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Application of Artificial Intelligence Techniques for Dissolved Gas Analysis of Transformers -A Review

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Abstract**—**The gases generated in oil filled transformers can be used for qualitative determination of incipient faults. The Dissolved Gas Analysis has been widely used by utilities throughout the world as the primarily diagnostic tool for transformer maintenance. In this paper, various Artificial Intelligence Techniques that have been used by the researchers in the past have been reviewed, some conclusions have been drawn and a sequential hybrid system has been proposed. The synergy of ANN and FIS can be a good solution for reliable results for predicting faults because one should not rely on a single technology when dealing with real–life applications.

Keywords**—**Dissolved Gas Analysis, Artificial Intelligence Techniques, Incipient Faults, Transformer Fault Diagnosis, and Hybrid Systems.

I. Introduction

THE transformer is an essential device of a transmission & distribution system. Failures of large power transformers are problematic for four reasons, namely failure of a transformer can cause operational problems to the system, generally large power transformers are placed in large tanks containing flammable oil and are environmentally hazardous, the utilities do not have a spare one in case of maintenance or breakdown, and finally the various types of thermal and electric stresses often age the transformer and subject them to incipient faults. Thus the utilities need to keep a track of the health of the transformer and also develop a diagnosis system.

In power transformers the insulation used is a combination of insulating liquid-the transformer oil and solid impregnated insulation- cellulose. Only with such a combination this static machine can be properly insulated. The life of a transformer depends directly on the life of its insulation. The deteriorating insulation and ageing are the two major causes of incipient events. The relevant factors generally recognized as causing ageing and deteriorating insulation include thermal stresses, electrical stresses, mechanical stresses, and moisture. The methods used for the evaluating the ageing process and the deteriorating cellulose material are Dissolved Gas Analysis (DGA) of the transformer oil, the degree of polymerization measurements, Furan Analysis of the paper.

The degree of polymerization assesses the aging of insulating paper from service-aged power transformers and voltage regulators. It is an invasive test which requires a sample of the paper which may present some difficulties such as taking the unit out of service. Each cellulose fiber of paper is composed by a bundle of cellulose molecules of different lengths, lying side by side. These molecules are held together due to hydrogen bonds between the hydroxyl groups (-OH) existing in their structure. The cellulose molecule is a linear polymer formed by a chain of glucose rings linked by glycosidic bonds. The glycoside bonds break and the molecule are shortened as the paper ages, thus causing the paper to lose its mechanical strength, and the useful life of the transformer is also reduced.

Furan Test is carried out to determine whether the paper in a given transformer has been or is being damaged by heat. Furans are produced from temperature buildups. These are generated either by a localized area of high heat and paper damage or by the general overall heating of the entire insulation system. As for now there are no limit values or normal values for these compounds. Hydrolytic, thermal, oxidative breakdown of paper insulation can be detected through furan analysis.

Among the existing methods of identifying the incipient faults, DGA is a method widely applied by utilities and researchers for fault diagnosis. By sampling and examining the insulating oil of transformers, ratios of specific gas concentrations, their generation rates, the total combustible gases are often used as the attributes of classification by diverse DGA approaches. Temperature measurements have been made for some time and can even be incorporated into certain key gases. The DGA has been widely used as a diagnostic tool for transformer maintenance.

The detection of certain gases generated in oil filled transformer in service is frequently the first available indication of malfunctioning that may lead to ultimate failure of a transformer, if not corrected. The gases generated in oil filled transformers can be used for qualitative determination of fault types; the gases are typical or predominant at various temperatures [1-3]. Based on this the incipient faults can be detected and preventive maintenance can be carried out and condition can be assessed.

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In this paper an attempt has been made to review the various conventional and non-conventional DGA methods used by various agencies and utilities to find the condition of the cellulose material within an in-service transformer. The various Artificial Intelligence (AI) Techniques that have been used by the researchers in the past have been reviewed and some conclusions have been drawn and a sequential hybrid system has been proposed.

II. DGA Methods

The detection of certain level of gases generated in oil filled transformer in service is frequently the first available indication of malfunctioning that may lead to ultimate failure of a transformer, if not corrected. Arcing, corona discharge, low energy sparking, overheating of insulation due to severe overloading, failure of forced cooling systems are some of the possible mechanism for gas generation. The gases generated in oil filled transformers that can be used for qualitative determination of fault type, based on which gas is typical or predominant at various temperatures. These gases are hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2). There are various types of DGA methods used by organizations and utilities to access the condition of a transformer

A. Dornenburgs' Ratio Method

This method utilizes four ratios that are CH_4/H_2, C_2H_2/C_2H_4, C_2H_6/C_2H_2 and C_2H_2/CH_4 and suggests the existence of three types of faults i.e. thermal fault, corona discharge and arcing. This method is based on thermal degradation principles. In this method the gas concentrations (in ppm) for H_2, CH_4, C_2H_2, and C_2H_4 exceeds twice the value for fixed limits of each gas and for gases CO, and C_2H_6 exceeds thrice the value for fixed limits is used to determine the validity of the ratio procedure. Then there is a procedure for determining the validity of the four ratios, each successive ratio is compared with certain values and finally if all four succeeding ratios for a specific fault type fall within the predetermined values, then the suggested diagnosis is said to be valid. This method is a part of ANSI/IEEE Standard C57.104-1991. It is a complex method formulated on the dissolved gases of transformer oil. The implementation of this method may result in significant number of "no interpretation," due to incompleteness of the ratio ranges [1].

B. Rogers Ratio Method

The Rogers ratio is a simple scheme based on ranges of ratios is used for diagnoses of faults. It uses four gas ratios that are CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. The four conditions of the oil insulated transformer that are detectable are normal ageing, partial discharge with or without tracking, electrical and thermal faults of various degree of severity. This method is also based on thermal degradation principles and is also included in ANSI/IEEE Standard C57.104-1991.The validity of this method is based on the correlation of results of a much larger number of failure investigations with the gas analysis of each case. There are diagnostic codes for the various faults and in this method there are values of ratios that do not fit into the diagnostic codes. Also for dissolved gases below the normal concentration value, no consideration is given and due to this the exact implementation of the method may lead to many misinterpreted cases [1].

C. IEC Method

Fault diagnosis scheme recommended by International Electrotechnical Commission (IEC) originated from Rogers' method except that the ratio C_2H_6/CH_4 was dropped since it only indicated a limited temperature range of decomposition. Normal ageing, partial discharge of low and high energy density, thermal faults and electrical faults of various degrees of severity are the four conditions that are detectable. However, no attempt is made to identify both thermal and electrical faults into more precise subtypes. The first edition of IEC method (IEC 60599-1978) is based on simple coding scheme while the second edition (IEC 60599 – 1999) utilizes the revised ratio ranges directly. Assessment of dissolved gases for 'normality' limits is required before being interpreted using ratios. Other improvement in the second edition of IEC method is the use of 3D graphical representation for the ratio ranges. Those cases where diagnosis of fault is not possible can be plotted onto the graph and its nearest distance to a certain fault region can then be observed [2]. The typical faults in power transformers are classified as partial discharges, discharges of low and high energy, and thermal faults of three degrees of severity depending upon the temperature of the fault. Many countries have adopted this standard as a reference standard like Brazile and India.

D. Duval's Triangle

This method uses values of only three gases CH_4, C_2H_4 and C_2H_2 and their location in a triangular map. For plotting on the triangle the gases are transformed into triangular co-ordinates. The three type of faults that are detectable are partial discharge; electrical fault (high and low energy arcing) and thermal faults (hot spots of various temperature ranges). This is a simple method but false diagnoses may be due to careless implementation of the method because no region of the triangle is designated to the normal ageing. Hence before using this method it should be assessed if the amount of dissolved gases is permissible for transformers that have been in service for the past many years [3].

E. Denkyoken Method

A special committee on "Conservation and Control of oil-insulated components by diagnosis of gas in oil" in Japan developed the Denkyoken Method. This is the diagnostic method is recommended by Electrical Cooperative Research Associates (ECRA). This method is based upon the amount of H_2, CH_4, C_2H_6 C_2H_4 and C_2H_2 gases in parts per million (ppm) the most abundant gas is taken as 100% and the amount of all other gases are then impressed with reference to this value for a given specimen data. Thirteen different patterns are designed for cause of failure in oil-insulating power apparatus [4].

F. CIGRE's Method

The method uses key gas ratios as well as gas concentrations for faults diagnosis. The five key gas ratios that are considered are C_2H_2/C_2H_6, H_2/CH_4, C_2H_4/C_2H_6, C_2H_2/H_2 and CO/CO_2. The key gas concentrations are C_2H_2, H_2, sum of carbon hydrides, CO & CO_2. The ratio ranges and concentration limits are suggested. There is no combined pplication of both these methods in case all the ratios and concentration are below the limits, a transformer is considered to be healthy. The advantage of this method is that two or more faults can be detected [4-5].

G. Nomograph Method

This method combines the fault gas ratios and the concept of threshold so as to improve the accuracy of the fault diagnosis. The nomographs are series of vertical logarithmic scales that represent the concentration of the individual gases. It provides a graphic presentation of the fault gas data and the means to interpret its significance. In the method, straight lines are drawn between adjacent scales to connect the points representing the values of the individual gas concentration. So as to determine the type of faults the slopes of the straight lines drawn are the diagnostic criteria. To identify the type of fault a visual comparison of the slopes of the line segments with the keys given at the bottom of the nomograph are needed. The severity of the fault is assessed by the position of the lines relating to the concentration scales. An arrow indices the threshold value of each vertical scale. For the slope of a line to be considered significant at least one of the two tie-points should be above a threshold value. The fault indication is not considered to be significant in case no point lies above a threshold value[6].

H. NBR7274 Method

This Brazilian standard is based in IEC599/78 and the five gases considered are H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 (in ppm). It employs three ratios that are C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 based on the three ratios the faults are classified in eight type including normal ageing [7].

I. IS 10593:2006 Method

This Indian standard is identical to the IEC 60599:1999 issued by IEC and was adopted by Bureau of Indian Standards-on the recommendations of Fluids for Electrotechnical Applications Sectional Committee and approval of the Electrotechnical Division Council. In this adopted standard reference appear to certain International Standards for which Indian Standards exist [8].

The gas in oil is widely accepted method for detection of incipient faults by the power utilities all over the world. Each of the methods discussed above suffer from some or the other drawbacks which can be summarized into six type.

- The methods have been developed based on experience and judgment of human experts only.
- Due to the in-completeness of the possible ratio combinations and uncertainty of the validity of the defined ranges of key-gas ratios there is high degree of inconsistency and ambiguity.
- When these schemes are applied some times the result is "no-interpretation" then the decision is dependent only on the expert.
- Concurrently within the power transformer multiple faults occur, all these methods are unable to detect with confidence such faults.
- Owing to a lack of expert knowledge within them, these schemes are unable to detect new or unknown faults.
- The ratio methods do not cover all ranges of data.

III. Artificial Intelligence Techniques Applied to DGA

Data of the dissolved gas in oil can be incorporated into expert systems to facilitate decision making. There also exists certain amount of uncertainty in the data concerning dissolved gas analysis due to generation, sampling, and chromatography analysis. There is thus variation in interpreting the variation of the gases by the utilities. Due to the diverse gas content of the insulating oil of transformers many AI techniques have been presented. The AI techniques studied and used by the researches for application to DGA are Expert Systems , Fuzzy Inference Systems (FIS) and various type of Artificial Neural Networks (ANN), Genetic Algorithm (GA)and even Novel Cerebellar Model Articulation Controller based method for off line and on line monitoring and Discrete Wavelet Transforms for on line monitoring.

A. Expert Systems

The expert system is decision support systems that have been applied for fault diagnosis and maintenance to advance the DGA information and incorporate it to build diagnostic rules [9]. The effectiveness of the knowledge expert systems depends on the precision and knowledge base, which is usually very complicated and must be constricted carefully. Such an expert system can neither acquire knowledge from new data samples through self-learning process and nor can it adjust its diagnostic rules automatically.

C. F. Lin et al. [9] developed an expert system to diagnose transformer faults using DGA and also suggested proper maintenance. Data of 251 samples from transformers of Taiwan Power Company were used; three cases are discussed in details for the last five to six tests carried out. For the first two samples the diagnostic results agreed with the actual fault type causes and appropriate maintenance was suggested. For the third case the transformer unit after more than seventeen years of operation suffered an arc tracing fault. After repairing and degassing the transformer oil a gas fingerprint of this transformer was developed.

B. Fuzzy Inference System

K. Tomsovic et al. [10] proposed a fuzzy information approach to integrate different transformer diagnostic methods. Five gases were considered and detailed analysis of four transformers had been carried out. A fault tree was proposed and there was a framework for performing diagnosis using fuzzy information system. The fuzzy relations were combined with the fault tree to provide best analysis possible. The fact that an older or a heavily loaded transformer will have high concentration of gases that have built up over a time was taken into account. The proposed framework could provide a good foundation for providing diagnosis on variety of power system equipment.

Yann-Chang Huang et al. [11] used Evolutionary Fuzzy Logic to develop a diagnostic system. The DGA method considered were Rogers Ratio, Doernenburgs' & IEC method. All the seven gases were considered. The conventional DGA diagnosis criteria were used to construct the preliminary frame work of the system. Then in accordance with the records the practical examination of the suspected transformer, an Evolutionary Programming (EP) based optimization algorithm was employed to modify the if-then rules and simultaneously adjust the membership functions of the fuzzy sets. It was concluded that conventional Doernburgs', Rogers' ratio DGA methods cannot classify the real situation with satisfactory accuracy. Of the 711 training samples used 561 were real samples and for the three discharges the Monte Carlo technique were used for simulating data of 150 samples. The time taken to construct the fuzzy diagnostic system by the proposed EP based development technique was less than that taken by the ANN methods.

Q. Su et al. developed a fuzzy dissolved gas analysis method for diagnosis of multiple incipient faults in a transformer [12]. The proposed Fuzzy IEC code-key gas method was a combination of fuzzy diagnosis using IEC codes and key gases. The new developed method employed fuzzy boundaries between different IEC codes with demi-Cauchy distribution functions and the critical level of key gases was also treated with the same fuzzy method. IEC method was considered and five results were compared. Multiple faults could be diagnosed using the method. It was concluded that the trend of each fault in a transformer can be determined from its fuzzy diagnostic vector after certain period of monitoring.

N.A Muhamad et al. [14] made a comparative study & analysis using fuzzy logic for six DGA methods namely Key Gas, Rogers Ratio, Doernenburg's, Logarithmic Nonograph, Duval Triangle, and IEC Method. 69 samples were used and a MATLAB program was developed to automate the evaluation of the methods. Some basic coding and construction of simulink block diagram was carried out. It was found that the accuracy gets reduced with fuzzy logic this was because the no of predictions when using fuzzy system is increased and this increases the possibility of incorrect prediction. The most accurate was found to be IEC method followed by Rogers Ratio method, Doernenbergs', Duval triangle, Nomograph and key gas ratio. Those methods using specific codes in their interpretation were found to be more accurate if they made predictions. When the data did not match with the available codes these methods were not able to give the predictions. Where direct values of fault gases were used; the interpretation give higher consistency but the predictions were incorrect for certain cases. This was because of the diagnosis being base on one specific value of fault gases as indicator.

C. Artificial Neural Network

Hong-Tzer Yang et al. [13] used Fuzzy Learning Vector Quantization (FLVQ) Networks for condition assessment. Doernenburgs' and Rogers Method were compared for 561 numerical samples associated with real time faults. Due to lack of data of high energy partial discharge, low and high energy discharge faults, 150 simulated data were created and mixed with the practical samples. Fuzzy logic and learning vector quantization networks were integrated and the advantages were the linguistic partition properties of fuzzy logic and fast and self learning capabilities of learning vector quantization networks. Also, few samples were needed to construct FLVQ. The learning time needed is extremely short as compared to that required by the Back Propagation Artificial Neural Networks (BPANN). The FLVQ networks have highest learning capabilities as compared to fuzzy system and BPANN. With the uncertainties and the limitations existing in DGA approaches, the FLVQ network could greatly improved the diagnosis capabilities of the traditional DGA approach.

Diego Roberto Moaris et al. proposed an ANN approach for Transformer Fault Diagnosis [7]. Forty sample sets from different transformers are used for training and testing of major fault type diagnosis. A two step Back Propagation Algorithm ANN approach was used. One ANN was used to classify the major fault type and the second ANN focused on determining in case cellulose is involved. The two step approach made ANN easier to train and more accurate in detecting faults.

For diagnosis of oil-insulated power apparatus using neural network simulation O. Vanegas et al. used real data from 26 samples [15]. NN Back propagation technique algorithm was used. NN were developed and the results between the Denkyoken method by ECRA and IEC method were compared. The results of the ECRA were better than the results of the IEC for the specimen data used.

An intelligent decision support for diagnosis of incipient transformer faults using self-organizing polynomial networks (SOPN) was proposed by Hong- Tzer Yang et al. [16]. Data of total 561 numerical samples from 156, 69kV power transformers of Tiawan Electricity Company was used, and simulation data by Monte-Carlo simulation technique for practical samples of high energy partial discharge, low energy discharge and high energy discharge was also used. In the first type of SOPN the input features (or variables) selected were the ratios while in the second SOPN the input features (or variables) selected were the gases H_2, CH_2, C_2H_6, C_2H_4, and C_2H_2. Two ANN- were built as well using the same sample data by error back propagation training algorithm. SOPNs' proved to be far superior to the existing ANNs' which were adopted as a comparative bench mark.

J. L. Guardado et al. [17] made a comparative study of Neural Network Efficiency in Power Transformer Diagnosis using DGA. 120 samples were provided by the utility and 30 were taken from DGA results published in literature. At random 33 samples were selected and used for neural network testing and 117 were used for training using sigmoidal function. Three layers were used to avoid slow training. The number of hidden neurons in the hidden layer was varied for each diagnosis criteria. NN Back Propagation- Learning algorithm was used. The various methods compared were IEEE-Doernenburgs' ratio, Rogers Ratio, Modified Rogers ratio , IEC Method, and CSUS Method. NN diagnosis based on CSUS criterion reached the highest efficiency and the IEC criterion obtained a high success rate.

For diagnosing failed distribution transformers using neural networks A. S. Farag et al. [18] used ANN. Work was done considering 506 overhead and 52 underground transformers. A feed forward neural network was trained to diagnose reasons for failure of distribution transformers. The training algorithm used was back propagation assuming initially a sigmoidal transfer function for networks processing unit. After the network was trained the units' transfer function was changed to hard limiters with thresholds equal to the biased obtained for the sigmoids during training. Six individual ANN were used for six important factors that were; age of the transformer, the weather conditions, damaged bushings, damaged bodies, oil leakage, and winding faults. The six ANN's are combined to one ANN to give recommendations complete diagnosis for working transformers to avoid possible failures. The developed ANN could give complete diagnosis of working transformer and be used as a decision support facilities to the companies for planning and maintenance schedule.

K. F. Thang et al. used Self-Organizing Map (SOM) algorithms for analysis and interpretation of dissolved gases in power transformers [4]. 755 measured DGA records from three different manufacturers and two voltage ratios and one power rating were used. It was a novel approach for analysis and interpretation of DGA data, that lead to more credible condition monitoring of power transformer. This method for analysis does not depend upon DGA interpretation schemes for its development; only measure DG data is needed. First the comparison of the DGA schemes and currently available AI methods was made then the SOM were proposed. The proposed approach has many important advantages over traditional methods of analysis and interpretation of DGA data. The novel approach does not depend upon any actual fault cases for its modeling, hence it is easy and cost effective to implement. It provides more consistent and convincing diagnosis as the revealed structure actually originates from the real measured DGA records.

Abductive Network Model-based diagnostic system for power transformer incipient fault detection was used by Y. C. Huang et al. [19]. A total of 630 numerical samples associated with their fault type from 162 transformers of 69kV were used. The Abductive Network Model (ANM) heuristically constructs a cascaded hierarchal network, with several layers of function nodes of simple lower order polynomials to model the highly non linear fault diagnosis problem based on abductive reasoning networks. The ANM is a layered network of feed forward function nodes. The coefficients, number, types and connectivity of function nodes are learned from the training data. The ANM have the ability to handle the complex problems by subdividing them into smaller, simpler ones and greatly simplifying the modeling process. The test results confirm that the ANM has remarkable diagnosis accuracy and requires far less effort than the conventional method.

M. H. Wang used Extension Neural Network [ENN] for power transformer incipient fault diagnosis [20]. The ENN allows classified problems to have a large range of features, supervised learning, continuous input and discrete output. ENN is a combination of extension set theory and neural networks. In extension theory, the extended correlation function can be used to calculate the membership grade between the tested data and cluster domain. It can quickly and reliably learn to characterize the input patterns and permit adaptive process for significant new information. 40 sets of field DGA data from power transformers in Australia, China and Tiawan were used. In order to take into account the errors and the uncertainties, 40 sets of testing data were created by adding $\pm$ 5% to $\pm$ 20% random uniform- distributed samples to test the robustness of the different diagnostic methods. The structure of the ENN for transformer fault diagnosis used nine nodes in the output layer and three nodes in the input layer. The training time of the ANN was found to be quite economical. The ENN has a shorter learning time than multi layer perceptron (MLP) and the accuracy was also quite high.

In an introduction of condition monitoring (CM) system of electrical equipment Zhan Wang et al. [21] used IEC method for unsupervised NN known as SOM algorithms. This was a prototype of CM system that integrates on line and off-line diagnosis technology to monitor the condition of electrical equipment especially power transformer. There were four parts namely, ANN based condition assessor, ANN based fault classifier, intelligent predictions and maintenance decisions and knowledge based expert systems. Through the analysis of historical data, electric test data and online data, it could also make decision for maintenance of electrical equipment. The test results showed that the system has high diagnosis accuracy and can make useful maintenance decisions.

D.V.S.S Siva Sarma et al. [22] proposed an ANN approach for CM of power transformers using DG. Five gases were considered while two separate ANN were trained for Rogers and IEC Method. For 30 test samples BPA (Back Propagation Algorithm) with sigmoidal function was used. Results obtained through ANN were highly reliable.

N. Yadaiah at al. [6] proposed fault detection techniques for power transformers. Both an off-line and an on-line method were proposed. 472 DGA samples were considered. The off line method included an ANN to detect incipient faults and compare it with the conventional method. A multilayer feed forward NN was used. The on line method- Discrete wavelet transform (DWT) was considered to identify the faults. For the on-line method the current signal on the primary terminal of the transformer is measured and determines the details and approximate coefficients of DWT which characterize the condition of the system. On comparing the performance of the ANN method with the Rogers method, it was found that the ANN detects more accurately. The wavelet technique is applied with different mother wavelets and compared the performance in identification of faults.

D. Artificial Neural Network & Fuzzy Logic

Transformer oil diagnosis using fuzzy logic and NN was proposed by James J. Dukaram using 150 real and synthetic examples [23]. Fuzzy was applied to Key gas analysis, Rogers' ratio method, and nomographs. Feed forward neural network were used. It was concluded that fuzzy logic can be used to automate standard methods of transformer oil DGA. In some cases NN could be used in combination with fuzzy logic to implement more complex diagnostic methods while maintaining a straightforward relation between the enhanced method and the original one. The main obstacle to developing a real diagnostic rule is the lack of sufficient high quality examples with which to train and validate a network.

Jingen Wang et al. applied fuzzy classification by Evolutionary Neural Network [24]. The method models the membership functions of all fuzzy sets by utilizing a three layer feed forward network, trains a group of neural networks by combining the modified evolutionary strategy with Levenberg-Marquardt optimization method in order to accelerate convergence and avoid falling into local minima. The method is better than neural network structure, tolerance ability and robustness than any traditional methods.

A hybrid tool for detection of incipient faults in transformers based on DGA of insulating oil was proposed by Diego Roberto Moaris et al. [25]. 52 samples of confirmed diagnosis for NN and 20 Transformers with historical data-totaling 212 samples- (180 normal+10 electrical faults+22thermal faults) were used. It is a combination of traditional method, ANN and Fuzzy logic system. Neural Network used was based on a Radial Bias Function (RBF). The proposed analysis included not only the gas levels but also the gas generation rates, the rates that were considered are Total Generated Gas Level (TGGL), Generation Rate (GR), and Total Gas Generating Rate (TGGR). It was found that this is a more reliable diagnostic due to more than one method being used; the results of NN alone are limited but could be improved with the use of more training data. Fuzzy analysis proved to be highly reliable.

M. A. Izzularab et al. [26] developed an on line method for diagnosis of incipient faults and cellulose degradation using neuro-fuzzy. Records of six gases were considered and for the cellulose degradation the ratio of CO_2/CO was used. A combination of neural networks and fuzzy sets was proposed to enhance the diagnostic system. Multilayered perceptron with sigmoidal activation function and error back propagation algorithm for training was used for 160 data samples of Egyptian Electricity Network. 75% for the data was used for training and remaining 25 % for testing. Three cases were considered and discussed in detail. Total combustible gases (TGC) was used to decide the normal and abnormal condition in a transformer. A comparison of the proposed technique and reported methods were carried out. The test results reveled that the proposed system had the highest reported classification capability.

Adriana Rosa et al [27] made an attempt on knowledge discovery in NN with application to transformer failure diagnosis. A new methodology for mapping a neural network into a rule based fuzzy inference system. The maping makes explicit the knowledge implicitly captured by the neural network during the learning stage, by transforming it into a set of rules. 292 training and 139 testing patterns were used. The control of convergence of ANN has been taken into account not only the mean square error (MES) but also the success in classification. The classification of transformer faults has been done as onto three type only namely thermal faults, discharges and partial discharges. This is applied to transformer fault diagnosis using DGA. Good results were achived and knowledge discovery was made possible.

E. Novel Cerebellar Model Articulation Controller Based Method

Wei-Song Lin et al. used a novel Cerebellar Model Articulation controller (CMAC) based method [28]. Virtual data and published transformer data of 20 power transformer DGA results was used. First a virtual training data based on IEC std. 599 was generated to replace the large amount of actual training data; then a CMAC-based diagnosis model was developed and using virtual training data to train the memory weights. The diagnoses demonstrated that the new scheme had high accuracy and high noise rejection abilities. The results also had the ability of multiple incipient faults detection trends and multiple fault analysis. The method did not require actual data to train the CMAC network and high diagnosis accuracy was obtained. The method could detect the main fault and also provide useful information for future fault type and it also suited to non training data.

F. Genetic Algorithm Approach

Yann-Chang Huang used a new data mining approach to dissolved gas analysis of oil-insulated power apparatus [29] using 820 actual gas records of Taipower Company from 172, 68 kV transformers. The Genetic Algorithm (GA) and ANN (back-propagation) has been compared with Genetic Algorithm Tunes Wavelet Networks (GAWN) for data mining of dissolved gas analysis records and incipient fault detection of oil insulated power transformers. The GAWN's have been tested using four diagnosis criteria, and compared with ANN and conventional methods. The GAWN's have remarkable diagnosis accuracy and require far less learning time than ANN's for different diagnosis criteria.

Wavelet network for power transformers diagnosis using DGA was proposed by Weigen Chen et al. [30]. 700 samples were used; 400 training samples and 300 testing samples. Wavelet Networks (WN's) are an efficient model of nonlinear signal processing developed in recent years. The training and testing samples are processed by fuzzy logic technology comparison and analysis of network training process and simulation results of five WN's. The proposed approach had many important advantages over traditional methods of analysis and interpretation of DGA data. The novel approach does not depend upon any actual fault cases for its modeling, hence it is easy and cost effective to implement. It provides more consistent and convincing diagnosis as the revealed structure actually originates from the real measured DGA records. The feed forward wavelet network used is divided into two types based on different activation functions of the wavelet nodes applied in fault diagnosis of power transformer. A GA base on real-encoded method of optimization in WN, was put forward (WN_GA) which is used to optimize the structure and parameters of the training process. The training process, diagnostic results and reasons for the difference in diagnosis are compared and analyzed. The Gauss activation function used achieve higher diagnostic accuracy because it can capture, the non-linear relationship among dissolved gas contents and corresponding fault information. The WN-GA had higher fault reorganization as compared the two other WN.

G. Discrete Wavelet Transform Method

Karen L. Butler-Purry et al. for identifying transformer incipient events for maintaining distribution system reliability have used Discrete Wavelet Transform (DWT) [31]. The approach has been applied to investigate the characteristics of incipient events in single phase transformer. MATLAB program was used to calculate the DWT of the signals. The Daubechies Db-4 type wavelet was used as a mother wavelet. On line incipient fault detection technique for distribution transformer was based on signal analysis. The method used discrete wavelet transform to identify incipient faults in single phase distribution transformers. The simulation method is based on Finite Element Methods (FEM) and ANSOFTs' Maxwell software was used for the circuit analysis. The simulation method takes into account the aging phase and the arcing phase. An experimental setup was made and the simulation methodology was tested. Time-domain results and frequency-domain results were compared for single phase transformer. The data obtained from tests and computer simulations were used to observe the variation. The results show the potential of using DWT-based method for fault prediction, maintenance and maintaining reliability of transformer.

Modeling transformers with internal incipient faults was done by Hang Wang et al. [32]. ANSOFTs' Maxwell Software was developed to calculate the parameters for an equivalent circuit of the transformer with internal short circuit fault using FEM. It is an on- line incipient fault detection method for single phase distribution transformer that utilizes parameter of voltage and current. There are two models, a degrading insulation model and an internal short circuit fault model. Since the degradation involves two stages ageing and arcing the degrading insulation model was composed of an aging model and an arcing model connected in parallel. The characteristics obtained from the simulation were compared with characteristics obtained from some experimental fault cases that convey incipient like behavior. The characteristics of the terminal current and circulating currents in the faulted windings were analyzed in time domain and frequency domain. The comparison between the incipient like fault experimental test cases and simulation results showed similar characteristics to those of simulation using parallel model combination.

H. Summary

The fuzzy expert systems (FES) allow the experience and knowledge of the experts to be incorporated into the system using fuzzy if-then rules; hence the use of FES is acceptable to DGA. The threshold of the gas attributes classifies the fault type; these are then fuzzified to manipulate the incompleteness and the imprecision of the DGA data. The efficiency of the model depends upon the completeness of the knowledge of the expert. The rules of the fuzzy logic based models cannot automatically adjust through the self learning process when new knowledge was acquired [9-13].

ANNs have been proposed to deal with the transformer fault diagnosis. It was found that they could handle this problem of classification. Through self learning the ANN are able to acquire new knowledge but suffer from the drawback that they behave like black boxes; having no explaining ability and also are slow in converging[6, 15-22].

The wavelet networks attracted attention for on line condition monitoring. The GA methods were used to improve the diagnostic accuracy and the learning ability of the ANNs[29-30]. Due to the global search abilities they could give remarkable accuracy in far less learning time than the ANN. DWT show potential of prediction maintenance and maintaining reliability of transformer [31-32].

A comparative study of the various DGA methods applied to FIS and it was found that the accuracy of the predicted cases was highest for the IEC method [14]. A similar study using NN back propagation learning algorithm also found the IEC criteria attaining highest success rate [18]. While training NN wherever the real data was not available for a particular fault, virtual/synthetic data was used [11, 14, 16, 23, & 28]. Online methods have been used for monitoring the health of the transformer [6, 20, 26, 31,& 32] and a combination of both off line and on line monitoring methods have also been used [6 & 26] .

IV. Proposed Sequential Hybrid System

Each of the soft computing methods has been inspired by biological computational processes and natures problem solving strategies. Each of these techniques, in their own right has provided efficient solutions to fault identification in transformers using DGA. Attempts on wide range of problems belonging to different domains have been made to synergize the three techniques - Fuzzy Logic, Neural Networks and Genetic Algorithm. The objective of synergy or hybridization is to overcome the weakness of one technology during its application, with the strengths of the other by appropriately integrating them. The hybridization of technologies has its pitfalls and should be done with care. The hybrid systems are classified as Sequential hybrid, Auxiliary hybrid and Embedded hybrid. Fig. 1 shows a sequential hybrid system.

When the output of one technology becomes another's input and they are used in pipeline fashion the system is said to be sequential hybrid. Since an integrated combination of the technologies is not present it is one of the weakest forms of hybridization. The Neuro-fuzzy hybrid system is one of the most researched form and has resulted in stupendous quantity of publication and research results. These systems have demonstrated the potential to extend the capabilities of the system beyond either of these technologies when applied individually. There are two ways of looking at this hybridization. One is to endow NN's with fuzzy capabilities, thereby increasing the networks expressiveness and flexibility to adapt to uncertain environment, the other one is to apply neuronal learning capabilities to fuzzy system to make the fuzzy system more adaptive to changing environments. This approach is also known in literature as NN driven fuzzy reasoning [32].

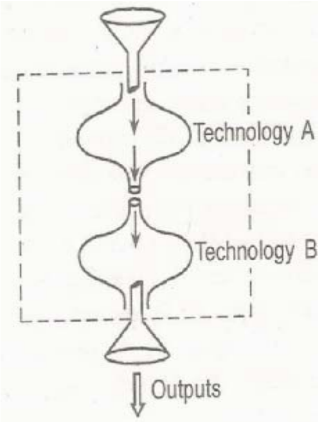

Fig. 1 Sequential hybrid system [32]

The IEC/IEEE ratio codes used in the recent research work are given in Table I. The codes used for interpretation are tabulated in Table II.

TABLE I
IEC/IEEE RATIO CODES

Ratios of characteristic gases	Range	Code of range ratios
C_2H_2/C_2H_4	<0.1	0
	0.1 – 1.0	1
	1.0 – 3.0	1
	> 3.0	2
CH_4/H_2	<0.1	1
	0.1 – 1.0	0
	1.0 – 3.0	2
	>3.0	2
C_2H_4/C_2H_6	<0.1	0
	0.1 – 1.0	0
	1.0 – 3.0	1
	>3.0	2

TABLE II
IEC/IEEE CODES FOR THE INTERPRETATION OF DGA METHOD [1-2]

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Characteristic fault type	Fault code
0	0	0	No fault	1
0	0	1	Low temp. thermal fault <150^{0}C	2^+
0	2	0	Low Temp thermal fault 150^{0}C - 300^{0}C	2^+
0	2	1	Medium temp. thermal fault 300^{0}C -700^{0}C	3
0	2	2	High temp. thermal fault >700^{0}C	4
0^*	1	0	Low energy partial discharges	5
1	1	0	High Energy partial discharges	6
1-2	0	1-2	Low energy discharges	7
1	0	2	High energy discharge	8

* non significant

It is established that the main difficulty for developing a good diagnostic rule is the lack of sufficient high quality examples with which to train and validate a network. So, as to overcome this in the proposed work real data from research publications [6, 9, 16, 18, 20, 22&27] and test records from utilities has been taken. Of the total samples randomly 60% are taken as training data, 20% as validation data, and the remaining 20 % as testing data.

The NN were trained and validated and the rules are extracted from the trained neural network. Since the NN have no explaining ability its difficult to interpret the results hence the extracted rules from the trained NN would be used for defining the membership functions of the FIS which can explicitly display the knowledge by the AI techniques The human understanding would be greatly improved and the engineers and technicians would gain confidence in fault diagnosis of transformers. The proposed system is shown in Fig. 2. The results of the work will be published in a separate paper.

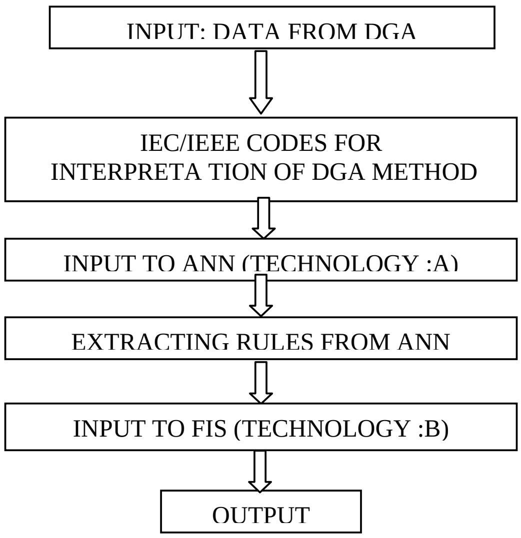

Fig. 2 Schema of proposed Diagnostic system]

V. CONCLUSION

After study of the AI methods applied for the fault detection in transformers based on DGA methods, it has been found that these can be used to evaluate the condition of the transformer provided sufficient amount of reliable DGA data is available. Each of AI techniques and combination of two of these, in their own right has provided efficient solutions to incipient fault identification. The synergy of ANN and FIS can be a good solution for reliable results for predicting faults because one should not rely on a single technique when dealing with real –life applications.

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