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A Review on Real Time Fault Detection and Intelligent Health Monitoring Techniques of Transformer

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ABSTRACT
This paper reviews real time fault detection and intelligent health monitoring techniques (IHMT) of transformer. Practically gas generation in transformer oil is induced by electrical and thermal faults resulting from unfavorable operating conditions in transformers. Along with aged conditions of transformers, operating factors such as high temperature, strong electrical fields, electrical discharges, mechanical stresses, insulation damage and contaminants pose imminent risks of malfunctioning and irreversible damage to the transformers. Real-time monitoring of transformers ensures equipment safety and essential intervention in exact time subsequently lessening the danger of non-plan energy power outages. In this paper reviewing the different types of faults on transformer & existing monitoring methods of the transformer are presented. Earlier the researchers work on chemical techniques used to health monitoring of transformer. Presently work on intelligent dissolved gas analysis (DGA) have gained great significance and attention to ensure timely and accurate diagnostics of the electrical and thermal faults occurring in the transformers.

.***Keywords* -** Intelligent Health Monitoring Techniques (IHMT), Dissolved Gas Analysis (DGA), Chemical Techniques, Transformer, Fuzzy, GA-LSTM

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I. INTRODUCTION

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). Mineral oil has been used as a traditional insulating liquid for transformers for over a century. However, in face of the increasing awareness of environmental protection recently, applying environmental friendly transformer liquids such as natural esters or synthetic esters in transformers of distribution or transmission level is getting more and more popular [1, 2, 3]. Up to now, ester-based transformer liquids have been widely used in distribution transformers and there are more and more development work in the aim of used by esters in transformers [4, 5]. DGA, short for dissolved gas analysis, is one of the most useful diagnosis tools for incipient fault indication of oil-filled transformers [6]. When either thermal or electrical faults are occurred, transformer oil will decompose and recombine into many kinds of fault gases. In the past several decades, experience of DGA based fault interpretation of mineral oil-filled transformers has been accumulated after a wide range of lab research and on-site operation practices. Many standards were established for assessing conditions of mineral oil-filled transformers, such as IEC 60599 and IEEE C57.104 [7, 8]. Among all kinds of DGA interpretation methods listed in the above guide, the most comprehensive one is Duval triangle which was established by Michal Duval offering graphical interpretation [9]. Due to the increased use of environmental friendly transformer liquids, mineral oil-based diagnosis methods need to be revised for the use of fault indication for nature ester-filled transformers. Researchers have already carried out some experiments on studying the gas generation characteristics of nature ester FR3 under thermal or electrical transformer faults [10-15]. Based on the results of large amount of experiments, the Duval triangle interpretation method was revised for FR3 in 2008 [16]. Traditionally, laboratory DGA technique, which required taking oil samples from transformers periodically and then sending them to the analytical laboratory, becomes mature for fault indication. Recently, affordable online transformer monitoring products, which can provide results based on up to hourly oil sampling, are installed at power level transformers for predicting faults and avoiding failures [17]. However, due to the lack of experience, there are still many concerns about the measurement accuracies of online transformer monitoring equipment. This paper reviews different types of technique for health monitoring of transformer are the chemical techniques for internal incipient faults detection with critical analysis and artificial intelligence-based techniques. Conclusion is presented in last section. The studies presented in below sections are summarized in Figure. 1.

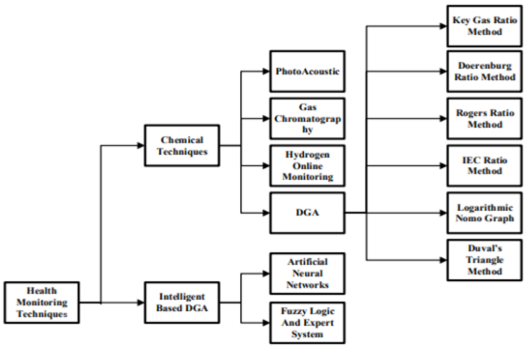

Fig.1: Health monitoring techniques for transformer [19]

II. INCIPIENT FAULTS IN TRANSFORMERS

Incipient faults in transformers originate from a permanent and irreversible change in the transformer conditions. The incipient faults are very common in transformers and occur intermittently, causing accelerated aging and deterioration of the insulation system. Incipient faults can serve as warning of faulty conditions in transformer, however failure to notice the faults can lead to permanent failure of the transformer. Table 1 summarizes common incipient faults and failure modes occurring in transformers [19-20].

Table.1: Most common modes of functional failures

System or Component	**Incipient fault**	**Failure Mode**
Dielectric System: Insulation Materials	Arcing discharge, Partial Discharges	Moisture, Particles, contamination, aged insulation materials
Electromagnetic Circuit: Core, Windings	Localized hotspot, General overheating, Arcing or Sparking discharges	Short-Circuited turn in winging conductor, circulating current

2.1 Partial discharge fault

A partial discharge is a highly localized electrical discharge of low intensity that occurs between two conductors placed apart [18-19]. Partial discharges appear as short pulses that are often accompanied by emission of sound, light, heat, and chemical reactions. The sources of partial discharges include voids and cracks in solid insulation, floating components such as water drops and air bubbles, and corona caused due to sharp edges of solid insulation, windings, or tank. After initializing, a partial discharge can carry on with increasing intensity until terminating as an arc discharge. Usually, this kind of fault is characterized by the generation of hydrogen and methane.

2.2 Arcing discharge faults

Sometimes a very high voltages can cause formation of plasma in oil through which electric current can flow freely as an arcing discharge. Arcing discharges generate very high temperatures (above 5000^0 C) and large amount of gases, mainly acetylene and hydrogen. This type of faults are very dangerous and if not controlled, can cause excessive pressure in the transformer tank, causing even explosion.

2.3 Thermal faults (Hotspots)

Thermal faults arise because of overheating of conductors, short circuits, overheating of windings due to eddy currents, loose connections and insufficient cooling. Thermal faults can be classified as low temperature fault for temperature up to 150^0 C, medium to high fault for temperature between 300^0 C and 700^0 C, and high temperature fault for temperature above 1000^0 C. Localized thermal faults are known as hotspots. Temperature of a hotspot on metal surface can reach up to 1500^0 C causing local heating of surrounding oil, leading to the generation hydrocarbon gases, mainly ethylene and methane. The generation of fault gases is strongly dependent on the temperature. Consequently, hydrogen and methane are produced at around 150^0 C, ethane at approximately 250^0 C, then ethylene at approximately 350^0 C and finally acetylene above 700^0 C [19].

2.4 Characteristic gas generation due to faults

Depending on the type of fault specific patterns of gases (the gas compounds and their ranks in terms of concentrations) are generated in oil. The amount of gases generated in a specific pattern depends on the factors such as intensity and duration of the fault. Table 2 summarizes the typical gas concentrations for threshold and warning levels, which are based on the analysis of statistical data collected from service transformers filled with naphthenic oil [18].

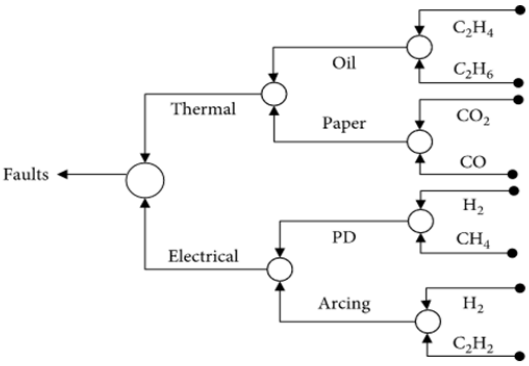

Fig 2: Flow chart for Faults Vs Gases

Table 2. Typical gas concentrations for threshold and warning levels [18]

Case	Characteristic gases	Threshold (ppm)	Warning (ppm)
Normal ageing	H_2, Hydrogen CH_4, Methane CO, Carbon monoxide CO_2, Carbon dioxide	20 10 300 500	200 50 1000 20000
Oil overheating	CH_4, Methane C_2H_6, Ethane C_2H_4 Ethylene	10 10 20	50 50 200
Partial discharges	H_2 Hydrogen	20	200
Breakdown discharges	C_2H_2, Acetylene	1	3
Decomposition of cellulose	CO, Carbon monoxide CO_2, Carbon dioxide	300 500	1000 20000

2.5 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 [18]-[22]. It has been at the forefront of most progressive utilities monitoring strategy for the last four decades [23]. 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 [24]. These different techniques are briefly discussed below.

2.5.1 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, and the diagnoses may be inconclusive if some of gases are not found [25].

2.5.2 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. 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 3 [26].

Table 3: Main Gases Vs Concentration (PPM)

Main gases (key gases)	Concentration (PPM)of □1
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

2.5.3 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.4 [34-35].

Table 4: Rogers ratio technique

Case	**Possible fault diagnoses**	**R1=C_2H_2/C_2H_4**	**R2=CH_4/H_2**	**R3=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°C	<0.01	≥1.0	<1.0
4	Thermal fault less than 700°C	<0.1	≥1.0	≥1.0 and <4.0
5	Thermal fault > 700°C	<0.2	≥1.0	≥4.0

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. 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 [21].

2.5.4 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 [15].

2.5.5 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. 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. 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 [33].

2.5.6 Duval triangle method

The Duval triangle graphic method was established firstly by Michel Duval in the 1960s. 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) [19]. 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 Figure.3. 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. However, all triangles have unclassified region thus faults classification will majorly depend on the expert's experience recognized by other techniques [19]-[20]. There may be chance for mixing the electrical faults with the thermal faults because their boundaries are closed with each other[27].

The triangle coordinates value can be computed by the DGA results in ppm as below:

$$\% C_2H_2 = 100 * C_2H_2 / (C_2H_2 + C_2H_4 + CH_4);$$
$$\% C_2H_4 = 100 * C_2H_4 / (C_2H_2 + C_2H_4 + CH_4);$$
$$\% CH_4 = 100 * CH_4 / (C_2H_2 + C_2H_4 + CH_4)$$

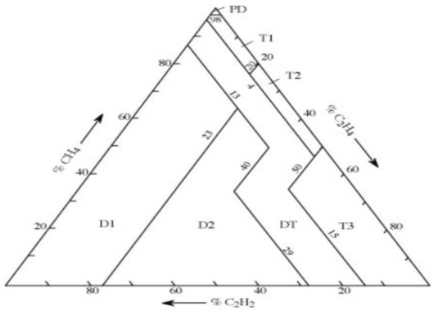

Fig.3: Duval's triangle

2.5.7 Gas chromatography:

Gas chromatograph is a type of chromatograph that is widely used in chemical analysis in order to separate and measure evaporable gas substances [28]. Figure 4 shows the diagram of gas chromatograph concept. As shown in Figure 4, the mobile phase flow, such as fault gases, is carried through the stationary phase which is used to retain the gas components. In the stationary phase, the weak retain substance will move faster while the strong retain substance will move more slowly. Consequently, different gas components will pass the stationary phase and reach the gas detector in different time ranges. Finally, the gas detector will give out the individual amounts of each gas according to the analysis time range.

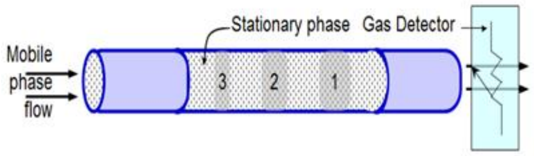

Fig 4: Gas chromatograph

2.5.8 Hydrogen online monitoring:

Hydrogen is a key gas that is generated when significant issues like overheating, partial discharge, and arcing occur in transformers. While some of these issues might persist for weeks, months, or years, these issues can also lead to failure in minutes, hours, or days. Annual oil samples are not frequent enough to catch fast-evolving transformer faults. (Photo acoustic spectroscopy).

III. PREDICTION OF DISSOLVED GAS IN TRANSFORMER OIL BASED USING ARTIFICIAL INTELLIGENCE TECHNIQUES

Traditionally, various chemical techniques identify the health of 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) [25]. 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 [29]-[30].

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 employed to classify the health of electrical insulation by spotting new samples with the predefined training pattern process [29]-[30].

3.2 Prediction of dissolved gas in transformer oil based using 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 [29]. 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

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. The increase in the moisture level in the oil reduces the breakdown voltage level of the insulation. There are a few indirect techniques for finding the moisture level in cellulose paper [30]. 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. Similarly, Oommen’s technique may be used for computing moisture level in the cellulose papers). 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 .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.

3.3 Prediction of dissolved gas in transformer oil based on LSTM-GA

By combining with dissolved gas analysis, time series prediction of dissolved gas content in oil provides a basis for transformer fault diagnose and early warning. In the view of that, a prediction model based on long short time memory (LSTM) network for time series of dissolved gas content in oil is proposed, which takes advantage of LSTM network's ability to deal with long-sequence prediction problems. Five characteristic gas concentrations are used as input to the model, and the hyper parameters of the model is optimized by Bayesian optimization algorithm to further improve prediction accuracy, then a LSTM prediction model is constructed. By case study, it is verified that the proposed model can precisely predict time series of dissolved gas content. Compared with gray model, BP neural network and support vector machine, the proposed model has higher prediction accuracy and can better track the trend of time series of dissolved gas content in oil [31]. A transformer combining genetic algorithm and long short-term memory (LSTM) neural network Prediction model of dissolved gas content in oil. The genetic algorithm (GA) is used to optimize look back (lb), lstm nets (ls), epochs (ep), and the dropout (dp), and then the genetic algorithm is combined with the long short-term memory neural network. The gas content is predicted. This model overcomes the problem of low prediction accuracy caused by selecting parameters based on experience. The analysis result of the calculation example shows that compared with the traditional prediction algorithm, the proposed method can better track the change law of the dissolved gas concentration in the oil, improve the prediction accuracy, and provide a strong guarantee for the safe and stable operation of transformers [32].

IV. CONCLUSION

This paper reviewed the real time fault detection and intelligent health monitoring techniques (IHMT) of transformer. 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 for these incipient faults. Based on the current rapid development of artificial intelligence technology, this paper mainly explain an expert system & fuzzy logic and a network model based on & LSTM-GA to track the change law of dissolved gas concentration in the oil. The amount of sampled dissolved gas content data is quite limited, the accuracy of multistep prediction is not high. The next step will focus on the application in larger-scale data and the improvement and optimization of LSTM network model to further improve the accuracy of prediction.

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