmitter, acquisition board and display device, which performs the collection, transmission, processing, and storage of information through a computer program installed in the monitoring computer. DGA, PD and frequency measuring methods can all use sensors and can be non-invasive. Web based online detection systems allow power system operators to remotely access new incoming data as well as pre-existing data. These systems allow faults to be detected and identified from remote locations thereby allowing faster response times.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

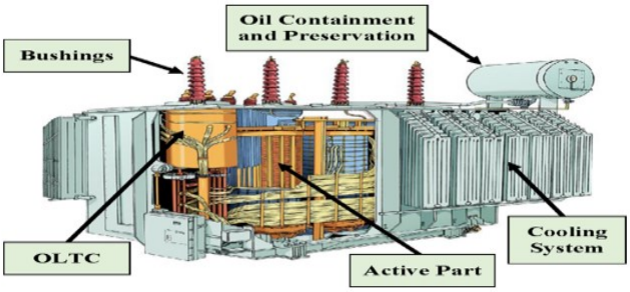

Figure 3. Subsystem of Transformers

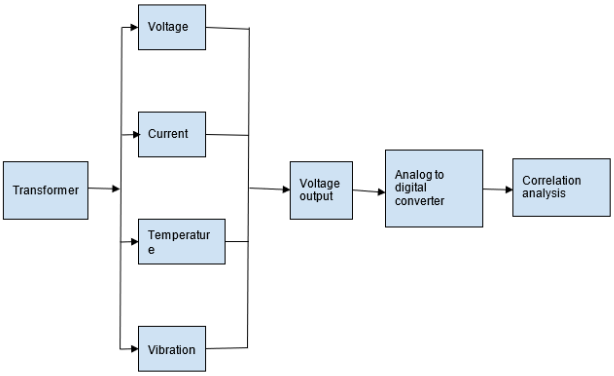

Figure. 4. Transformer CM using a multi-sensor monitoring system

D. Miscellaneous Topics

Diversity of methods developed for CM of transformers has led to many alternative techniques. Not all methods are as widely researched as DGA and PD. Those methods will be considered under the miscellaneous section. Several key methods including Frequency Response Analysis (FRA), Thermal analysis, Vibration analysis, etc. fall under this category. FRA is based on the deformation of the transformer's windings, causing its frequency to change [17]. Vibration analysis is performed by monitoring the vibrations induced in the windings of the power transformer. Under steady state conditions, any abnormal changes in vibration help extract diagnostic information and indicate the presence of faults [18]. Thermal CM works by monitoring the top oil temperature, hot spot temperature, oil interfacial tension, total amount of combustible gases etc. The heat generated by components allows for a diagnosis of their health. As loading and line disturbances frequently occur, thermal condition becomes an important marker of transformer capability and performance [19].

III. CONDITON MONORTING OF TRANSFORMERS

A. DGA Based Methods

In 2007, the dissolved oil compounds and moisture were tested in transformer Kraft insulation paper. Testing indicated the ability of dissolved oil compounds and moisture to show faults in power transformers [20]. Oil Impregnated Paper (OIP) test showed that oil and moisture have correlations with the health of power transformers [21]. As of 2011, different DGA techniques were used to determine a range of faults in transformers. CM methods can depend solely upon gases or the concentration of a particular gas present in the transformer's oil tank [22]. In later years, sensors were used to detect the presence of hydrogen in the oil tank. A fiber Bragg grating sensor was able to detect hydrogen in transformers oil which showed that compound detection in transformer oil was possible [23]. The importance of transformer bushings in DGA was also further explored. The Periodic manual bushing test gave the best results in DGA. Manual checks help with proper assessment of the health of the bushings and overall transformer, compared to remote web based online checks [12]. A study in 2020 dealt with the uses of spectral analysis. This method measured the frequency of the oil to determine its viscosity. Simultaneously, this method was used by researchers to determine the health of the transformers oil [24]. More faults occurring in bushings were examined and chromatography was used to determine specific compounds located in the transformer oil. Infrared was utilized to determine bushing heat, and to give a better idea of the health of the bushings [25].

B. PD Based Methods

For online measurements, a detection-based method that uses Ultra-High Frequency (UHF) signals emitted by the discharging source was used to detect faults in power transformers [6]. Three different types of PD sources using three different defect models (HV corona, floating part, and surface discharge) were tested in transformer oil. There is a distinction between the three types of PD issues which shows this method can be used practically. Finite Difference Time Domain (FDTD) and Numerical Electromagnetic Code (NEC) were used to find the partial discharge in a power transformer [26]. This method can isolate the location of the discharge. Another PD study found that the sensors inside and outside differ in response and the results vary because of the difference. It was concluded that this method is only accurate at a certain range for different sensors [27]. More research was done on a new type of antenna sensor to measure UHF [28]. This antenna is called the microstrip-fed planar elliptical monopole antenna. The research concluded that this antenna was able to monitor properly and is suitable for CM.

C. AI and Sensor Based Methods

(i) Methods using AI: The methods that use AI encompass many methods used in traditional CM. In many research papers, DGA data, PD data, and other miscellaneous data were collected to be used in the AI based model for CM. This section reviews research on AI and Sensor based methods that utilize data collected from online sources, data collected from DGA, data collected from PD, and data collected from other miscellaneous methods.

1) Data Collection from Online sources**:** Researchers used a design modeled after the Hidden Markov Models (HMM). This model received signals from the transformer and used them to predict and identify where the fault was located at. The researchers found this method of CM to be very effective [29]. Ontology Reasoning was also used where a multi agent system helped determine the fault and relate it to

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

other data [30]. Later, soft computing techniques were used, but those methods were not capable of producing a precise measurement, other than the general idea that there was a fault [31]. Another method considered the CM of power transformers as a health index rating based on its age. Using this method, current health score, future health score (after 2 years), current and future Probability of Failure (PoF) and end of life (EoL) for each transformer were calculated. A simple spreadsheet was used to calculate the health of the transformer based on observed measurements [32].

2) Data collected from DGA Based Methods**:** Some researchers used temporal characteristics to identify faults [33]. For continuous online analysis, the sliding window model was used. The use of Fuzzy Logic to detect faults was considered. But, the disadvantage of a fuzzy logic-based approach was that if the interface system was not provided with good data, it would not perform accurately [34]. Consequently, Feed Forward Artificial Neural Network (FFANN) was applied for fault detection. This network was fed preexisting data to be able to find the health index [35]. Another method proposed was the Neuro-Fuzzy technique (NFS) method that was based on the DGA of windings. Researchers found that this method had better accuracy than other methods as it combined fuzzy logic and ANN [36]. A new Fuzzy Logic method combined Roger, IEC, Doernenburg, key gas, and Duval techniques into one functioning fuzzy logic analysis. This analysis was able to detect many preexisting faults [37]. Another ML based approach called the Random Forest (RF) analysis was studied, where the algorithm was adjusted to pick from a pool of faults in order to identify a specific fault prediction [38]. Then a General Regression Neural Network (GRNN) method was used for CM of transformers. Data was collected via an external source to use as a reference for the newly collected data. The technique used a scoring system to detect faults [39]. Another research used a computer program that was built using MATLAB to detect deterioration in oil health. This research paper developed a standalone system for CM that was able to yield successful results [40].

3) Data Collected from PD Based Methods**:** In 2006, a Numerical Electromagnetic Code (NEC) was created where the simulation environment was a box of electromagnetic response of antennas and other metal structures. PD effects were simulated in a current transformer [26]. A new method was then developed by researchers, that combines PD and DGA (that fuses their data) to develop a more reliable and accurate way to detect faults in transformers. The model was based on D-S theory which is an extension of probability theory [41]. A practical CM method based on multi source information fusion was proposed using an assessment index system and a text preprocessing technique. This assessment was based on real time operation data and was proven to be helpful in early diagnosis and alerting of transformer's emergent faults [42].

4) Miscellaneous Methods**:** In some newer methods, transfer functions were used that utilized frequency response to determine faults [43]. An analytic model using Internet of Things (IoT) was created to measure the vibration signals in power transformers [44]. In this method, algorithms were created to predict faults and ultimately identify them. This method was able to detect winding turn-to-turn short circuit, transformer under- and over-excitation and also predict short-circuit currents. ML algorithms were proposed to model the transformer thermal behavior, to monitor the health of transformers. Here the thermal models were built using the data consisting of load profile, tap position, winding indicator temperature (WTI) measurement, ambient temperature, wind speed and solar radiation [45]. The researchers then built a new ML method that combined an evolutionary clustering method and dissolved gas subset analysis [46]. The first step was to cluster the data using an evolutionary k-MCA using Genetic Algorithm and then propose a traditional diagnosis sub models to separate the different faults related to the subsets.

(ii) Methods using Sensors: Sensors have been used in CM of transformers based on what type of data was needed for monitoring. The data collected from sensors was from one of the following methods viz., DGA based methods, PD based methods or miscellaneous methods based on their applications.

1) Data collected from DGA Based Methods: A dual sensor method was proposed for DGA based CM of transformers [47]. The method was composed of two parts. First the CO and H_2 were filtered and separated. The gas concentration measurement analysis of this research used two sensors to measure the CO and H_2. Another sensor system was developed that used a heat sensor inside the oil tank, loading monitors, noise monitors, and a human machine interface (HMI) interface using which data was accessed [48].
2) Data Collected from PD Based Methods*:* A sensor system using PD measurements was proposed for Ultra High Frequency (UHF) [49]. Four Radio frequency current transducers (RFCT) were used with an antenna on each. This allowed more frequency irregularities to be captured by the antennas. A new design for the UHF probe was developed [50]. The probe was described to have several key features that make it better than the commercial counterpart. This probe was able to withstand harsh environments while being more sensitive to PD frequencies. Another method used power transformers, secondary cables and voltage dividers [51]. These were used to measure discharge, and to measure discharge against each other. Some researchers used a special oil-immersed antenna as a sensor [52]. The antenna was placed inside epoxy resin which is used as an insulator for the internal antenna. A method of using online algorithms to monitor PD was developed, that used sensors attached to all substations [53] and a waveform classification algorithm was used to classify the waveforms by comparing the signal magnitude detected by each sensor. This method was able to identify the insulation status from the outside in a live hot line condition using the sensors.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

3) Miscellaneous Methods: A winding monitoring method was proposed in which a Distributed optical fiber Raman temperature sensing technology technique was proposed [54]. In this method Optical fiber OTDR technology is employed to measure the temperature of the winding via sensors. A new approach to measure leakage flux was developed [55] where the researchers created a device using FEM software and sensors to measure the current and leakage. The sensors were of low quality and were only used to measure the flux. Another researcher used the method of optic fiber-based PD monitoring with the Fiber Bragg sensor [56]. This sensor is mounted on top of an acrylic sheet instead of on the tank directly.

(iii) Web Based Methods: In 2006, a data storage system was implemented using Oracle 9i database that stored all the data in tables [57]. Later, a Computer Supported Collaborative Work (CSCW) technology system was developed. This system allowed for the data to be stored and viewed from all around the community. The community can collaborate on the direction of ideas [58]. A web-based platform was used to test a new method in a high voltage lab [59]. The new method is called Transmission Line Diagnostics (TLD). The researchers found that this method was just as sensitive to the windings as other methods. In this method, tests were taken from transformers and data was collected online to find similarities. Later, a C++ interface was created using Windows CE [60]. This interface stores data as well as shows vibration graphs. Methods such as Photo-Acoustic Emission Spectroscopy (PAS) and Gas Chromatography (GC) were able to relay data online with alarms if faults or irregularities were detected [61]. Zigbee technology was used as an interface for short range communications [62]. It's low power and low cost made it viable. An online web-based interface was created using UHF in a hydro power plant. This method incorporated online pulse recognition to identify the pulses and determine the pulse type [63]. Some techniques were proposed for online and on-site PD diagnosis of transformers in service, to detect defects in coil insulation [64].

Researchers examined a newly created method of PD [65] for the capacitance and dissipation factor measurement. Several techniques were described in this paper to differentiate between internal and external noise. The proposed method relayed all data back to a computer via optic lines which allowed the data to be examined. LabVIEW software was used to store large quantities of data. There were alarm codes embedded in datasets [66]. Later, an Online Monitoring of Distribution Transformer (OMDT) system was created. This system also used Zigbee technology. This method used an LCD monitor at transformers to relay the data [67]. A review of the precision 6 power transformers using online PD discharge method was conducted [68]. In 2017, a GSM system was proposed [69]. A Global Service Mobile (GSM) System accounts for nearly all types of CM methods including DGA and load currents. This method used a modem to relay error messages to mobile devices so that the engineers could detect and repair the problem. A Supervisory Control and Data Acquisition (SCADA) system was developed where this system monitors, as well as predicts abnormalities in real time [70] In addition, it can also estimate down time for repair. An IoT based transformer monitoring method was developed using open-source software using a Arduino Mega 2560 microcontroller and a ThingSpeak web interface was proposed [71]. This method was able to store data in a cloud device and was able to display that data. In another research, Wi-Fi was used as a form of data transfer in an IoT based CM system [72]. A design based on a Radio Frequency Identification Device (RFID) was proposed by researchers [73]. This system includes an energy management module, signal acquisition module, signal processing module and RF module. The RF module was fed by a power supply. Another method proposed a remote online monitoring system for transformer winding deformation using a cloud-based system [74]. The main data used was a current–voltage characteristic graph. The researchers observed that the tested model performed as it should. An IoT CM method was developed by researchers [75] to monitor the temperature of transformer oil and detect various gases like Methane, Carbon monoxide, Hydrogen, Acetylene, Ethane etc. In this method, the communication system sends data through Wi-Fi and SMS, if faults are detected. Another IoT based online program that updates and alerts in real time was developed [76]. It used sensors to gather data and utilizes AI algorithms to detect faults. This method used preexisting data to test against new data and the system was updated when a fault was detected.

(iv) Some other miscellaneous methods are discussed in this section.

1) Frequency Response Analysis (FRA): In 2005, a new type of FRA analysis using a synthetic spectral analysis was used to conduct research on a test transformer. This new analysis was 90% accurate [77]. A method that simplifies the graphs of FRA was introduced. The proposed approach used polar plot to try and simplify the graphs so that it is easier to interpret. The researchers used already existing FRA analysis to base the creation of polar plots on. They found that the polar plot method may become useful for FRA data [78]. Sweep Frequency Response Analysis (SFRA) was introduced. This technique relied on assessing mechanical movements in power transformers. The researchers used a transformer to conduct their test on this method and found SFRA was a viable method for CM. A lumped parameter model was introduced that could consider different transformers at different health levels and allow FRA to analyze them [79].

2) Thermal Analysis: The thermal monitoring approach [80] used heat around the transformer to anticipate faults. There are temperature sensors, load probes, fan probes, a remote monitoring data system, and an Intelligent Electronic Device (IED) to read the data. This approach was able to make a model of the transformers heat at any given time in the recorded data. In another approach, a thermal imager was used to show hotspots in power transformers [81]. The drawback of using thermal imagery is that this method had to be manually done.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

3) Vibration Analysis: The use of vibrations for power transformer monitoring was researched on and was found to be helpful in ensuring the transformer's health in systems influenced by adjacent HVDC lines also [82]. A Laser Doppler Vibrometer was used to make measurements of the winding vibration. Researchers investigated the winding vibration of a live transformer to characterize the changes in spatial and frequency features of vibration under conditions of mechanical faults in the transformer winding [83]. Vibration research also focused on the vibration of the transformer tank [84]. It was observed that the vibrations of the core directly affected the health of the power transformer. In another method, researchers created a database using a Health and Usage Monitoring (HUM) system [85]. It was concluded that this method could distinguish the transformer operating conditions.

4) Other Methods: Prony's method- a non-invasive monitoring technique was used to monitor the transient vibration signals of the (OLTC) or On Load tap Changer [86]. But this method was unable to distinguish a new contact from an aged one. Another method analyzed OLTC measurements using a vibration signal interpretation algorithm and a waveform-based vibration signal comparison method [87]. The results improved the visibility of OLTC's mechanical operation. A polymerization method was developed to identify moisture content in the oil and oil insulation paper [88]. This research found that this method was very effective in identifying moisture levels. This research also found that a key role in moisture content is the environment itself [88]. Another method was researched to assess insulation condition, their responsiveness to aging and how their status can be correlated to transformer age and condition [89]. The results showed some correlation between transformer aging, paper aging and oil aging. Two types of techniques were applied by the researchers to solve CM in power transformers [89]. The first being Transformer Inrush Current (TIC) and Transformer Internal Faults (TIF). This method was found to yield efficient results for blocking tripping signals during external faults.

IV. FUTURE SCOPE

Based on the literature review, condition monitoring of power transformers is a vital part of keeping our power grid intact. With such importance, power transformers must be monitored in a precise, and intuitive manner. In order to accomplish this, there must be a mixture of well-established technological methods and newer artificial intelligence/machine learning methods. Such a newly developed framework for CM of power transformers should include techniques that can increase the lifespan and reliability of the power transformers. Newer online condition monitoring methods must be developed to manage the maintenance cycle and increase the life of a transformer.

AI algorithms continue to prove themselves as a key technology in the ever-growing field of CM. An AI algorithm combined with human intuition can make for a sound method of condition monitoring of power transformers. Newer intelligent machine learning methods were proposed [90] for diagnosing both power and distribution transformers. The authors listed several disadvantages of intelligent diagnostic techniques and provided possible solutions and future directions. The major challenges that were listed are (a) possibility of high error (b) algorithm selection (c)small dataset (d) imbalanced dataset and (e) real time capabilities. Future trends in application of ML techniques for CM of transformers can be categorized into 2 areas. One of the critical challenges in using ML for CM of transformers is the insufficient failure data that ML needs for its training phase. Power transformers operate under normal conditions most of the time and so acquiring relevant data corresponding to faulty operating conditions becomes difficult. Even if data were collected, there would not be any big variations in the data for the ML to differentiate between normal operations and faulty operations. For the ML algorithm to work effectively, there needs to be diverse sets of transformer fault and failure data under various disturbance conditions. But availability of diverse datasets is scarce compared to normal operations datasets. Due to the scarce availability of trustworthy datasets, additional efforts must be made to build reliable mathematical models/experimental methods to obtain the necessary datasets for training ML algorithms. It was observed that several factors must be considered while deciding on the most effective ML model for a particular task [91]. A tradeoff between problem constraints and the performance of every monitoring and diagnostic technique were compared quantitatively to determine the optimal solution for the given problem. Other researchers also reviewed using a health index to assess transformer insulation systems based on oil quality, DGA and condition of the paper and handling the data uncertainty arising due to data unavailability [92]. Even Though AI methods exhibit strong data mining capability, when AI is being used in classification problems, due to its inherent nature of comparing new events with past data, the resulting diagnosis would have a lower accuracy [93]. A comprehensive review of ML methods used for CM of transformers is given in [94]. The authors had presented a state-of-the-art review on ML based intelligent diagnostics applied for PD detection, localization, and pattern recognition. It was observed that Deep Learning (DL) based methods were yet to be explored for PD localization and there was not a mathematical foundation to DL methods compared to traditional ML methods. Some potential solutions to overcome problems of insufficient data, lack of consistency between training and testing data, real time capability, unbalanced data, complexity of the model were proposed. The real challenge to solve the above-mentioned problems in CM and diagnostics of transformers would be to develop ML methods that would yield accurate and practical results even if (1) the datasets are imbalanced and (2) CM is expected to provide results about the health of the transformer under real time. Newer faster intelligent ML methods must be developed to handle these challenges so that the lifespan of the transformer can be increased by reducing the possibility of catastrophic failures in transformer health.

V. CONCLUSION

In conclusion, this paper significantly contributes to the field of CM of transformers through an extensive literature review. In this regard, the traditional methods used in CM such as

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

DGA and PD were analyzed first along with their disadvantages. Then the newer methods using AI and machine learning were discussed along with their challenges. Among them, several authors attempted to improve the accuracy and robustness of CM by using intelligent algorithms and modifying a certain section of the algorithm or building a hybrid method combining corresponding approaches of other intelligent methods. The key components that are essential for practical CM of power transformers have been identified, including data collection and processing, analysis and dissemination. It was observed that machine learning based methods can provide a paradigm shift in the status where the conventional analytical approaches and model-based approaches fail to yield accurate results especially in the presence of large quantities of data. Considerable effort is needed to build reliable and accurate models that are capable of outputting the much-needed data for the training part in ML. Also due to significant differences in volume of oils used, different types of insulation materials used, different classes of voltages and the unpredictability of the CM process itself, obtaining near perfect accuracy on the forecast of transformer faults is impossible. In such instances, the intelligence provided by newer and smarter machine learning techniques can provide predictions and decisions that are based on the data collected, resulting in accurate health monitoring of transformers.

REFERENCES

[1] H. Sun, Y. Huang, and C. Huang, “Fault Diagnosis of Power Transformers Using Computational Intelligence: A Review,” Energy Procedia, vol. 14, pp. 1226-1231, 2012. https://doi.org/10.1016/j.egypro.2011.12.1080.

[2] K. Meng, Z. Y. Dong, D. H. Wang , and K. P. Wong, "A Self-Adaptive RBF Neural Network Classifier for Transformer Fault Analysis," in IEEE Transactions on Power Systems, vol. 25, no. 3, pp. 1350-1360, Aug. 2010, doi: 10.1109/TPWRS.2010.2040491.

[3] J. Singh, Y. R. Sood and R. K. Jarial, "Condition Monitoring of Power Transformers - Bibliography Survey," in IEEE Electrical Insulation Magazine, vol. 24, no. 3, pp. 11-25, May-June 2008, doi: 10.1109/MEI.2008.4591431.

[4] D. A. Barkas, I. Chronis, and C. Psomopoulos, “Failure mapping and critical measurements for the operating condition assessment of power transformers”, Energy Reports, vol.8, no.9, pp.527-547, 2022,https://doi.org/10.1016/j.egyr.2022.07.028.

[5] S. A. Wani, A. S. Rana, S. Sohail, O. Rahman, S. Parveen, and S. A. Khan, “Advances in DGA based condition monitoring of transformers: A review,” Renewable and Sustainable Energy Reviews, vol. 149, 2021. https://doi.org/10.1016/j.rser.2021.111347.

[6] R. A. Jongen, P. Morshuis, S. Meijer and J. J. Smit, "Identification of partial discharge defects in transformer oil," Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 565-568, 2005. doi: 10.1109/CEIDP.2005.1560745.

[7] D. Nedelcut, D. Sacerdotianu, G. Tanasescu, S. Nicolae, and L. Voinescu, "On-line and off-line monitoring-diagnosis system (MDS) for power transformers," International Conference on Condition Monitoring and Diagnosis, pp. 949-955, 2008. doi: 10.1109/CMD.2008.4580440.

[8] Y. Liang, Z. Wang , and Y. Liu, "Power transformer DGA data processing and alarming tool for on-line monitors," IEEE/PES Power Systems Conference and Exposition, pp. 1-8, 2009. doi: 10.1109/PSCE.2009.4840217.

[9] S. Tenbohlen and F. Figel, "On-line condition monitoring of power transformers," 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.00CH37077), Singapore, 2000, pp. 2211-2216 vol.3, doi: 10.1109/PESW.2000.847699.

[10] M. R. Hussain, S. S. Refaat, and H. Abu-Rub, "Overview and Partial Discharge Analysis of Power Transformers: A Literature Review," IEEE Access, vol. 9, pp. 64587-64605, 2021. doi: 10.1109/ACCESS.2021.307528

[11] N. A. Muhamad, B. T. Phung, T. R. Blackburn, and K. X. Lai, "Comparative Study and Analysis of DGA Methods for Transformer Mineral Oil," IEEE Lausanne Power Tech, Lausanne, Switzerland, pp. 45-50, 2007. doi: 10.1109/PCT.2007.4538290.

[12] B. D. Malpure, and S. E. Chaudhari, "Importance of bushing- DGA in condition assessment of power transformers," IEEE International Conference on Condition Monitoring and Diagnosis, pp. 589-592, 2012. doi: 10.1109/CMD.2012.6416213.

[13] S. Tenbohlen , M. Siege, and M. Beltle, “Partial Discharge Monitoring of Power Transformers by UHF Sensors,” Advanced Research Workshop on Transformers, 2016, pp. 1-6.

[14] M. Žarković, and Z. Stojković, “Analysis of artificial intelligence expert systems for power transformer condition monitoring and diagnostics,” Electric Power Systems Research, 2017, pp. 125-136.

[15] H. Samimi, M. and Dadashi Ilkhechi, H, “Survey of different sensors employed for the power transformer monitoring,” IET Sci. Meas. Technol., 14: pp. 1-8, 2020. https://doi.org/10.1049/iet-smt.2019.0103

[16] W. Li, T. Fang, C. Guo, J. Xie, H. Ma, and Z. Chi, "Transformer fault detection method based on multi- source sensing data correlation analysis," International Conference on Wireless Communications and Smart Grid (ICWCSG), Hangzhou, China, pp. 284-288, 2021. doi: 10.1109/ICWCSG53609.2021.00062.

[17] N. Hashemnia, A. Abu-Siada, and S. Islam, "Improved power transformer winding fault detection using FRA diagnostics – part 2: radial deformation simulation," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, no. 1, pp. 564-570, Feb 2015. doi: 10.1109/TDEI.2014.004592.

[18] S. A. Rikardo, C. B. Bambang, C. Sumaryadi, T. D. Yulian, S. E. Arief and, S. F. Irvan Kharil, "Vibration monitoring on power transformer," International Conference on Condition Monitoring and Diagnosis, pp. 1015-1016, 2008.doi: 10.1109/CMD.2008.4580454.

[19] Y. Tamsir, Sumaryadi, H. Gumilang, A. Pharmatrisanti, B. Cahyono, and R. Siregar, "Thermal condition assessment for power transformers operated in tropical conditions,"International Conference on Condition Monitoring and Diagnosis, pp. 559-561, 2008. doi: 10.1109/CMD.2008.4580349.

[20] Z. Poniran, and Z. A. Malek, "Life Assessment of Power Transformers via Paper Ageing Analysis," International Conference on Power Engineering, Energy and Electrical Drives, pp. 460-465, 2007. doi: 10.1109/POWERENG.2007.4380104.

[21] C. Chakradhar Reddy, E. Johnson, and T. S. Ramu, "On the life estimation of oil impregnated paper insulated transformer bushings," 2007 Electrical Insulation Conference and Electrical Manufacturing Expo, USA, pp. 13-16, 2007. doi: 10.1109/EEIC.2007.4562578.

[22] H. Ding, R. Heywood, J. Lapworth, and S. Ryder, "Learning from success and failure in transformer fault gas analysis and interpretation," IET Conference on Reliability of Transmission and Distribution Networks (RTDN 2011), pp. 1-6, 2011. doi: 10.1049/cp.2011.0522.

[23] G. Ma, C. Li, Y. Luo, R. Mu, and L. Wang, “High sensitive and reliable fiber Bragg grating hydrogen sensor for fault detection of power transformer,” Sensors and Actuators B: Chemical, vol. 169, pp. 195-198, 2012. ISSN 0925-4005,

[24] A. R. Aarathy, S. S. Pillai, D. Gopinath, S. S. Sajan, A. R. Nair, and B. Aryanandiny, "Spectral analysis for condition assessment of Transformer oil under different aging conditions," IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC), pp. 1-5, 2020. doi: 10.1109/STPEC49749.2020.9297709.

[25] Z. Lu, R. Wei, Y. Duan, P. Hu, J. Zou, and Y. Fang, "Fault Analysis of Medium Voltage Bushing of 110kV Main Transformer Based on Infrared Accurate Temperature Measurement and Oil Chromatographic Analysis," IEEE International Conference on Power Systems Technology (POWERCON), pp. 1-5, 2022. doi: 10.1109/POWERCON53406.2022.9929803.

[26] S. Xiao, P. J. Moore and, M. D. Judd, "Time-Frequency Modelling of Partial Discharge Radiation from Current Transformers," Proceedings of the 41st International Universities Power Engineering Conference, pp. 921-925, 2006. doi: 10.1109/UPEC.2006.367614.

[27] S. Meijer, M. D. Judd, and S. Tenbohlen, "Sensitivity check for radio frequency partial discharge detection for power transformers," International Conference on Condition Monitoring and Diagnosis, pp. 1031-1035, 2008. doi: 10.1109/CMD.2008.4580458.

[28] H. Chai, B. T. Phung, and D. Zhang, "Development of UHF Sensors for Partial Discharge Detection in Power Transformer," 2018 Condition Monitoring and Diagnosis (CMD), pp. 1-5, 2018. doi: 10.1109/CMD.2018.8535779.

[29] Q. Suxiang, J. Weidong, H. Hongsheng and, Y. Gongbiao, "Transformer Power Fault Diagnosis System Design Based On The HMM Method," IEEE International Conference on Automation and Logistics, pp. 1077-1082, 2007. doi: 10.1109/ICAL.2007.4338728.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

[30] F. Davoodi Samirmi, W. Tang, and H. Wu, "Power transformer condition monitoring and fault diagnosis with multi-agent system based on ontology reasoning," IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), pp. 1-6, 2013. doi: 10.1109/APPEEC.2013.6837251.
[31] J.I. Aizpurua, B.G. Stewart, S.D.J. McArthur, B. Lambert, J.G. Cross, and V.M. Catterson, "Improved power transformer condition monitoring under uncertainty through soft computing and probabilistic health index," Applied Soft Computing, vol. 85, 2019. https://doi.org/10.1016/j.asoc.2019.105530.
[32] A. Nikam , and A. Thorat, 2021, "Condition Monitoring of Power Transformer: A Practical Approach," INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT), vol. 10, no. 05, May 2021.
[33] Y. Kong, J. Yuan, T. Zhang, and Z. Zhao, "A Method for online monitoring the dissolved gas in power transformer oil based on temporal characteristics," International Power Engineering Conference , pp. 344-348, 2007.
[34] B. Nemeth, S. Laboncz, and I. Kiss, "Condition monitoring of power transformers using DGA and Fuzzy logic," IEEE Electrical Insulation Conference, pp. 373-376, 2009. doi: 10.1109/EIC.2009.5166373
[35] A. E. B. Abu-Elanien, M. M. A. Salama, and M. Ibrahim, "Determination of transformer health condition using artificial neural networks," International Symposium on Innovations in Intelligent Systems and Applications, pp. 1-5, 2011. doi: 10.1109/INISTA.2011.5946173.
[36] H. Malik, A. K.Yadav, S. Mishra, and T. Mehto, "Application of neuro-fuzzy scheme to investigate the winding insulation paper deterioration in oil-immersed power transformer," International Journal of Electrical Power & Energy Systems, vol. 53, pp. 256-271, 2013. https://doi.org/10.1016/j.ijepes.2013.04.023.
[37] A. Abu-Siada, and S. Hmood, "A new fuzzy logic approach to identify power transformer criticality using dissolved gas-in-oil analysis," International Journal of Electrical Power & Energy Systems, vol. 67, pp. 401-408, 2015. https://doi.org/10.1016/j.ijepes.2014.12.017.
[38] K. Deng, W. Xiong, L. Zhu, H. Zhang, and Z. Li, "Prediction of dissolved gas in power transformer oil based on random forests algorithm," 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), pp. 1531-1534, 2015. doi: 10.1109/DRPT.2015.7432473.
[39] M. M. Islam, G. Lee, and S. N. Hettiwatte, "Application of a general regression neural network for health index calculation of power transformers," International Journal of Electrical Power & Energy Systems, vol. 93, pp. 308-315, 2017. https://doi.org/10.1016/j.ijepes.2017.06.008.
[40] J. Torres, J. M. Guerrero, W. Leones and, C. A. Platero, "Implementation of a Condition Monitoring Software for Mineral Oil-Immersed Transformers via Dissolved Gas In-Oil Analysis," IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe, pp. 1-6, 2021. doi: 10.1109/EEEIC/ICPSEurope51590.2021.9584615.
[41] L. V. Feng, D. U. Hai-lian, H. Sun, Z. Wang, and L. I. Yuan, "Power Transformer Fault Diagnosis Based on Data Fusion," IFAC Proceedings Volumes, vol. 41, no. 2, pp. 11013-11017, 2008.
[42] C. Xie, G. Zou, H. Wang and Y. Jin, "A new condition assessment method for distribution transformers based on operation data and record text mining technique," China International Conference on Electricity Distribution, pp. 1-7, 2016. doi: 10.1109/CICED.2016.7576179.
[43] A. Setayeshmehr, H. Borsi, E. Gockenbach and I. Fofana, "On-line monitoring of transformer via transfer function," IEEE Electrical Insulation Conference, pp. 278-282, 2009. doi: 10.1109/EIC.2009.5166357.
[44] M. Bagheri, V. Nurmanova, A. Zollanvari, S. Nezhivenko and, B. T. Phung, "IoT Application in Transformer Fault Prognosis Using Vibration Signal," IEEE International Conference on High Voltage Engineering and Application (ICHVE), pp. 1-5, 2018. doi: 10.1109/ICHVE.2018.8641873.
[45] A. Doolgindachbaporn, G. Callender, P. L. Lewin, E. Simonson, and G. Wilson, "Data Driven Transformer Thermal Model for Condition Monitoring," IEEE Transactions on Power Delivery, vol. 37, no. 4, pp. 3133-3141, Aug. 2022, doi: 10.1109/TPWRD.2021.3123957.
[46] A. Nanfak, S. Eke, F. Meghnefi, I. Fofana, G. M. Ngaleu, and C. H. Kom, "Hybrid DGA method for power transformer faults diagnosis based on evolutionary k-means clustering and dissolved gas subsets analysis," IEEE Transactions on Dielectrics and Electrical Insulation, doi: 10.1109/TDEI.2023.3275119.
[47] Y.Qiping, X. Wude, and L.Zhida, "Application of Group Sensor for Transformer On-line Monitoring," IEEE/PES Transmission & Distribution Conference & Exposition, pp. 1-4, 2005. doi: 10.1109/TDC.2005.1546919.
[48] A. A. Nelson, G. C. Jaiswal, M. S. Ballal, and D. R. Tutakne, "Remote condition monitoring system for distribution transformer," Eighteenth National Power Systems Conference (NPSC), pp. 1-5, 2014. doi: 10.1109/NPSC.2014.7103848.
[49] C. Yonghong ,"Study of on-line monitoring method of partial discharge for power transformers based on RFCT and microstrip antenna," Proceedings Electrical Insulation Conference and Electrical Manufacturing Expo, pp. 103-107, 2005. doi: 10.1109/EEIC.2005.1566268.
[50] A. Reid, M. Judd, and C. Johnstone, "Development of UHF transformer probe sensors for on-line partial discharge measurement," 44th International Universities Power Engineering Conference (UPEC), 2009, pp. 1-4.
[51] Z. Zhang, P. Yue, and W. Shi, "A New Method for Over-voltage Online Monitoring Based on Chain Parameters," Asia-Pacific Power and Energy Engineering Conference, pp. 1-4, 2010. doi: 10.1109/APPEEC.2010.5449265.
[52] M. Liu, and Z. Li, "An Online UHF PD Monitoring System for Power Transformer and Its Applications," Asia-Pacific Power and Energy Engineering Conference, pp. 1-4, 2010.doi: 10.1109/APPEEC.2010.5449362.
[53] Y. Kakimoto et al., "Long-term Online Partial Discharge Trend Monitoring for Cast Resin Transformers in Switchboard," 8th International Conference on Condition Monitoring and Diagnosis (CMD), pp. 133-135, 2020. doi: 10.1109/CMD48350.2020.9287273.
[54] D. Yu, L. Jing, W. Shengbin, Z. Aide, Z. Hesan, and Z. Chao, "Study on On-line Monitoring of Temperature of Transformer Winding Based on Distributed Fiber Optical Temperature Sensing Technology," IEEE 8th International Conference on Properties & applications of Dielectric Materials, pp. 250-253, 2006. doi: 10.1109/ICPADM.2006.284164.
[55] M. F. Cabanas, "A New Online Method Based on Leakage Flux Analysis for the Early Detection and Location of Insulating Failures in Power Transformers: Application to Remote Condition Monitoring," IEEE Transactions on Power Delivery, vol. 22, no. 3, pp. 1591-1602, July 2007, doi: 10.1109/TPWRD.2006.881620.
[56] B. Sarkar, C. Koley, N.K. Roy, and P. Kumbhakar, "Condition monitoring of high voltage transformers using Fiber Bragg Grating Sensor, Measurement," Science Direct, vol. 74, pp. 55-267, 2015. https://doi.org/10.1016/j.measurement.2015.07.014.
[57] F. Poza, P. Marino, S. Otero, and F. Machado, "Programmable electronic instrument for condition monitoring of in-service power transformers," IEEE Transactions on Instrumentation and Measurement, vol. 55, no. 2, pp. 625-634, April 2006. doi: 10.1109/TIM.2006.870122.
[58] Su, H., Dang, J., and Zhao, "A Web-Based CSCW System for Remote Substation Fault Diagnosis. In: Information Technology For Balanced Manufacturing Systems. BASYS," IFIP International Federation for Information Processing, vol. 220. https://doi.org/10.1007/978-0-387-36594-7_41.
[59] A. Singh, T. De Rybel, J. R. Marti, and K. D. Srivastava, "Field Validation Tests of the TLD Box for Online Power Transformer Winding Monitoring Systems," Canadian Conference on Electrical and Computer Engineering, pp. 141-144, 2007. doi: 10.1109/CCECE.2007.42.
[60] T. -T. He, J. -D. Wang, J. Guo, H. Huang, X. -X. Chen, and J. Pan, "A Vibration Based Condition Monitoring System for Power Transformers," Asia-Pacific Power and Energy Engineering Conference, pp. 1-4, 2009. doi: 10.1109/APPEEC.2009.4918121.
[61] E. A. Mackenzie, J. Crossey, A. dePablo, and W. Ferguson, "On-line monitoring and diagnostics for power transformers," IEEE International Symposium on Electrical Insulation, pp. 1-5, 2010.doi: 10.1109/ELINSL.2010.5549734.
[62] X. Chen, Z. Xu, D. Li, and M. Wei, "Wireless Sensor Technology Used in Transformer's Condition Monitoring System," 2010 International Conference on E-Business and E-Government, pp. 1488-1490, 2010. doi: 10.1109/ICEE.2010.378.
[63] W. Yuan, G. Chuanli, W. Zhipeng, D. Pengcheng, and L. Yun, "Online UHF PD Monitoring for Step-up Transformers of Hydropower Plant," Third International Conference on Measuring Technology and Mechatronics Automation, pp. 771-774, 2011. doi: 10.1109/ICMTMA.2011.476.
[64] C. -S. Xu, Z. -Q. Sun, and G. -J. Zhang, "On-line and on-site PD monitoring and diagnosis of power transformer," IEEE International Conference on Condition Monitoring and Diagnosis, pp. 293-296, 2012. doi: 10.1109/CMD.2012.6416434.
[65] M. Koch, and M. Krüger, "A new method for on-line monitoring of bushings and partial discharges of power transformers," IEEE International Conference on Condition Monitoring and Diagnosis, pp. 1205-1208, 2012. doi: 10.1109/CMD.2012.6416378.
[66] C. B. Xu, F. H. Wang, and Z. J. Jin, "Design and implementation of vibration on-line monitoring system of power transformer," IEEE Power & Energy Society General Meeting, pp. 1-5, 2013. doi: 10.1109/PESMG.2013.6672659.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

[67] T. S. Abin, K.C. Ajesh, B. M. Varghese, R. Nadesan, and A. Sivan, “Design and Implementation of High Precision Automated Online Monitoring of Distribution Transformer (OMDT) Device,” INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) vol. 3, no.5, May 2014.

[68] O. D. L. Campos , H. Zhu, "Condition assessment of 653 instrument transformers with on-line PD testing," International Conference on Condition Monitoring and Diagnosis (CMD), pp. 168-171. doi: 10.1109/CMD.2016.7757797.

[69] S.Gaikwad, R. Mehta, P. Shetye, J. Khut, and K. Bani, “GSM based distribution Transformer Monitoring System,” INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) ICIATE, vol. 5 , no.1 , 2017.

[70] M. S. Ballal, G. C. Jaiswal, A. Doorwar , and B. Venkatesh, "Online Condition Assessment of Power Transformers using Neural Network," Innovations in Power and Advanced Computing Technologies (i-PACT), Vellore, India, pp. 1-4, 2019.doi: 10.1109/i-PACT44901.2019.8960161.

[71] O. Yaman, and Y. Biçen , “An Internet of Things (IoT) based Monitoring System for Oil-immersed Transformers,” Balkan Journal of Electrical and Computer Engineering, vol.7, pp. 226-234. DOI: 10.17694/bajece.524921.

[72] A. A. Sonune ,A. A. Akotkar , M.S. Talole , P. S. Jaiswal, S. V. Sonkusale, and V. N. Gayki, “Condition Monitoring of Distribution Transformer using IOT,” INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) ,vol 9, no. 6 , June 2020.

[73] W. Jian, Z. Mengzhao, Z. Wenbing, G. Zhaoliang, W. Xuelei, and Z. Qingdong, "The Self-powered RFID Sensor System for Power Transformer Condition Monitoring," IEEE 4th Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), pp. 613-617, 2021.doi: 10.1109/IMCEC51613.2021.9482331.

[74] Y. Zhou, Y. Ma, M. Dai, T. Zhu, J. Du, H. Wu, and Z. Liao, “Remote online monitoring system for transformer winding deformation based on current–voltage characterized graph,” Energy Reports, vol. 9, no. 1, pp. 688-695, 2023. https://doi.org/10.1016/j.egyr.2022.11.032.

[75] D. S. Shastrimath , S. Vasudevamurthy , S. Shastrimath , K. Prathyusha , Panchavati, N. Sushma , and S. Yashaswini , “IoT based Condition Monitoring of Transformer,” INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) vol.11, no.01, January 2022.

[76] M. H. Hashemi, and S. Dikmen, "Real-Time Condition Monitoring of Power Transformers Using the Internet of Things (IoT) and Dissolved Gas Analysis," XIX International Scientific Technical Conference Alternating Current Electric Drives (ACED).

[77] J. Kim, B. Park, S. C. Jeong, S. W. Kim, and P. Park, "Fault diagnosis of a power transformer using an improved frequency-response analysis," IEEE Transactions on Power Delivery, vol. 20, no. 1, pp. 169-178, Jan. 2005. doi: 10.1109/TPWRD.2004.835428.

[78] B. J. Small, and A. Abu-Siada, "A new method for analysing transformer condition using frequency response analysis," IEEE Power and Energy Society General Meeting, pp. 1-5, 2011.doi: 10.1109/PES.2011.6039470.

[79] A. Shintemirov, "Modelling of power transformer winding faults for interpretation of frequency response analysis (FRA) measurements," 4th International Conference on Power Engineering, Energy and Electrical Drives, pp.1352-1357, 2013. doi: 10.1109/PowerEng.2013.6635810.

[80] Sumaryadi, B. Cahyono, A. Pharmatrisanti, R. Siregar , and Y. Tamsir, "Automatic thermal monitoring on power transformers," International Conference on Condition Monitoring and Diagnosis, pp. 485-487, 2008. doi: 10.1109/CMD.2008.4580331.

[81] T. Mariprasath, and V. Kirubakaran, “A real time study on condition monitoring of distribution transformer using thermal imager,” Infrared Physics & Technology, vol. 90, pp. 78-86, 2018. https://doi.org/10.1016/j.infrared.2018.02.009.

[82] M. Beltle , and S. Tenbohlen, "Usability of vibration measurement for power transformer diagnosis and monitoring," IEEE International Conference on Condition Monitoring and Diagnosis, pp. 281-284, 2012. doi: 10.1109/CMD.2012.6416431.

[83] J. Zheng, J. Pan, and H. Huang, “An experimental study of winding vibration of a single-phase power transformer using a laser Doppler vibrometer, Applied Acoustics,” vol. 87, pp. 30-37, 2015. https://doi.org/10.1016/j.apacoust.2014.06.012.

[84] M. Jin, and J. Pan, “Vibration transmission from internal structures to the tank of an oil-filled power transformer, Applied Acoustics,” vol. 113, pp. 1-6, 2016. https://doi.org/10.1016/j.apacoust.2016.05.022.

[85] K. Hong, H. Huang, Y. Fu, and J. Zhou, “A vibration measurement system for health monitoring of power transformers, Measurement,” vol. 93 , pp. 135-147, 2016. https://doi.org/10.1016/j.measurement.2016.07.002.

[86] F. A. Wegelin, R. S. Magalhaes, L. A. L. de Almeida , and M. Fontana, "Condition Monitoring of Power Transformers Using Acoustic Signal Prony's Analysis," IEEE Instrumentation and Measurement Technology Conference Proceedings, pp. 1384-1387, 2005. doi: 10.1109/IMTC.2005.1604376.

[87] J. Seo, "A Practical Scheme for Vibration Signal Measurement-Based Power Transformer on-Load Tap Changer Condition Monitoring," Condition Monitoring and Diagnosis (CMD), pp. 1-4, 2018. doi: 10.1109/CMD.2018.8535923.

[88] M. Ariannik, A. A. Razi-Kazemi, and M. Lehtonen, “An approach on lifetime estimation of distribution transformers based on degree of polymerization,” Reliability Engineering & System Safety, vol. 198, 2020. https://doi.org/10.1016/j.ress.2020.106881.

[89] B. Noirhomme, E. David, H. Garbi, M. C. Lessard , and R. Boissonneault, "Application of dielectric response techniques for the condition assessment of power transformers," CEIDP '05. Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 273-276, 2005. doi: 10.1109/CEIDP.2005.1560674.

[90] E. Nezhad, A., and M. Samimi, “A review of the applications of machine learning in the condition monitoring of transformers. “ Energy Syst ,2022. https://doi.org/10.1007/s12667-022-00532-5.

[91] O. Surucu, S.A.Gadsden, and J. Yawney, “Condition Monitoring using Machine Learning: A Review of Theory, Applications, and Recent Advances,” Expert Systems with Applications, vol. 221, 2023. https://doi.org/10.1016/j.eswa.2023.119738.

[92] D. Rediansyah, R. A. Prasojo, Suwarno, and A. Abu-Siada, "Artificial Intelligence-Based Power Transformer Health Index for Handling Data Uncertainty," IEEE Access, vol. 9, pp. 150637-150648, 2021. doi: 10.1109/ACCESS.2021.3125379.

[93] Z. Yan, T. Yufeng, L. Yongqiang, and L. Zhaowen, “Fault diagnosis of transformer using artificial intelligence: A review “Frontiers in Energy Research” vol.10, 2022. , DOI=10.3389/fenrg.2022.1006474 .

[94] S. Lu, H. Chai, A. Sahoo, and B. T. Phung, "Condition Monitoring Based on Partial Discharge Diagnostics Using Machine Learning Methods: A Comprehensive State-of-the-Art Review," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 27, no. 6, pp. 1861-1888, Dec. 2020.doi: 10.1109/TDEI.2020.009070.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)