Expert System for the Fault Diagnosis of Oil-Filled Power Transformer Using Dissolved Gas Analysis

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INTRODUCTION

Faults and damage in oil-filled power transformers has a devastating effect on the overall reliability of electrical power systems. Several factors, especially electrical and thermal stresses age the transformer and subject them to incipient faults. These faults, if left undetected will cause deterioration and eventually lead to failure of the transformer [1]. The presence of faults such as arcing, sparking, partial discharges and overheating in transformers results in chemical decomposition of the insulating materials [2].

The paper insulation in the transformer provides the dielectric strength and dielectric spacing for the transformer windings. The ageing of paper depends on operating temperature, moisture, oxygen, acidity levels of the oil and the type of paper used. Mineral oil in the transformer provides cooling for the transformer. Transformer oil also degrades due to electrical and thermal stresses. Several gases are formed during transformer faults. These are: H_2, O_2, N_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and C_2H_8. These gases are either entirely or partially dissolved in the mineral oil [1,2]. This is due to the differences in solubility of gases in oil. These dissolved gases can be analysed by Gas Chromatography [3]. Therefore, knowing the concentration of gases dissolved in the mineral oil provides the necessary information on the serviceability of the transformer. The concentrations of the dissolved gases and the generation rates of each gas over a period of time can assist in determining the condition of the transformer [4].

The present advancement in artificial intelligence (AI) modelling techniques has enabled power engineers and researchers to develop powerful and versatile AI software to diagnose transformer faults. This reduces the manpower and financial overhead required by utilities to perform such operations. This paper presents a proposed expert system that utilizes fuzzy logic implementation into traditional dissolved gas in oil analysis techniques. Furthermore, two proposed diagnosing techniques and a knowledge database, containing recommended actions, possible causes of faults and further diagnostic methods are incorporated into the system. This is to provide the user with more accurate results and better condition awareness of the transformer.

DISSOLVED GAS ANALYSIS AND INTERPRETATION TECHNIQUES

Dissolved gas analysis (DGA) is the most widely used technique to monitor the condition and to diagnose faults of a transformer. This analysis uses the relationship of gases generated in relation to different types of transformer faults. There are a number of transformer fault interpretation methods utilizing DGA data, namely Roger's Four Ratio method [5], Northern Technology & Testing (NTT) Flagpoint Method [6] and Total Dissolve Combustible Gas Analysis (TDGA) [7]. The Roger's Four Ratio method uses the magnitudes of four ratios of gases; similar to that of the Roger's ratio method of IEEE Standard C57.104-1991 [7], with an additional ratio of Ethane/Methane to generate a four-digit code interpretation table. This code interpretation table contains 12 major faults.

The NTT Flagpoint [6] method sets specific threshold limits for developed gases. According to this method, if a particular gas concentration in a transformer exceeds the threshold limits as shown in Table 1, this transformer is assumed to experience a specific fault or faults.

Table 1: An extract of NTT Flagpoint methods [6]

Gas	Normal (<)	Abnormal (>)	Interpretation
H_2	150 ppm	1500 ppm	Corona, Arcing
CH_4	25 ppm	80 ppm	Sparking
C_2H_6	10 ppm	35 ppm	Local Overheating
C_2H_4	20 ppm	150 ppm	Severe Overheating
C_2H_2	15 ppm	70 ppm	Arcing
CO	500 ppm	1000 ppm	Severe Overheating
CO_2	10,000 ppm	15,000 ppm	Severe Overheating

Total Dissolved Combustible Gases (TDCG) [7] allows the user to determine the condition of the transformer based on the increase of fault gases within a specific duration, sampling interval or different concentration threshold limits for the combustible gases. It provides vital co-relation information among rate of increase in gas concentration, present gas concentration and the fault conditions of the transformer.

PROPOSED EXPERT SYSTEM AND DIAGNOSIS TECHNIQUES

To achieve a synergy in analysing transformer faults, a combination of different methods with artificial intelligent techniques are incorporated in this proposed expert system. This proposed system consists of an input section, a transformer condition verification mechanism, an integrated diagnosis mechanism and an output section. The dissolved gas analysis data (DGA data), is entered into the system in parts per million (ppm). The condition of the transformer is then verified for any abnormal operations. If the condition of the transformer is classified under abnormal condition, the diagnosis mechanism will be activated. This mechanism consists of 5 proposed steps [8].

a. Fuzzify Roger's Four Ratio Method
b. Fuzzify NTT Flagpoint Method
c. Generation Rate Ratio Method
d. Fault correlation
e. Recommended actions

Fuzzy logic was selected for the implementation into Roger's four ratio and NTT Flagpoint method. A fuzzy system allows the representation of imprecise human knowledge in a natural and logical way. A fuzzy logic system is more robust, compact and simpler to design compared to other AI modelling techniques. The fuzzication of both the methods were based on the 3 operation sets, Union (1), Intersection (2) and Complement (1). These 3 operation sets can be defined as:

$$\left(\chi_{A\cup B(X)}\right)=\max\left\{\chi_{A(X)},\chi_{B(X)}\right\}=\chi_{A(X)}\vee\chi_{B(X)} \quad (1)$$

$$\left(\chi_{A\cap B(X)}\right)=\min\left\{\chi_{A(X)},\chi_{B(X)}\right\}=\chi_{A(X)}\wedge\chi_{B(X)} \quad (2)$$

$$\chi_{A'(X)}=1-\chi_{A(X)} \quad (3)$$

The union function $\left(\chi_{A\cup B(X)}\right)$ of fuzzy logic is modelled by the fuzzy expression (1). The maximum intersection between subset *A* and subset *B* forms the union for a given fuzzy universal set (*X*). The intersection function $\left(\chi_{A\cap B(X)}\right)$ of the fuzzy logic is modelled by the fuzzy expression (2). The minimum overlapping between subset *A* and subset *B* forms the intersection for a given fuzzy universal set (*X*). The complement function $\chi_{A'(X)}$ is modelled by the fuzzy expression (3). The complement of a fuzzy subset $\chi_{A'}$ will be equivalent to that of 1 $-\chi_{A(X)}$. Therefore, this can be used to model the individual codes of a ratio, into linguistic expressions. In the case of ratio R1, the code 5, 0,1 and 2 can be expressed, as very low, low, medium and high. The intersection rule of minimum incursion between subsets of ratio can be 0.1 $Min\left\{\chi_{A(X)},\chi_{B(X)}\right\}$, for a full range of 5, for the universal fuzzy set (*X*). The value of 0.1 incursion or intersection between subsets allows transition (union or intersection) between subsets. This is approximately 2% intersection between each subset. Fuzzy Triangle rule is applied to calculate the fuzzy number for the Roger's four ratio and NTT Flagpoint method. The defuzzification process uses the Centroid Defuzzifier method to determine the final ratio values. This method identifies the centre of gravity of the fuzzy central spaces (Roger's ratio).

In the flagpoint method, individual generated gas indicates a particular fault formation. However, a single DGA data set is insufficient in some fault cases. The proposed Generation Rate (GR) ratio method applies the principle of trend analysis and fault indication with the concentration of individual fault gas. This proposed method uses the ratio between present fault DGA data and previous or pre-fault DGA data set. The formula (4) for the GR ratio is:

$$Generation\_Rate_{GAS}=\frac{fault(data)-prefault(data)}{fault(data)} \quad (4)$$

The fault data is the most current DGA data and the pre-fault data is the data before the occurrence of the fault condition. The above 3 methods output numerical possibilities of the 6 major fault conditions of a transformer (partial discharge (PD), sparking, arcing, local overheating, severe overheating and with or without the involvement of cellulose) These numerical possibilities will be summed up and then averaged to find the fault of the greatest possibilities. Since the electrical fault may leads to the formation of thermal faults and vice versa. Therefore, it is necessary to correlate the primary fault condition (fault condition with highest possibility) with that of the secondary fault condition (related fault condition with second highest possibility). This can be best illustrated with Table 2 on the relationship between the primary thermal/electrical and secondary thermal/electrical fault conditions.

Table 2: Correlation between primary and secondary fault conditions.

Primary fault condition	Secondary fault condition
Local Overheating (Thermal fault)	Sparking (Electrical fault)
Severe Overheating (Thermal fault)	Sparking or Arcing (Electrical fault)
Partial Discharge (PD) (Electrical fault)	Temperature too low to relate to any thermal faults
Sparking (Electrical fault)	Local or Severe overheating (Thermal fault)
Arcing (Electrical fault)	Local or Severe overheating (Thermal fault)

Local overheating can be correlated with overheating of components, overloading of the transformer, failure of cooling devices and moderate intensity electrical discharge (temperature <500°C); Whereas, severe overheating can be correlated to overheating of transformer components/joints, short circuit of windings, ground faults and high intensity electrical discharge (temperature >500°C). Partial discharge (PD) was not correlated to any thermal faults, as the intensity of the discharge causes minimum formation of higher molecular weight gases, such as acetylene and ethylene. Sparking and arcing are of higher intensity electrical discharge, formed between temperatures 300 to 1000°C. Therefore sparking and arcing are correlated to both local and severe overheating of the transformer oil.

Finally the section for recommended actions describe transformer condition assessment, likely causes of faults and recommended further diagnosis methods. Condition 2,3 and 4 of TDCG [7] were used in the condition assessment to classify the condition of the faulty transformer. The proposed system will provide the likely causes of a particular fault and then recommend further diagnostic methods to assess the magnitude of the fault. This can be achieved by studying both the fault characteristic of each fault and the advance diagnosis methods for each fault. For example, sparking causes slight overheating with involvement of cellulose, the likely causes can be loose or undersize HV contacts and fault components. This causes a fault temperature of 300°C to 500°C, which produces moderately high molecular weight gas. Infrared, acoustic emission or radio interference emission monitoring can be employed to determine the specific location of the hotspots. Furthermore, furan analysis is also recommended to determine the degree of ageing of the cellulose.

RESULTS

The proposed expert system was implemented using Microsoft Visual C++ Version 6®, into an executable file (Win98 OS format) of single dialog box. Twenty-two fault cases of oil-filled transformers of various ratings were used for verifying the accuracy of the proposed expert system. Of these 22 cases, 14 fault cases contain pre-fault DGA data.

The following fault case (as shown in Table 3) is extracted from the 22 tested cases. The actual result of the transformer is first presented. It is known to be experiencing arcing, causing overheating within the onload tap changer compartment. Only the result from the expert system with GR ratio exhibits similar output to the actual fault, the possible causes and remedial actions were also advised. The results from both the traditional and fuzzy Roger's four-ratio methods were also compared. In this case both methods are not able to produce accurate results. The last set of results is output by the proposed expert system without the use of GR ratio method (without pre-fault data). This set of results was not accurate as compared to the expert system with GR ratio.

Table 3: DGA data of extracted transformer fault case

Set \ Gas	Set A Fault Data (ppm) (Nov 1996)	Set B Pre-fault Data (ppm) (Feb 1996)
CH_4	104	19
C_2H_6	231	162
C_2H_4	153	69
C_2H_2	363	2
H_2	911	16
CO_2	1080	1401
CO	82	159

<u>Actual diagnosis result of transformer:</u>
Tap changer diverter failed to operate on odd tap positions causing selector switch to switch current inside transformer.

<u>Result of proposed Expert System with GR method:</u>
Fault condition of the transformer
- NOTE !!! Arcing causing Local Overheating, not involving Cellulose

Advisable actions to be taken
- Extreme High Gas concentration, consider removing unit from service

Likely causes for this transformer fault
- On-Load Tap Changers, HV contacts, bushings and short circuit of winding

Recommended further diagnosis method
- Infra-red emission monitoring for determining of hotspots, analyse for specific traces of metal

<u>Result of Fuzzy Roger's Four-Ratio Method:</u>
Slight Overheating 200 to 300°C

<u>Result of traditional Roger's four-ratio method:</u>
Required Further Diagnosis

<u>Result of proposed Expert System without GR method:</u>
Fault condition of the transformer
- Transformer experiencing Local Overheating without involvement of Cellulose

Advisable actions to be taken
- Extreme High Gas concentration, plan outage and prepare backup transformer

Likely causes for this transformer fault
- May be due to constant overloading and failure in cooling devices

Recommended further diagnosis method
- Infra Red monitoring for possible hotspots

The proposed expert system achieved an accuracy of 97.73% (for 22 fault cases), which is a 29.55% increase over the traditional Roger's Four Ratio method. Furthermore, the GR ratio method was also tested, and it improves the accuracy of the expert system by 14.29%. Two graphs are plotted to illustrate the accuracy of the proposed expert system as shown in Figures 4 and 5.

Figure 4: Accuracy of three different methods used to diagnose all the 22 fault cases

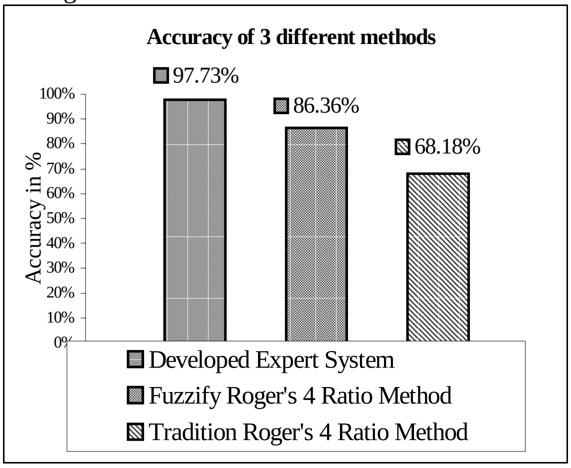
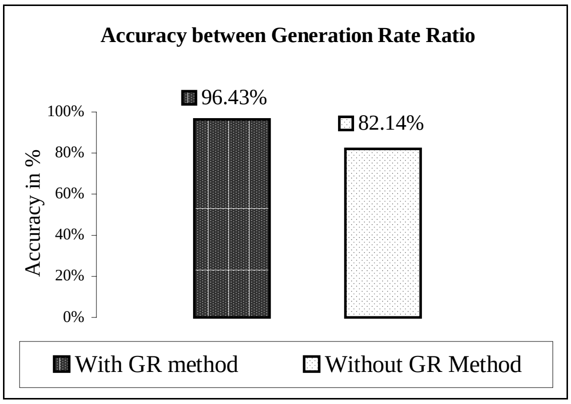


Figure 5: Accuracy of expert system with and without (GR) Generation Rate ratio method on 14 fault cases



CONCLUSIONS

The integration of artificial intelligence (fuzzy logic) with traditional Dissolved Gas in Oil Analysis has enabled this expert system to give a more accurate analysis of the overall condition of a transformer. Moreover, the careful study of fault cases and the functions of each component allows for a more in-depth understanding of various fault conditions of the transformers.

Due to limited availability of faulty data cases, this proposed expert system is tested with only 22 transformer fault cases. Nevertheless, this system is able to achieve a high accuracy (97.73%) in diagnosis of 22 fault cases.

Furthermore, this expert system provides additional information to the user. This makes the user more aware of the conditions of the transformer and further actions to be taken before the fault causes a breakdown of the transformer. The availability of more DGA data will aid in setting of the fuzzy membership parameters.

Finally, the diagnosis of transformer fault condition is a form of art subjected to variability, as there are numerous conditions affecting the overall complexity of the system. Conditions such as different manufacturing techniques, loading conditions, operating temperature and solubility of gases in oil affects the fault characteristics of individual transformers.

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