FUZZY LOGIC AND TRANSFORMER STATUS INDICATOR BASED EXPERT SYSTEM FOR DGA ANALYSIS

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Abstract: Since power transformers are critical assets of distribution utilities, transformer failures would have considerable economic and service level impact on the operation of distribution utilities. With the increasing age of the population of power transformers, it is of paramount importance embark on program of condition and health assessment of power transformer in service to be ensure failure risks and appropriate mitigating decisions and actions which could be instituted and avoid any catastrophic failures. This has led to the development of various on- and off-line non-intrusive testing techniques aimed at diagnosing the health of power transformers to optimize the maintenance effort and ensuring maximum availability and reliability.

Dissolved Gas Analysis (DGA) is a widely used technique to estimate the condition of oil-immersed transformers. The measurement of the level and the change of combustible gases in the insulating oil is a trustworthy diagnostic tool which can be used as indicator of undesirable events occurring inside the transformer, such as hot spots, electrical arcing or partial discharge. There are standards available to interpret the result of DGA using various diagnostic methods, but the interpretation of DGA should also be based on other information about the reliable particular transformer. This paper describes a realistic method for power transformer diagnosis using readily available data discussed using examples from different tests and measurement. The method considers practical limitations on obtaining data and possible constraints on the parameters for the Hungarian transformers utilize IEC, IEEE, and CIGRE criteria. The main thesis of this paper is to make a new connection between the transformer status indicator (Health Index) and the DGA using fuzzy logic and give a solution in an expert system.

1 INTRODUCTION

The power transformers are the most important and expensive equipments in the electrical distribution and transmission systems. It is very important to know as far as possible the status of the equipment. There are a lot of diagnostic methods to do this. To analyze a dissolved gas in the oil, it is very useful, because it is a global test, but the result can give approximately the type and the location of the failure in the transformer. The evaluating is based on the gasses volume and ratio. There are a few evaluating method for the dissolved gas analysing. But there are other important parameters above the DGA. These are from the operational parameters and the environmental parameters. The Transformer Status Indicator (TSI) is an expert system what is collecting these parameters into one status parameter [1][4].

2 DGA DIAGNOSES METHODS

The organic parts of the insulation of the transformers (paper, oil, wood) producing different gasses through its normal ageing and during overloading (overheating) too. Each cases the phenomena producing different type and different volume of the gases. So if the types of the gases and their ratio are known, the fault type (high- or low temperature overheating, partial discharge, low or high energy discharge etc.) can be detectable by the next methods [2][12].

2.1 Key Gas method

Decomposition of gases in oil and paper insulation of transformers caused by faults depends on temperature of faults. Various faults produce certain gases and the percent of some gases have been found to mention fault types, such as overheated oil and cellulose, corona in oil and arcing in oil.

2.2 Ratio methods

The ratio methods are the most widely used technique. **Roger's**, **Doernenburg**'s and **IEC** ratios are all used by utilities. Typically, three or four ratios are used for sufficient accuracy, such as the original Roger's ratio method uses four ratios (CH4/H2, C2H6/CH4, C2H2/C2H4, C2H4/C2H6) to diagnose eleven incipient fault conditions and a normal condition. This method took information from the Halstead's thermal equilibrium and Doernenburg's ratios along with information from faulted units.

2.3 MSZ-09-00.0352

The MSZ-09-00.0352 is a Hungarian National Standard [3]. In this Standard four-level of criteria have been developed to determine the risks of the transformers. These criterions help to determine weather a transformer is behaving normally, especially when there is no previous dissolved gas history or the transformers have been under operation for many years. The criterion uses total concentration of all combustible gases presented in Table 1., for the type of Generator Step-Up (GSU) Transformers and Grid Transformers separately. The transformer is considered “Normal” when the total dissolved combustible gas (TDCG) are below levels and also when any individual combustible gas does not exceed specified levels presented in Table 2, if not additional investigation is needed.

Table 1: Condition vs. operation time of the transformer

Condition	Concentrations of the total combustible gas (ppm)			
		Operation time of the transformer		
	Type	<8 year	8-15 year	>15 year
V0- Normal	Grid	<350	<450	<800
	GSU	<500	<650	<1000
V1- Dubious	Grid	≥350 <450	≥450 <800	≥800 <1600
	GSU	≥500 <650	≥650 <1000	≥1000 <1600
V2- Faulty	Grid	≥450 <800	≥800 <1600	≥1600 <3000
	GSU	≥650 <1000	≥1000 <1600	≥1600 <3000
V3 – Dangerous	Grid	≥800	≥1600	≥3000
	GSU	≥1000	≥1600	≥3000

Table 2: Concentration limit of dissolved gas

Dissolved gas	Concentrations limit (ppm)	
	GSU Transformer	Grid Transformer
Hydrogen (H2)	200	160
Methane (CH4)	100	60
Ethane (C2H6)	60	60
Ethylene (C2H4)	60	60
Acetylene (C2H2)	4	4
Carbon-monoxide (CO)	700	360
Carbon-dioxide (CO2)	10 000	10 00

The Standard offers the existence of three ratio codes presented in Table 3 (C2H2/C2H4, CH4/H2, C2H4/C2H6) to diagnose eight types of faults given in Table 4.

Table 3: MSZ Standard’s ratio for key gases

Ratio limits	C2H2/C2H4	CH4/H2	C2H4/C2H6
	Ratio codes		
<0,1	0	1	0
≥0,1…1≤	1	0	0
>1…3≤	1	2	1
>3	2	2	2

Table 4: Fault diagnosis

Case	C2H2/C2H4	CH4/H2	C2H4/C2H6	Suggested fault diagnosis
0	0	0	0	Normal
1	0	1	0	Partial discharge of low-energy
2	1	1	0	Partial discharge of high-energy
3	1-2	0	1-2	Low energy arcing
4	1	0	2	High energy arcing
5	0	0	1	Hot spot 110°C…150°C
6	0	2	0	Hot spot 150°C…300°C
7	0	2	1	Hot spot 300°C…700°C
8	0	2	2	Hot spot above 700°C

2.4 Duval triangle

The Duval triangle method considering the concentrations (ppm) of methane (CH4), ethylene (C2H4), and acetylene (C2H2) are expressed as percentages of the total (CH4 + C2H4 + C2H2) gas. The evaluating based on a work point in a triangular coordinate system on a triangular chart which has been subdivided into fault zones. The fault zone in which the point is located designates the likely fault type which produced that combination of gas concentrations.

2.5 CIGREE guideline

Accordig to the data from the lot of countries, the CIGRÉ 15.01 working group suggest additional gas ratios for improving the efficiency and accuracy of the DGA method.

3 APPLICATION OF SOFT COMPUTING TECHNIQUES

To improve the diagnosis accuracy of the conventional dissolved gas analysis (DGA) approaches, this part proposes a fuzzy system development technique based combined with neural networks (fuzzy-neural technique) to identify the incipient faults of transformers. Using the IEEE/IEC and National Standard DGA criteria as references, a preliminary framework of the fuzzy diagnosis system. The artificial neural network (ANN) based fault diagnosis is presented, which overcomes the drawbacks of the previously applied fuzzy diagnostic system that is it cannot learn directly from the data samples.

3.1 Fuzzy logic

Advantages of the application of fuzzy logic in fault gas analysis were published by several authors [7]. It was pointed out, that uncertainties of diagnosis due to the values close to limit values of classification procedures can be effectively handled by fuzzy sets. "Fuzzy version" of different methods, like Key gas analysis were made. A typical solution is the application of a fuzzy interference system to approximate the relationship between the measured values and the faults causing the different gas combinations.

Its application for fault gas analysis is presented through the National Standard's ratio method (however, it can be used in other methods as well). There are two important differences between the original method and the fuzzy logic based version. The first one is the application of fuzzy membership functions for the classification of fault gas ratios. It is important to remark, that setting the crossing of membership functions the degree of uncertainty can be taken into consideration. The second difference, that by the use of these functions, an upper and a lower limit is calculated for the specific faults. The rule base can be seen in Table 5.

Table 5: Fuzzy logic rulebase

C2H2/C2H4	CH4/H2	C2H4/C2H6	Diagnosis
- / low	- / low	- / low	Normal
- / low	high	- / low	Partial discharge of low-energy
high	high	- / low	Partial discharge of high-energy
high / very high	- / low	high / very high	Low energy arcing
high	- / low	very high	High energy arcing
- / low	- / low	high	Hot spot 110°C…150°C
- / low	very high	- / low	Hot spot 150°C…300°C
- / low	very high	high	Hot spot 300°C…700°C
- / low	very high	very high	Hot spot above 700°C

Expression '-/low' means that the cell is not involved into the calculation of the maximal degree of existence while it is involved into the calculation of the minimal one.

Table 6:
Gas concentration for each case

	Case 1	Case 2	Case 3
Carbon-dioxide(CO2)	1300	4881	5963
Ethylene (C2H4)	1	113	36
Ethane (C2H6)	18	47	30
Acetylene (C2H2)	2	1	2
Hydrogen (H2)	394	80	50
Methane (CH4)	64	66	79
Carbon-monoxide (CO)	137	756	717

It is assumed that the appearance of fault gases and any not low ratios of the components (according to the National Stadard's ratio method) is a symptom that is caused by the fault at the end of the row. A specific rule contains the fuzzy AND connection between the symptoms connected to a given fault. The method was used for different illustrative examples originated from the everyday practice, presented in Table 6. The result of analysis for the three different cases presented in Table 7.

Table 7: Fuzzy logic diagnosis

Diagnosis	Case 1		Case 2		Case 3	
	min	max	min	max	min	max
Normal	0	0	0	0	0,1	0,1
Partial discharge of low-energy	0	0,7	0	0	0	0
Partial discharge of high-energy	0,7	0,7	0	0	0	0
Low energy arcing	0	0	0	0	0	0
High energy arcing	0	0	0	0	0	0
Hot spot 110°C…150°C	0	0	0,8	1	0,1	0,6
Hot spot 150°C…300°C	0	0	0	0,2	0,5	0,9
Hot spot 300°C…700°C	0	0	0,2	0,2	0,6	0,5
Hot spot above 700°C	0	0	0,2	0,2	0	0

3.2 Artificial Neural Network

Artificial intelligent (AI) techniques were studied worldwide recently for pattern recognition such as fault diagnosis [6]. These techniques include expert system, fuzzy logic and artificial Neural Network (ANN). ANN approach is automatically capable of handling highly nonlinear input-output relationships, acquiring experiences which are unknown to human experts from training data and also to generalize solutions for a new set of data. This feature will enable ANN to overcome some limitations of an expert system.

This permits a best fit of the data, providing at least the best guess under the given circumstance, and avoiding the "no decision" problem sometimes occurs in the ratio methods.

The process of detection of incipient faults in transformers using an ANN can be seen as the process of associating inputs (patterns of gas concentrations) to outputs (fault types or normal condition).

Input-output patterns

Neural network training requires the definition of input and output patterns.

The input data include all information related to an oil sample such as gas concentrations and gassing rates. For each input pattern there exists an output pattern which describes the fault type for a given diagnosis criterion.

Diagnosis outputs include diagnosed fault type, diagnosis confidence and maintenance action recommendations. All the fault type classification are used in the system output, which were included in the previous DGA methods, such as no fault overheating, low energy discharge, high energy discharge - arcing and cellulose degradation. Both patterns constitute a neural network training set.

Neural network configuration and training

Several ANN units are responsible for individual fault diagnosis. In the neural network, the most basic information-processing unit is the neuron model [8][13]. They are organized in three or more layers, such as the input layer, single output and one or several hidden layers, use a backpropagation algorithm for training, presented in Figure 1.

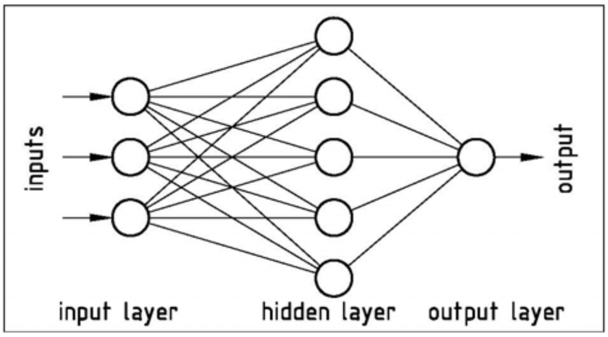

Figure 1: Neural network model

The number of neurons in the hidden layer was variable for each diagnosis criterion, depending on the problem complexity.

4 EXPERT SYSTEMS

4.1 DGA expert system

Expert system and fuzzy logic can take DGA methods and other human expertise to form a decision making system. Information such as the influence of transformer type, operation time, with or without on-load tap

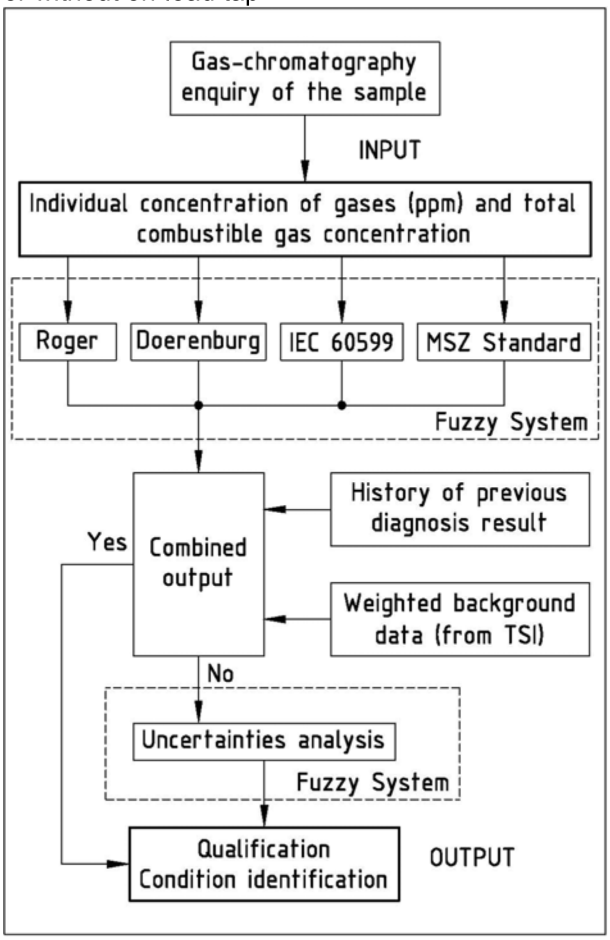

Figure 2: Fuzzy expert system flowchart

changer, voltage class, gassing rates and history of the diagnosis result can be utilized [10].

These information is served by the Transformer Status Indicator expert system.

A fuzzy expert system can reduce the uncertainties related to the oil sampling and chromatography analysis, avoiding the crispy limits between states considered in DGA methods. Figure 2 shows the suggested build-up of the system [5][9]. In the Build-up of the expert system on Figure 2 there are four evaluating methods (Roger's ratio, Doerenburg's ratio, IEC60599 and the national standard: MSZ standard: MSZ-09-00.0352), what are described in the section no.2.

The expert system uses these evaluating methods to give accurate results. In the case of distorted gas ratio the expert system can give a good result. Because the results of the four discrete evaluating method are confirm or confute each others in the finally result. Thanks to this, the evaluating system gives result for every case, as opposed to the "classic" methods.

Practical solution of the expert system

The transmission system substation equipments have been maintained and diagnostized by the National Power Line Company Inc. in Hungary. Moreover, the National Power Line Company Inc. provides the same service for a lot of other partner.

To continue the maintaining provision on this high grade, and to comply with its maintenance functions to remain a reliable and competitive stakeholder of the market, the National Power Line Company Inc. had to introduce a better, more flexible, up-to-date registration of the committed equipments. Hence the National Power Line Company Inc. opted for introducing the substational machinery's maintenance and diagnostic data registry and maintenance task management system (asset management) namely "KarMen". The KarMen is able to manage the objects, machineries, assemblies and accessory parts; to store, visualize and track reports, diagnostic measurements data, lifetime and nascent documentation.

The KarMen system is able to manage the transformer's main parameters, and it does yeoman service to track continuously the lifecycle of them.

The LabSoft software which primary aims is to generate uniform, administration-supporting, user-friendly reports from the laboratory samples, and to archive the results.

The fuzzy-neural based expert system is the Transformer Analyzing System (TRANSYS) what is containing the fuzzy and ANN evaluating methods.

At present there is a connection between Labsoft, KarMen and Transys. The data stream between these programs is the next. The Labsoft reading the data from the measuring unit and send it to the TRANSYS to make an evaluation. After that, the TRANSYS send the report to KarMen to storing it. Nevertheless the report must be qualified when downloading it to KarMen.

Test results of the DGA fuzzy expert system (TRANSYS)

To check the reliability and accuracy of the TRANSYS expert system, it was tested by a lot of transformer DGA results. 15 sample case come from the Hungarian transformers [13], and 30 sample case come from an IEEE study [15]. The Hungarian samples were diagnosed by the National Power Line Company Inc.

All of these equipments were failed. During the reconstruction or reparation, the reason of the failure was investigated. The test based on to compare the known source of failure and the result of an evaluation from the historical DGA data. The evaluation was made by the fuzzy-neural system and the basic evaluation too. The basic evaluation combines the “classic” evaluation methods: Roger’s ratio, Doerenburg ratio, IEC60599 and MSZ standard.

The results are in the Table 8 for the 30 IEEE transformers and Table 9 for the 15 Hungarian transformers.

Table 8:
Test results of the DGA fuzzy expert system (30 transformers)

Accuracy of the expert system		
method	right diagnoses (%)	bad diagnoses (%)
MSZ 09-00.0352:1988 standard	83,33	16,67
IEC 60599:2007 standard	80	20
Roger's Ratio method	73,33	26,67
Döerenburg ratio method	83,33	16,67
Duval triangle method	90	10
Fuzzy based evaluating	83,33	16,67

The Table 8 shows that the accuracy of the fuzzy based DGA expert system is 83,33% in these case. The Table 9 shows the evaluating results in reference to the 15 sample transformers. The accuracy of the fuzzy based evaluating is the same as the case of 30 transformers.

Table 9:
Test results of the DGA fuzzy expert system (15 transformers)

Accuracy of the expert system		
method	good diagnoses (%)	bad diagnoses (%)
MSZ 09-00.0352:1988 standard	73,3	26,4
IEC 60599:2007 standard	80	20
Roger's Ratio method	73,33	26,4
Döerenburg ratio method	73,3	26,4
Duval triangle method	100	0
Basic evaluation	66	34
Fuzzy based evaluating	80	20

The Fuzzy – based system gave right diagnosis amount to about 80% of all failures observed, however the original systems amount to about 66% of all failures. The Fuzzy methods gave right diagnosis amount to about 20% earlier, or adverted to the chance of the development [13].

4.2 TSI expert system

The operational reliability is influenced the most by the quality of the insulation but even other state markers/features play an important role. The status of the insulation is depending on the operational and environmental parameters. The TSI marks the status of the transformer only one number [11][11], which is the TSI factor (TSIF). The TSI gives the background data for the DGA expert system.

Operational parameters

- Oil quality test
- Recovery Voltage Measurement (RVM)
- Loading factor history
- Utilization
- Insulation resistance
- Furan content
- Thermograph (infrared camera)

Environmental parameters

- Exterior and auxiliary equipments quality
- Age
- Maintenance history
- Geographical data
- Location in the grid

Physical Values

Each physical effect has one or more physical values. These are measurable values, for example the furan content is 4 ppm. Every Physical Values has a weight factor (W_i), because each Physical Values causes variant degradation in the insulation.

Classification Value

Every Physical Value has a variant scale. Therefore it is necessary to use a Classification Value (S_i) in the course of making TSI factor. The chart of Oil test (Classification Values and weights) is shown on the Table 10.

Table 10: Example to the classification (S_i) value

Physical Value	S_i					W_i
	1	2	3	4	5	
annual average temperature [°C]	10-12	13-17, 9-7	18-25, 8-5	26-30, 4-1	>30, <1	5

$$TSICi = \frac{\sum_{i=1}^{n} S_i \times W_i}{\sum_{i=1}^{7} W_i} \quad (1)$$

$$TSIF = 0{,}5 \times \frac{\sum_{i=1}^{5} TSIC_i \times K_i}{\sum_{i=1}^{5} K_i} + 0{,}3 \times \frac{\sum_{i=6}^{10} TSIC_i \times K_i}{\sum_{i=6}^{10} K_i} + 0{,}2 \times \frac{\sum_{i=11}^{13} TSIC_i \times K_i}{\sum_{i=11}^{13} K_i} \qquad (2)$$

Every operational and environmental parameters have one TSI code (TSIC) what is calculated by the (1) equation. The full TSI factor (TSIF) can be calculated according to the equation number (2).

5 CONCLUSION

Fuzzy logic and ANN based Power Transformer Fault Diagnosis and a result has been presented.

It has been showed that using the fuzzy diagnosis method, more detailed information about the faults inside a transformer can be obtained. This is an improvement over the conventional ratio method, which may be due to the more realistic representation of the relationship between the fault type and the dissolved gas levels with fuzzy membership functions.

However, it has to be mentioned, that usually fuzzy inference systems are sensitive on the quality of the human knowledge base; appropriate membership functions and rules are necessary to obtain acceptable accuracy. On the other hand, fuzzy expert system needs a large knowledge base that must be constructed manually and cannot adjust their diagnostic rules automatically thus cannot acquire knowledge from new data samples through a self-learning process.

ANN approach can be used for this purpose since this method capable of automatically acquiring experiences from training data and the experiences they obtained includes not only those of human knowledge, but also those which may be still unknown to human experts.

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