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The analysis of electrical and mechanical faults in power transformers by Fuzzy expert system

Nihat Pamuk[1]* and Yilmaz Uyaroğlu[2]

[1]Turkish Electricity Transmission Company, Sakarya, Turkey.
[2]Department of Electrical Electronics Engineering, Faculty of Engineering, Sakarya University, Turkey.

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Energy is one of the basic data for economic and social development. Sufficient electrical energy, high quality, continuous, low-cost and environmentally compatible manner should be available to consumers. Power system reliability depends on the reliability of the equipments in the system. For this reason, transformers of the power system are the most important equipments. In power transformer, failure rate is quite high compared to that in some parts of the world; and as such, the necessity to work in the best operation case of transformer and preventing transformer failures have obviously emerged. This study proposes the failure of insulating oil in power transformers. However, the electrical and thermal effects of cellulosic materials subjected to degradation have been analyzed in details and these gases emission show different type of failures. Also, these failures are seen in the production rate point to the magnitude of the failures. Analysis of failures using Fuzzy logic computer program have been tried in order to achieve the optimum method of evaluating the causes that play a role in the formation of probable transformer failures.
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Key words: Power transformers, gases, fault analysis, Fuzzy expert system.

INTRODUCTION

Reorganizing the structure of the electricity market requires the power sector companies in the market to control the different challenges and overcome these challenges. Electricity generation, transmission, distribution and other companies in the market have to do with optimal management in order to balance the economic management and allocate for lower investments in the sector. The need for transformers, whose financial and technical importance is too high, is increasing in the sector (Yilmaz, 1988). The creation of assets by investing in infrastructure for secure systems in the energy system is very important, and the assets that are managed effectively and efficiently are also very important. This is the most valuable assets in the occupation of the power transformer. Likewise, economic values and functions compared with other assets constitute the largest cost (Thang et al., 2003).

With modern methods of power system, operations and management business in the effective management of all assets is extremely important in terms of financial performance. As such, the strategies are used to implement risk assessments, powerful inventory and the evaluation of the remaining useful life of the transformers (Dietrich, 1983). As such, the life of power transformer changes between 20 and 35 years. Practically, the life of the transformer can go up to 60 years (Garcia et al., 2002). The risk of the faults in the transformers increases while transformers are getting old due to the weakness of the material. Electrical and mechanical strength of new transformers against abnormal operating conditions in the system is sufficient unless a design problem occurs. Insulation levels in the system may decrease due to some faults such as short-circuit fault or transient over voltages (Huang, 2003). Regular testing and preventive maintenance needs to be done in order to avoid problems in the power system and transformers to ensure a safe operation (Sağiroğlu and Yile, 2007). Transformer maintenances based on faults must be done

*Corresponding author. E-mail: nihatpamuk@gmail.com.

with very serious monitoring and maintenance practices. In order to avoid large failures, power transformers should be determined in advance with technical devices and equipment. Therefore in this study, using Fuzzy logic method was compared with conventional solutions; and as such, to identify the causes of expensive and large power transformer failures, optimum business was tried.

GAS FORMATION IN ISOLATION OIL

Oil filled high voltage equipment such as transformers, reactors and circuit breakers may break down for various reasons. Transformer's isolation oil shows the working condition of the transformer. Analysis values of the oil show early warning about transformer's faults. So, problems with transformers, such as degradation of paper insulation, detection of hot spots, moving parts failures and problems can be found easily.

Performing the regular analysis tests for oil and gas provides the system to work safely and seamless. As such, C, H, CH_2, CH_3 and a lot of others create hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3), ethylene (CH_2=CH_2), acetylene (CH≡CH), C_3 and C_4 hydrocarbon gases through rapid and complex reactions (Saraçoğlu, 2000). These gases are soluble in oil or release from the gas, if it is formed in large quantities. These gases accumulate at the relay bucholz in the power transformers. The formation temperature of ethylene is higher than methane and ethane gases and it is above 500℃. For the formation of acetylene gas, oil temperature must reach at least 800 to 1200℃. Therefore, acetylene gas is formed only with arc and the temperatures of ionized conductive channels reaches up to 1000℃. New stable products occur at lower temperatures and as such, the temperature of the oil which is around the arc field is under 400℃. Gases which are separated with oil steam appear together in this region. During oil arc process, carbon particles are formed in the very hot spots which are about 500 to 800℃ (Chang et al., 1994).

CO_2 / CO rate in the isolation oil

When the cellulosic materials begin to deteriorate, very small amounts of other gases, especially CO and CO_2, are formed; whereas as the temperature rises in oil, impregnated paper insulation for the formation of CO and CO_2 increased rapidly. At the same time, these gases are formed if the excess oxygen-containing oil reaches the sufficient temperature.

Before CO_2 / CO rate is determined, the amount of CO_2 and CO should be controlled. If the CO_2 and CO adjusted rate is less than 3, the existence of a defect in the paper insulation could be possibly discussed (Şakrak, 1999). In the normal processes of aging, the rate increases with high temperature thermal breakdowns and arcs.

O_2 / N_2 rate in the isolation oil

During the breakdown interpretations, nitrogen and oxygen gases are not used as the guide gases. Excessive pressure in the system provides useful information on leaks and temperature changes. Only oxygen gas is responsible for the deterioration of cellulose materials and the oil. Therefore it needs to be kept as low as possible. The rapid decline of the oxygen shows the changes of the oil properties and the formation of other gases shows overheating. Temperature changes of transformers in gas insulated systems affect the amount of nitrogen. When the isolation oil is heated and cooled, the nitrogen gas pressure goes up and falls down. These rises and falls change the resolution of nitrogen and other gases. As such, the rates of O_2 / N_2 in the transformers are about 0.5. If this rate gets a smaller value than 0.3, the insulating oil is subject to oxidation.

C_2H_2 / H_2 rate in the isolation oil

The tap changers in the power transformers bring about the low-energy discharges when it is working and meanwhile, some gases are exposed. If the ratio of C_2H_2 / H_2 in the main tank is greater than 2 and close to 3, this situation shows that the level tank pollutes the main tank. However, C_2H_2 / H_2 rate and the amount of acetylene effect changes according to the number of tap changer operation and the contamination on the size of the main tank. As such, water in the electrical equipment should stay, possibly, at the lowest level. Moreover, the water was found in the Free State, dissolved in oil or insulating paper, and it always have a negative impact on the equipment. Hydrated cellulosic materials are subjected to corona discharge rather than to dry amount of hydrogen gas exposed. If water temperature increases, the amount of hydrogen in the core cause the released of air and lead to unwanted electrolysis events in the transformer (Hochart, 1992).

EFFECT OF THE GASES FORMED IN THE ISOLATION OIL TO DETECT FAULT

If all gases were below the normal value and analysis values were normal, the hardware appears to work safely. At least one guide gas or regular gas is on the top and as such, the ratio of the gas must be calculated. However, the type of failure should be determined by the tables and graphs. Types of oil insulation defects seen in the corruption case are:

1. Partial discharges (PD): In such a partial corona

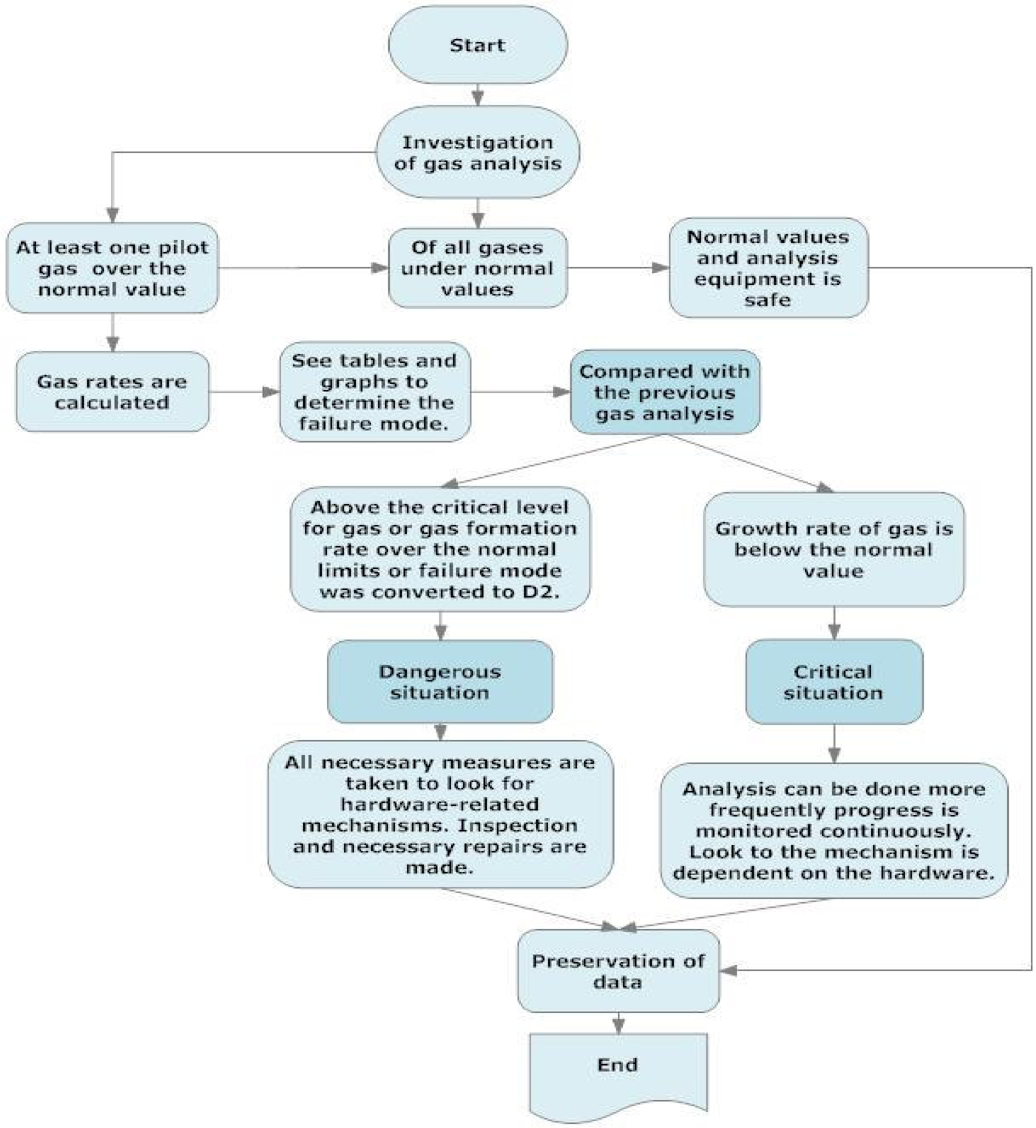

Figure 1. The construction flow chart of gas analysis.

discharge, where there is a spark type of insulation paper, partial discharges occur. Small holes in the paper insulation of transformers and carbonized path are opened. As such, this species is very difficult to find fault.

2. Discharges of low energy (D1): A part of the paper insulation in transformers is to be carbonized and large holes are opened. However, carbonized paper is trailed under load, as in the process of modifying the carbon particles in oil form.

3. Discharges of high energy (D2): Powerful discharges occurred and the paper caused the damage by excessive carbon recovery. To melt the metal parts in very large discharges, excessive carbon recovery is seen in oil. In this case, the flow through the defective region disables the equipment

4. Thermic faults: Under 300℃ (T1), the isolated paper is brown and above 300℃ (T2), it turns into an insulation paper, but when it is on 700℃ (T3), it becomes a carbon insulation oil. However, when it is above 800℃, the metal parts are incandescent and when it is over 1000℃, it melts (Dilli et al., 2008). Gas analysis is the construction of the flow chart shown in Figure 1.

Failure to interpret graphs, the rate of increase in daily gas, the percentage of gas and the total gas amount of flammable gas is diagnosed by looking for failures. As such, new developments in the gas analysis program are prepared and can be monitored. In guide gases, the relationship between the types of problem is as follows (Allan, 2005):

H_2…………………..Corona
O_2 and N_2………… Failure is not connected to gas
CO and CO_2………. .Cellulose insulation breakdown
CH_4 and C_2H_6……… Low-temperature oil drilling

(e)

Table 1. Possible failure indicators.

Failure mode	Definition of failure	Samples of failure
PD	Partial discharges	Gas-filled cavities are caused by inadequate impregnation, excess moisture in the paper, excessive saturated oil, oil vacancy and x-wax in the cavity formed by the line conductor discharges it occurred in.
D1	Discharges of low energy	Have different potential in a bad connection, display public, in toroid, winding or conductor adjacent to the disc, broken in welding or soldering, core in the closed loop and arc occurring. Fittings, bushing-tank, high-voltage and line-to-earth (core, tank and yoke) between the discharges. Board materials, adhesives and insulation between the windings formed on the dielectric discharges occurring on roads. Oil drilling, under load tap changer selector switch and cutting current.
D2	Discharges of high energy	Jumps, ways of conducting discharge, high energy and their power in local arc to continue. Low voltage-to-ground, bushing-tank, winding-core, copper bar between the tank links, coils in the oil ducts and pipes caused in short-circuit. Insulation between conductors, core insulation of the screws holding the arm and the core of the metal ring around the magnetic fluxes occurrence.
T1	Thermic faults T<300℃	The work overload of the transformer in case of emergency. Flux between the windings and oil reduction of blockages. The uneven pressure iron yoke leakage flux.
T2	Thermic faults 300℃<T<700℃	Selector switch positions in the bolted connections between the contacts are damaged badly in contact, the contact shifts in the carbon formation, bad contacts in the cable and bushing connection. Connection between the yoke and bolts and connections between the hair, grounding wire, the magnetic screen or in the worst sources connection (in print) caused by circulating currents. Side by side between the windings of the parallel conductors in the insulating material wears.
T3	Thermic faults T>700℃	Tank and a large circulating current in the core. Unbalanced high magnetic fields, a smaller tank that was caused by currents in the wall. Short circuits that occur in the core.

C_2H_4……………… High-temperature oil drilling
C_2H_2……………… .Arc

As a result of gases used in the analysis of gases' values obtained by dive, the possible fault types in their host failure indications are displayed in Table 1.

As such, the gases used in the interpretation of instructions are C_2H_2/C_2H_4 rate, CH_4/H_2 rate and C_2H_4/C_2H_6 ratio. However, failure rates of the gases are determined by the value to check whether these ratios exceed the limit value of gas or the control. After controlling the limit values, given in Table 2, each of the six types of defects and characteristic of hydrocarbon gases are indicated in pairs (Chia et al., 2009).

Table 2contains values, other than the gases rates, that do not fit the typical failures. In this case, the gas is subjected to multiple malfunctions; otherwise new failures would occur in this situation. However, the value of money has been reviewing the results of previous values for that gas and the gas that is being extracted from the final analysis.

FUZZY LOGIC METHOD

That some values are used in engineering is, in fact, not certain and is well known to have limit. To this value, however, some experimental results are clarified with

Table 2. Possible types of failures.

Failure mode	Definition of failure	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial discharges	<0.01	<0.1	<0.2
D1	Discharges of low energy	>1	0.1 - 0,5	>1
D2	Discharges of high energy	0.6 - 2.5	0.1 - 1	>2
T1	Thermic faults T<300℃	<0.01	>1	<1
T2	Thermic faults 3000℃<T<7000℃	<0.1	>1	1 - 4
T3	Thermic faults T>700℃	<0.2	>1	>4

Table 3. Rule base of Fuzzy logic system.

C_2H_2/C_2H_4 CH_4/H_2 C_2H_4/C_2H_6 Thermic	PD	D1	D2	T1	T2	T3
EL	D1	D1	D2	T1	T3	D2
L	PD	T1	D1	PD	D2	T2
M	PD	D1	T2	D1	T1	PD
EM	D1	T2	T1	D2	T3	D2
H	D2	PD	D2	T2	T2	T3
EH	D1	D2	PD	T2	D1	T3

EL = Extra Low; L = Low; M = Medium; EM = Extra medium; H = High; EH = Extra high; PD = Partial discharges; D1 = Discharges of low energy; D2 = Discharges of high energy; T1 = Thermic faults t<300℃; T2 = Thermic faults 300℃<t<700℃; T3 = Thermic faults t>700℃.

some assumptions that are known. Fuzzy logic is a very similar human thought and linguistic variable than the traditional logic systems. Fuzzy logic [0, 1], with varying degrees of infinite membership, is defined as a set of objects (Zadeh, 1965). Membership function is a function used to calculate the Fuzzy set of objects showing the degree of membership values (Djuro and Jaime, 2000). The aim of the Fuzzy control systems is to control the system instead of the Fuzzy rule-based expert system. Fuzzy controller output is controlled based on the information from sensors: that is, it translates them into linguistic variables or the Fuzzy membership function make up the Fuzzy. As such, the Fuzzy sensor values, the rule base and data mining, including the base unit and Fuzzy (if-then) rules, will be evaluated according to the logical variable obtained by the Fuzzy output (Aminzadeh, 1994). Obtained from the Fuzzy output values, using the weighted average of the exact method will be converted to a numeric value. This numerical value is derived from Fuzzy control and the control signal is applied to the system.

THE DESIGNED FUZZY LOGIC METHOD

According to the Mamdani inference system using Fuzzy logic modeling, a four input and output are considered. Thermal failure, C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 variables are input, and fault definition is used as the output data.' The general structure of the model is as shown in Figure 2.

In the Fuzzy decision making system, minimum function is used as the “AND” binder and “IMPLICATION” expression, and the maximum function is used as the “COMBINATION” method. “Smallest of maxima” method is used as the clarification method. In this method, the element which has the greatest degree of membership, but has the smallest value on the horizontal axis from the space of outputs is taken as the clarification output (Saraiva and Miranda, 1995).

While creating the Fuzzy model, the number of sub-regions thermal failures, such as C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 that will be separated and the kind of membership functions (triangular, trapezoidal and Gaussian curve) that will be used should be determined. In this study, the triangular type of membership function is used. As such, rule bases of Fuzzy logic controller are given in Table 3.

C_2H_2/C_2H_4 input variable is formed from 4 membership function. These are: extra low, low, medium and high membership functions. C_2H_2/C_2H_4 is varied between 0 and 3. C2H2/C2H4 membership function is as shown in Figure 3.

CH_4/H_2 input variable is formed from the 4 membership functions which are extra low, low, medium and high and it varied between 0 and 2. CH4/H2 membership function

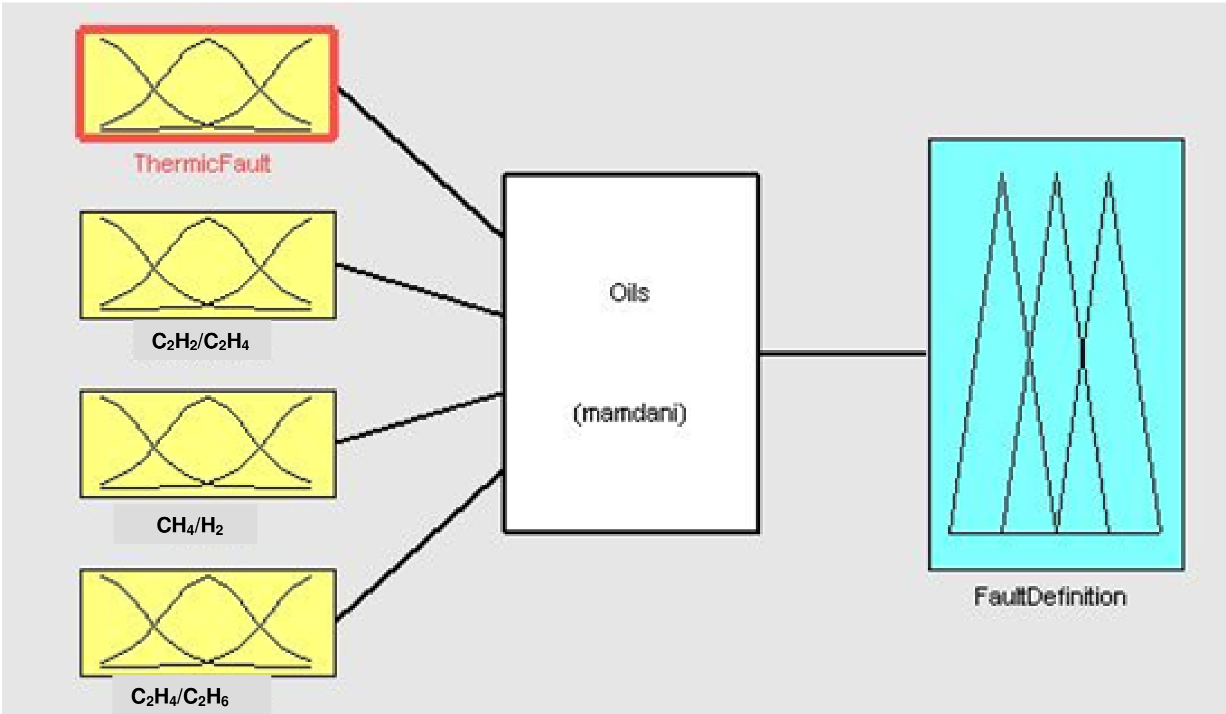

Figure 2. The general structure of the developed model.

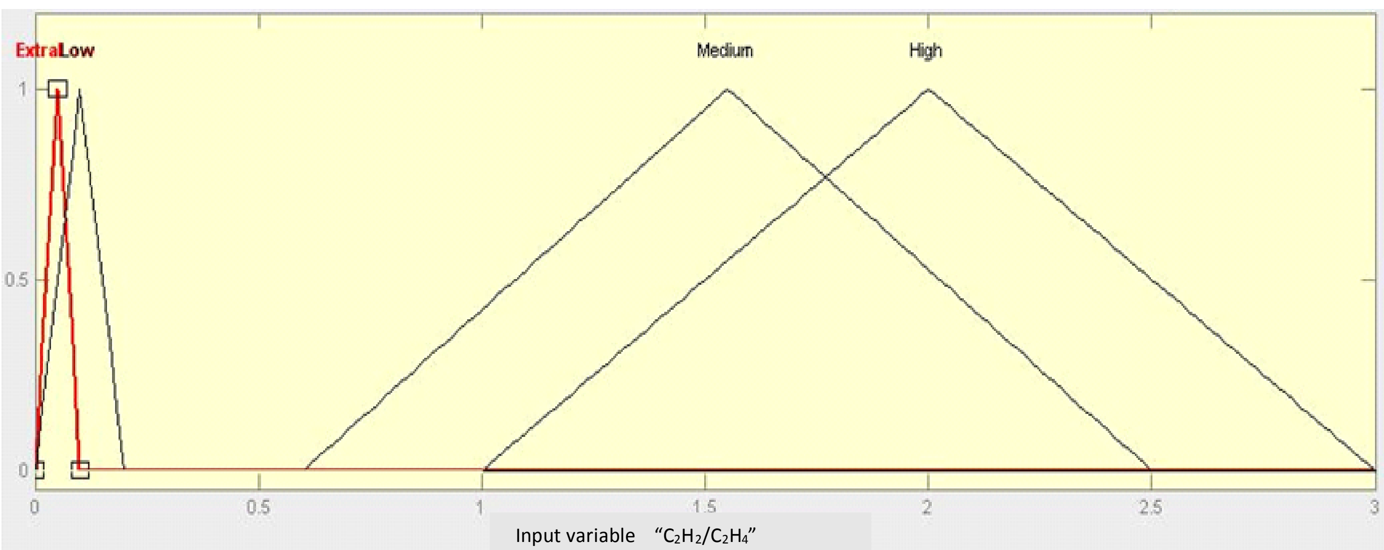

Figure 3. C_2H_2/C_2H_4 membership function.

is as shown in Figure 4.

C_2H_4/C_2H_6 input function is formed from 6 membership function. These are extra low, low, medium, extra medium, high and extra high membership functions. As such, C_2H_4/C_2H_6 varied between 0 and 5. C2H4/C2H6 membership function is as shown in Figure 5.

Thermal breakdown input variables are formed from the three membership functions and the range varies from 0 to 1400. Thermal breakdown of the membership function is as shown in Figure 6.

Corresponding to that, "fault definition" which consisted of 6 membership functions as the output variable, is used. These are PD, D1, D2, T1, T2 and T3 membership functions as shown in Figure 7.

Rule bases of Fuzzy decision making system consist of 36 rules. The connection between C_2H_2/C_2H_4, thermal

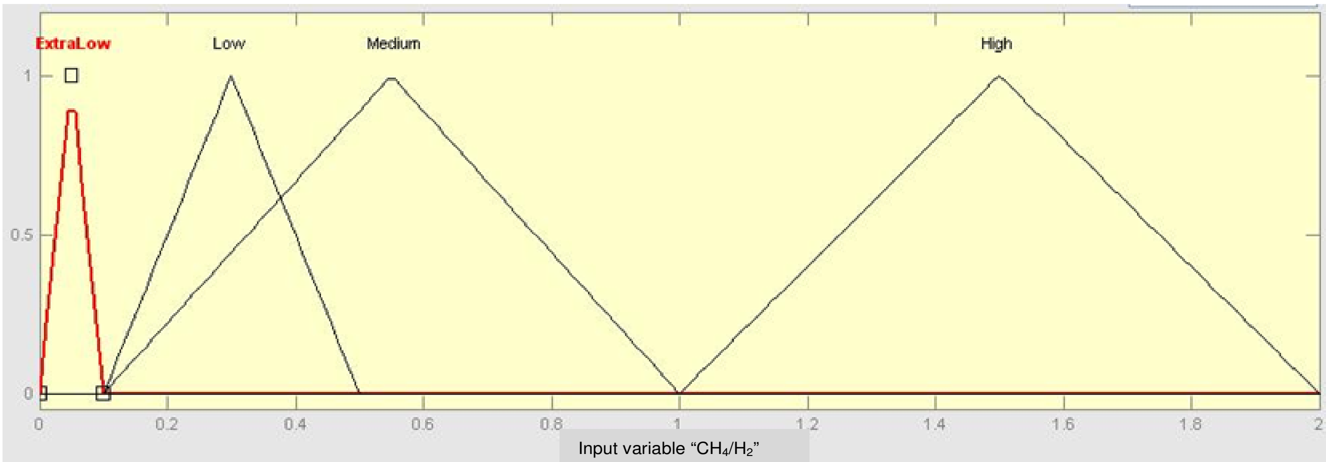

Figure 4. CH_4/H_2 membership function.

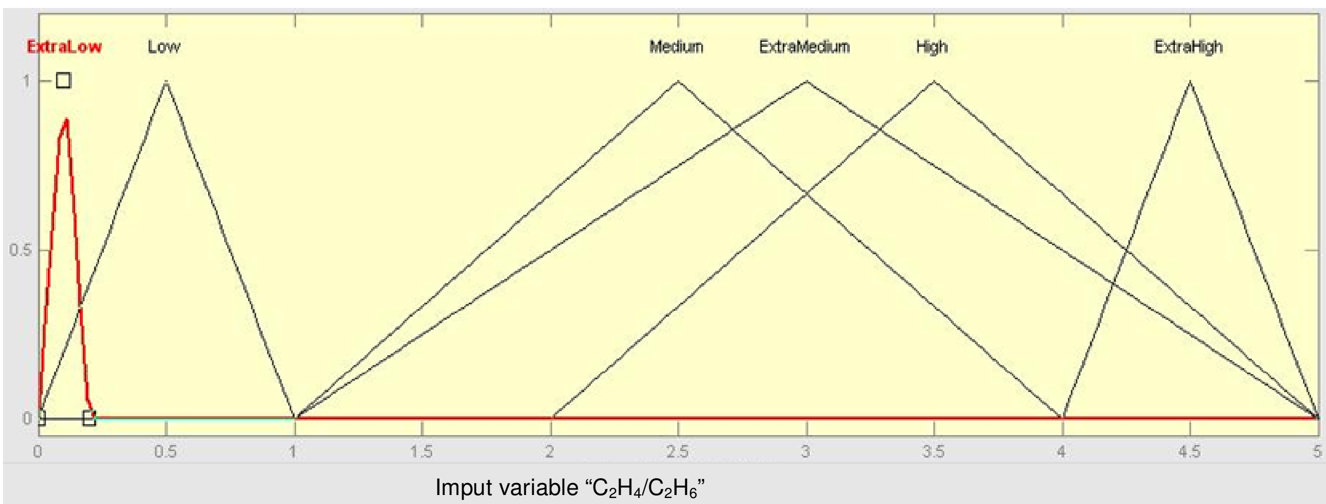

Figure 5. C_2H_4/C_2H_6 membership function.

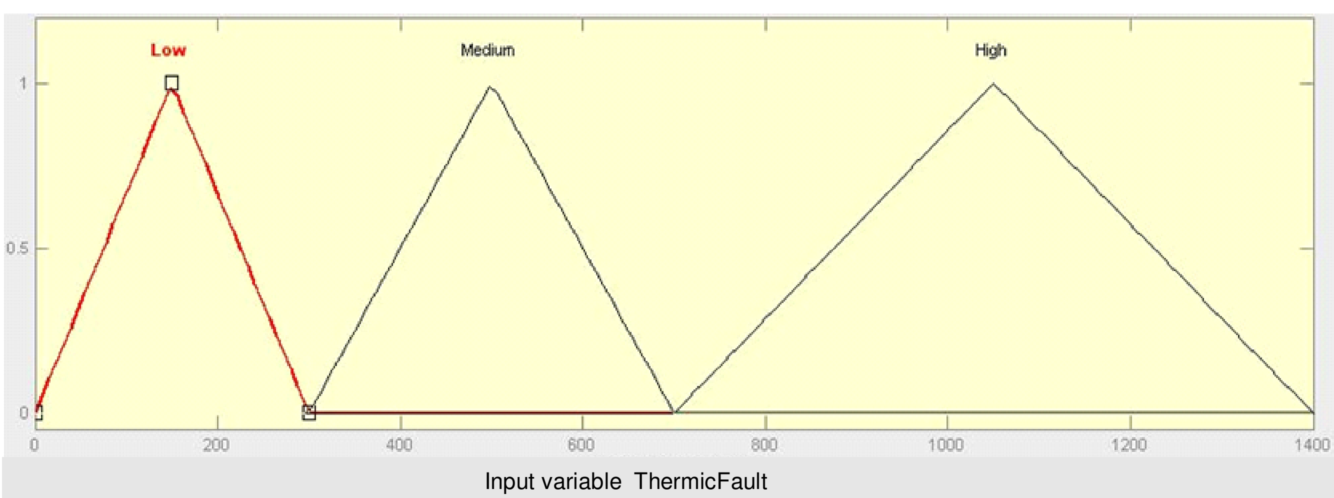

Figure 6. Thermal breakdown of the membership function.

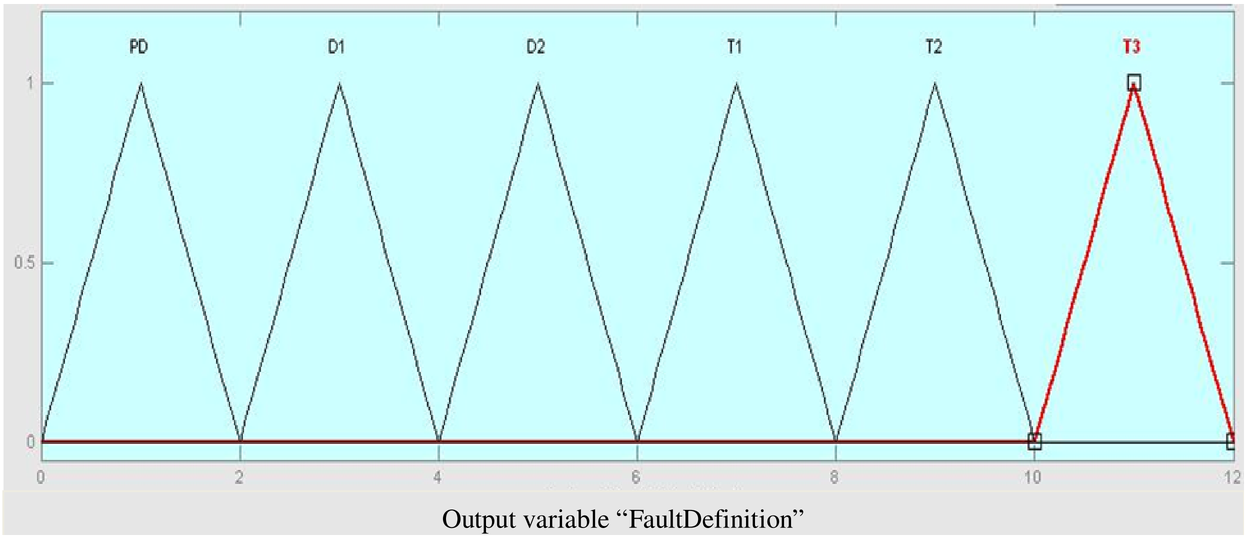

Figure 7. Membership function as a result.

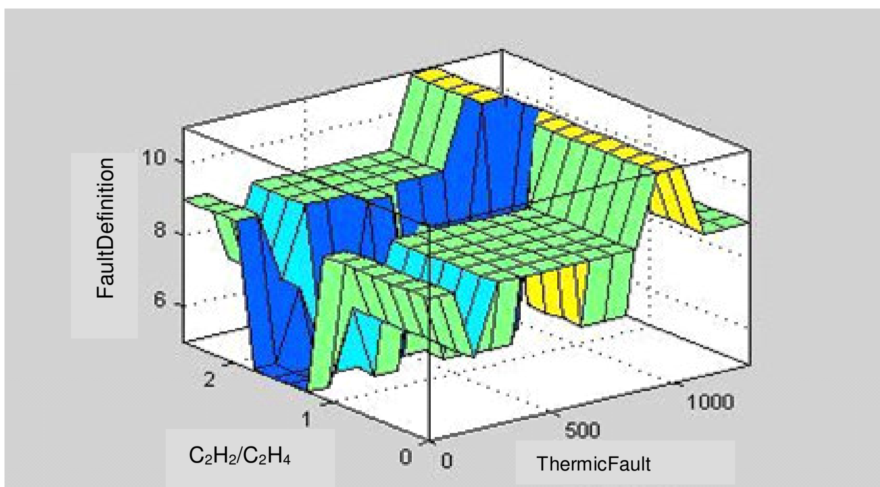

Figure 8. Thermal fault and C_2H_2/C_2H_4 variation graph.

fault and fault definition is given in Figure 8. When the change of the definition of failure is examined, we can see that the thermal breakdowns above 1000°C are found as T3, and C_2H_2/C_2H_4 rate takes a value between 1 and 2 in the parts that discharge faults occur.

EVALUATION OF THE MODEL RESULTS

In this model, 113 pieces of failure information which are taken from different power transformer substations between the years 1990 to 2010 and 17 pieces of failure information obtained in laboratory experiments' results has been considered (Saraçoğlu, 2000).

A total of 20 pieces of information failures are examined with the help of Fuzzy logic in order to test these failures. These examples used in the test are given in Table 4.

As a membership function of thermal breakdown, C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 rate data are taken and Mamdani Fuzzy inference system is modeled to find out the kind of fault. Mamdani method is a widely used Fuzzy logic method which is applicable to any problem and requires specialist knowledge. It is preferred because the creation of the model is simple and it is the basis for other Fuzzy logic modellings (Sakawa, 1993). Rules and the number of membership functions were found to be of major importance on the results. At least, one rule for each written value must be triggered. As such, we can reach the intended result by changing the base values of the membership function or adding a sub-cluster if it is needed. It is possible to solve different samples by

Table 4. Comparison chart.

Comparison diagram					
Thermic fault	**C_2H_2/C_2H_4**	**CH_4/H_2**	**C_2H_4/C_2H_6**	**Fault type**	**Fuzzy fault type**
-	**2**	**0.4**	**3**	**D1**	**D1-D2**
-	0.005	0.02	0.1	T3	T3
135	0.04	2	0.5	D1	D1
-	0.006	0.9	0.7	PD	D1
430	0.2	1.6	3.3	T2	T2
800	0.1	2	5	T3	T3
370	0.88	0.9	2.2	D1	PD-D1
210	1.5	0.75	1.32	D2	D2
-	2.8	0.18	0.85	D2	D1-D2
-	1.7	1.95	4.85	PD	PD
610	0.01	1.16	3.7	T3	T2
315	0.9	0.65	1.9	D2	D1-D2
88	3	0.09	0.42	T1	T1
1035	1.85	1.35	4.17	PD	PD-D2
740	0.87	0.5	3.7	T3	T3
279	0.065	0.85	2.93	T1	T1
-	0.72	0.35	1.63	PD	PD
1390	2.42	0.09	1.08	T2	T2
645	1.66	1.88	0.72	T3	T3
290	1.31	0.41	0.92	D1	D1

making data entry into the program later or making small changes. The most important issue here is getting enough data and determining the appropriate degrees of membership of these data and sub-cluster intervals. These intervals of sub-clusters can be changed to the intended values later. In addition to that, better results can be obtained by forming a lot of sub-clusters in the Fuzzy logic method (El-Gamal and Abdulghafour, 2003).

CONCLUSIONS AND SUGGESTIONS

Generally, hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethene (C_2H_6), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2) and oxygen (O_2) are detected in gas analysis in the oil. Isolation structure and densities, rates and sums of gases which are obtained from the samples are used in order to detect the failures. Analysis results are evaluated according to certain criteria and some important findings about the transformer's failures are obtained. So the type of failure, region and intensity are determined. Usually, major breakdowns can be avoided by preventing very slowly, growing failures without opening the hardware. So, unplanned downtimes and unwanted losses can be prevented.

In this study, we can see that there are 3 failures at the PD, D2 and T2 regions each, 2 at the T1 region, 5 at the D1 region and 4 at the T3 region when we examine the 20 failures from the view of failure types. When we compare the failure types which are found using Fuzzy logic to the real failure types, we get a 90% success. Therefore, it is seen that the Fuzzy logic model can be applied successfully to the determination of transformer failures with the gas dissolved in oil analysis. With Fuzzy logic method, the results are provided by taking advantage without using complex calculations in less time.

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