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Development of nominal rules on the Fuzzy Sugeno method to determine the quality of power transformer insulation oil using Dissolved Gas Analysis data

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Abstract
This paper aims to develop the nominal rules on the Fuzzy Logic Method using the Sugeno-Fuzzy Inference System (FIS) for Dissolved Gas Analysis (DGA) and determine the quality of the power Transformer 1 and Transformer 6 insulating oil at the Buduran 150 kV substation. The nominal number of proposed fuzzy rules is 1920 rules. Implementing the Fuzzy-Sugeno method on Transformers 1 and 6 shows that the six input variables from the DGA test can produce a Total Dissolved Combustible Gas (TDCG) output value of 32.67 and 26.19 ppm, respectively. Both values indicate that the insulating oil of Transformers 1 and 6 are in condition one and, at the same time, indicates that the dissolved gas composition is in Normal status. Furthermore, the TDCG value, condition, and quality status of the insulating oil have the same or 100 % accuracy compared to the DGA test by PLN (UPT Surabaya). Thus, the nominal development of fuzzy rules using the Fuzzy-Sugeno method can perform DGA analysis more accurately to determine the quality of power transformer insulation oil compared to previous studies.

Keywords:
Dissolved Gas Analysis;
Fuzzy Inference System;
Fuzzy Rule;
Fuzzy-Sugeno;
Membership Function;
Total Dissolved Combustible Gas;

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INTRODUCTION

The power transformer increases and decreases the voltage in the transmission or distribution system of electricity. As long as it is connected online to the power system, this equipment is also susceptible to operating failure. One of the causes of transformer failure is overheating. The heat phenomenon is caused by various factors such as overloading, hysteresis losses, eddy currents, and oxidation processes that produce rust and water, which can reduce the transformer's insulation capability. Thus, the transformer requires a cooling system to control the heat generated. Unfortunately, excessive heat can trigger a chain reaction that will accelerate the decline in the age and working quality of the insulation system for both insulating oil and paper insulators and a decrease in the effectiveness of the cooling system, so it can eventually damage the transformer as a whole.

Transformers require various insulator tests, both solid insulator and oil (liquid) insulator testing. Physical testing is carried out by testing solid insulating materials and transformer coils, while the oil test is done by testing the characteristics of the transformer insulation oil. Therefore, it is necessary to test the quality of the transformer insulating oil to maintain the reliability of the transformer. Dissolved Gas Analysis (DGA) is one of the methods to determine oil quality by analyzing the dissolved gas content in transformer insulating oil. A number of these gases are generally not detected by testing the characteristics of ordinary oil. The DGA test method is then used to identify the type and amount of dissolved gas in transformer oil.

Dissolved Gas (DGA) analysis on vegetable oil under electrical disturbance has been investigated in [1]. The analysis was carried out on six gas concentrations contained in the vegetable oil samples, both rice bran oil (RBO) and palm oil (PO). DGA investigations were carried out using methods, i.e., IEC, Roger's ratio, The Dornenburg ratio, and the Duval Triangle method, respectively. These methods were previously commonly applied to transformer oil made from mineral oil. The test results show that the highest gas concentration of all the gas samples was produced from C2H2 and H2. Duval's Triangle method was also the best method of detecting faults for these oils under electrical stress.

Several electrical equipment faults using DGA measurements after power transformer faults have been investigated in [2]. The three selected incident samples were overheating of the core bolt on a 400 kV autotransformer, the connection of an overheated winding conductor in a 275 kV reactor, and a dielectric fault in a 23.5 V/432 kV generator step-up transformer. The advantages and disadvantages of power transformer design-with information on the history of operation and maintenance of other equipment were very helpful in interpreting the DGA results correctly.

The modification of the Duval triangle for transformer fault analysis using the DGA procedure has been observed in [3]. The evaluation was carried out on DGA data from three different dynamic load transformer fault groups, i.e. temperature rise due to overload, cooling system failure and over-excitation, respectively. The results showed that the disturbance caused by gas in the transformer oil increased the excitation current, causing an increase in the core temperature of the transformer. Furthermore, the application of a multilayer perceptron-type artificial neural network (ANN) in the DGA method has been investigated in [4]. The ANN could automatically determine the parameters, connection weights, and training errors to achieve the best structure based on the algorithm to solve complex classifications that were previously unable to be solved by the classical DGA method.

The DGA using fuzzy logic-based IEC and gas ratio method to classify the type of fault in the power transformer have been investigated in [5] and [6], respectively. Two different fuzzy-IEC models applied to 13 samples of gas concentration values could accurately determine the type of fault in the transformer compared to the classical IEC method. The gas ratio method with four input variables can determine the kind of disturbance in the transformer with 91% accuracy. A comparison of Roger's ratio and IEC methods with the fuzzy inference system (FIS) approach for diagnosing transformer insulating oil faults has also been observed in [7]. The FIS implementation using the Roger ratio method is able to identify transformer fault diagnosis more efficiently than the IEC method.

The dissolved gas in camellia insulating oil under typical thermal and electrical disturbances in transformers has been tested [8]. The thermal fault simulation was tested under conditions: low temperature, medium temperature and high temperature, while the electrical fault testing simulation included partial damage, breakdown, and arc discharge. The triangle method H2, C2H4, C2H2&H2, CH4, C2H6 and no code diagnostic method resulted in a better fault diagnostic method for camellia insulating oil. The winding resistance method (WRM) and DGA in power transformer oil filling diagnostics have been observed in [9]. Acetylene, ethylene, methane and hydrogen were mainly produced due to poor contact between connections or tap changer contacts which can cause oil overheating. Poor connections were shown on the WRM result as an indicator of helping operators find and repair the equipment.

The comparison of DGA with vegetable-based ester oils (VOs), mineral insulating oils (MOs), and blended insulating oils (BOs) under thermal stress have been tested in [10]. This research showed that the nature of gas generation in thermally aged BO differs from that of thermally aged individual MO and VO. Formation of gas C2H6, CO and CO2 more in the BO. A DGA case study for fault diagnosis in oil-immersed power transformers using interpretations of IEEE std C57.104 and IEC 60599 has been tested in [11]. From the results of the DGA tests that have been carried out, these two methods can be used to identify the type of faults that occurs in the power transformer.

The solid oxide fuel cell (SOFC) detector based on oxygen consumption accumulation (OCA) for calculating traces of gas dissolved in transformer oil has been implemented in [12]. Experiments show that the relative standard deviation was less than 0.5% and the measurement error for five gas features less than 10% at a given concentration. These results were able to produce a competitive performance against other gas sensors using the curve fitting method.

The effect of humidity on the detection of dissolved gas in transformer oil for gas sensors based on tin oxide based on (SnO2, Pd/SnO2 and Zn/SnO2) has been investigated in [13]. The results showed that the metal doped gas sensor has better sensitivity and stability compared to pure SnO2 gas sensors. DGA results and detailed DGA data on load transformer operation have been discussed in [14]. Partial discharge detection and thermal fault detection in transformers at thermal power plants in India were selected as cases. DGA data interpretation was performed using the key gas method and validated by the ratio method (Rogers ratio and Doernenburg ratio).

The fuzzy logic method to help standardize the interpretation of DGA consistently and identify based on the critical level of the DGA data transformer in 2000 and 380 oil sample data has been observed in [15] and [16]. This method was used to diagnose several possible significant misinterpretations due to mixing the gas produced in the oil. As a result, the fuzzy logic method using IEC standards for DGA data interpretation and diagnosing many types of transformer faults has been developed [17]. The same method has also been done in [18] by taking transformer oil samples at Kenjeran Substation, Perak Substation, and Rungkut Substation. The simulation results of transformer oil conditions using DGA data with the fuzzy logic method on the three substations can produce a much better calculation accuracy than the method that PLN has done.

A fuzzy logic approach to dissolved gas analysis to determine the failure index of transformer oil insulation and fault identification has been investigated in [19]. This study identified problems due to power transformers' disturbances during load conditions using DGA analysis with four methods, i.e. key gas, IEC ratio, Duval triangle technique, and fuzzy logic approach. The fuzzy logic method is able to accurately and automatically identify errors that appear in the transformer. The intelligent method is proposed as a maintenance strategy and time interval for effective planning to minimize the breakdown damage, which can occur with the power transformer and its network. The interpretation of the DGA test results using a fuzzy logic approach based on the Duval Triangle method has been observed in [20].

This paper proposes nominal rules on the fuzzy logic method with FIS Sugeno to determine TDCG output variables. The FIS-Sugeno method, with the Singleton function having membership degrees of 1 and 0, is proposed to overcome the number of membership functions and reduce the simulation time in the FIS-Mandani method in determining DGA output variables. The paper is arranged as follows. First, the methods section presents the proposed method, the concept of DGA, the Fuzzy-Sugeno simulation design, the input and output variable, the input and output membership function, the FIS model, the fuzzy rules base, as well as input and output linguistic model. Then, the results and discussion section presents DGA test data of insulation oil power transformer, display of rule viewer as 1920 nominal fuzzy rule base, determination of six DGA data tests and TDCG as input and output variable as well as the final status of level oil transformer, i.e. normal, repair, danger or fault. This section also validates the nominal TDGC accuracy of the proposed method to show effectiveness compared to previous research. The parameter is the FIS model, nominal of input and output variable, TDGC using Fuzzy, TDGC using the test, as well as its accurate level. Finally, the paper is concluded in Conclusion Section.

METHODS

Proposed Method

The analysis of the state of the transformer insulating oil was carried out using the DGA method with a fuzzy logic approach. The oil samples were taken from 150 kV Transformers Number 1 and Transformer Number 6 at the Buduran Substation. In addition, further oil testing was carried out at PT. PLN UPT Surabaya, which is located on Jl. Ketintang Baru No. 9 Surabaya during the period March to May 2021. The Fuzzy Logic Method uses the Fuzzy Inference System (FIS) Sugeno algorithm, hereinafter referred to as FIS-Sugeno. The method is used to process DGA parameter input data to determine the insulating oil condition level output parameter. The flowchart diagram is shown in Figure 1.

The input variables in the FIS-Sugeno membership functions (MFs) are six gases, namely Hydrogen (H2), Methane (CH4), Ethane (C2H6), Acetylene (C2H2), Carbon Monoxide (CO), and Ethylene (C2H4). Nitrogen (N2) and Carbon Dioxide (CO2) are not included in the membership degree because the value of Nitrogen (N2) and Carbon Dioxide (CO2) has exceeded the TDCG value, so it can interfere with the Matlab simulation results. Therefore, the next stage is to determine the membership function values for each of the six gas parameters and divide them into four boundary degrees. The respective MFs values are normal, caution, abnormal, and danger, where the boundaries for each gas condition are shown in Table 1. The MFs limits for each gas input variable condition use the IEEE Standard.

This study uses a trapezoidal membership function curve (trapmf) to obtain the degree of membership of each dissolved gas input variable.

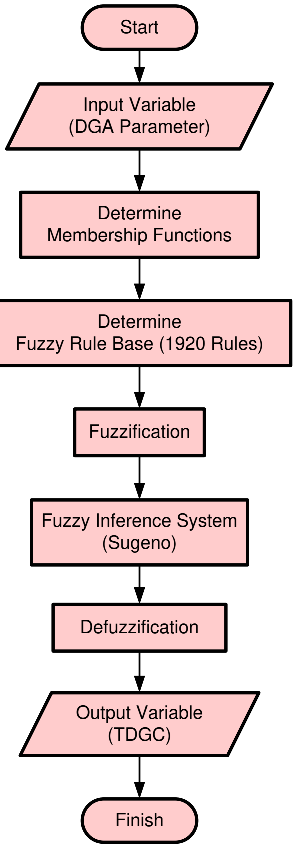

Figure 1. Flowchart of the proposed method

The number of membership functions is 1920, which will go through the fuzzification stage to be processed by FIS-Sugeno. Next, after going through the defuzzification stage, FIS-Sugeno will determine the TDCG value output variable. There are four levels of TDGC output value, each, i.e. normal, repair, danger, and fault and if each is quantified in numbers, i.e. 0.25, 0.5, 0.75, and 1.0.

The value of the fuzzy rule is taken in the 1920 rule, which is adjusted to the possible TDCG value based on the IEEE Standard IEEE Standart C57.104-2008 [21]. This value is already within the minimum input limit of DGA MF that meets Hydrogen (H2) for danger conditions greater than 1800. Therefore, if the TDGC value taken is 1921-4630 or greater than 4630 is selected as the fuzzy rule number, then the simulation time with Matlab will be longer.

Dissolved Gas Analysis

DGA can be interpreted as an analysis of the condition of the transformer, which is carried out based on the amount of dissolved gas in the transformer oil. DGA analysis is performed to detect the quantity of the content of certain types of gas from an oil sample. Although actually, under normal conditions, there are also gases dissolved in the oil, DGA testing is important to monitor the concentration of dissolved gases in the transformer oil to prevent fires in the power transformer. The concentrations of several dissolved gases in the oil sample were identified and associated with various types of electrical and thermal failures or abnormalities. This identification will then be useful as information regarding the working quality of the transformer. The parameters that must be considered from the data are the concentration values of various types of gases detected from the DGA test results are shown in Table 1 [21].

In the DGA test with the chromatography scheme, nine output gases will be analyzed to determine the state of the transformer insulation oil, as shown in Table 1. The results of the DGA test are then adjusted and analyzed based on the concentration of each gas produced. The standard value of the content of each gas can be seen in Table 2 [21].

The normal case (level<720) indicates that the TDCG value of the transformer is operating properly or normally. The caution (721-1920) case shows the TDCG value of the gas level is starting to be high where the dissolved gases are flammable and require vigilance. In case of abnormal (1921-4630), TDCG in this range indicates a high degree of decomposition of the insulating cellulose and/or oil. In this condition, we must be careful and need further treatment by increasing the sampling frequency. Finally, in case of danger (>4630), TDCG in this range indicates widespread excessive decomposition of insulating cellulose and/or transformer oil.

Table 1. Types of Gases Dissolved in Insulating Oil

No.	Gases Name	Chemical Symbol
1	Hydrogen	H_2
2	Methane	CH_4
3	Carbon Monoxide	CO
4	Carbon Dioxide	CO_2
5	Ethylene	C_2H_4
6	Ethane	C_2H_6
7	Acetylene	C_2H_2
8	Nitrogen	N_2
9	*Total Dissolved Combustible Gas*	(TDCG)

Table 2. Oil Condition with Gas Content

Gases in (ppm)	Gases Status			
	Normal	Caution	Abnormal	Danger
H_2	100	101-700	701-1800	>1800
CH_4	120	121-400	401-1000	>1000
C_2H_2	35	36-50	51-80	> 80
C_2H_4	50	51-100	101-200	>200
C_2H_6	65	66-100	101-150	>150
CO	350	351-570	571-1400	>1400
CO_2	2500	2500-4000	4001-10.000	>10.000
TDGC	720	721-1920	1921-4630	>4630

Continued operation may result in transformer failure. Using the fuzzy Sugeno method, the TDGC output value, i.e. converted into normal, repair, danger, and fault conditions and quantized in numbers, i.e. 0.25, 0.5, 0.75, and 1.0. The condition of normal, repair, danger, and fault is stated in condition 1, condition 2, condition 3, and condition 4.

Fuzzy-Sugeno Simulation Design

Fuzzy-Sugeno is the development of Fuzzy-Mamdani in a fuzzy inference system represented in the IF-THEN rule, where the output (consequent) of the system is not a fuzzy set but a constant or linear equation. The FS method uses a singleton MF with a membership degree of 1 in a single crisp value and 0 in other crisp values. Fuzzy Mamdani and Fuzzy-Sugeno differ in determining the output of the crip generated from the fuzzy input. Fuzzy-Mamdani uses a defuzzification output technique, while Fuzzy Sugeno uses a weighted average to calculate the crisp output. The ability to interpret Fuzzy Mamdani's output is lost to Fuzzy Sugeno because the consequences of the rules are not fuzzy. Thus, Fuzzy Sugeno produces a faster simulation duration because it has a weighted average replacing the defuzzification phase, which takes a relatively long time [22].

The Fuzzy Sugeno method functions as an artificial intelligence control in this research. The input from Fuzzy Sugeno is six dissolved gases, namely hydrogen, methane, ethane, acetylene, carbon monoxide, and ethylene, while the output is the TDCG value. The researcher proposes a Fuzzy-Sugeno control design including fuzzification, knowledge base (inference mechanism and rule base), decision-making unit, and defuzzification. The diagram is illustrated in Figure 2.

The fuzzification stage uses the trapezoidal MF curve method because it has a more accurate membership function with safe operating limits for gas contamination in the insulating oil in the transformer.

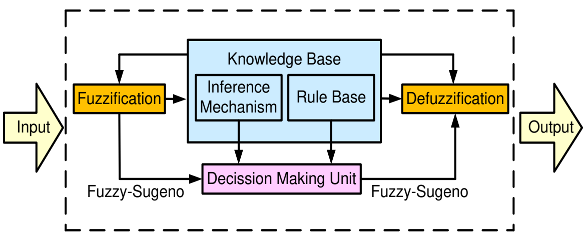

Figure 2. Desain Fuzzy Sugeno

The trapezoidal MF curve in this system is used to describe the membership function of each gas because the trapezoidal curve approaches the operating limit contained in the transformer insulating oil [23]. The input variables are six gases, namely, Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Acetylene (C_2H_2), Carbon Monoxide (CO), and Ethylene (C_2H_4). For Nitrogen (N_2), Carbon Dioxide (CO_2) does not enter the membership degree because the memberships function value of the two gases is greater than TDCG, which can interfere with the Matlab simulation results. Then, the simulation output variable is the TDCG value. The results of the DGA test were obtained from PT. PLN UPT (Persero) Surabaya.

The limit of MF for each gas input refers to the IEEE Standard in Table 2. The limit of MF with gas concentrations under normal conditions is entered into the normal MF. The gas concentrations in a state of caution are entered into the MF caution. Next, the degree of abnormal membership is entered into the MF abnormal. Then, the gas concentration in a state of danger is entered into the MF of danger. Based on the MFs interval of six gases input shown in Table 2, the authors choose a trapezoidal curve as the input MFs variable using equation 1. The trapezoidal MF curve is shown in Figure 3 [18].

Based on the equation, the degree of membership of the trapezoidal curve can be solved in (1).

$$\mu(x) = \begin{Bmatrix} 0\,, x \leq a \text{ } atau \text{ } x \leq d \\ \frac{(x-a)}{(b-a)}, \quad a \leq x \leq b \\ 1\,, \quad b \leq x \leq c \\ \frac{(d-x)}{d-c)}, \text{ } x \geq d \end{Bmatrix}, \qquad (1)$$

The Fuzzy-Sugeno rule used to determine the state of the insulating oil was obtained based on previous experiments. For example, for rule 1, when the concentration of TDCG is very high, nitrogen is very high, and hydrogen gas concentration is also very high, arcing occurs.

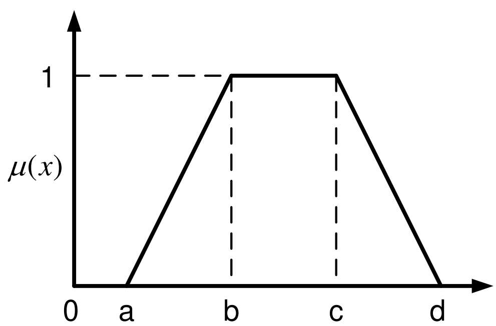

Figure 3. Trapezoidal membership function

This arcing is the most dangerous condition in the indication of transformer failure. The reason is that arcing in the insulating oil will trigger a fire surge in the transformer insulating oil that can cause damage to the transformer. The way to overcome this must be to replace the insulating oil. For remedial conditions, a failure indicates an overheating of the insulating oil, so an oil wash (purification/filter) must be carried out immediately to repair and prevent transformer failure. As for normal conditions, there are no indications of disturbances so the transformer can be operated normally. The input of the defuzzification process is a fuzzy set generated from the composition process, and the output is a value. In the Fuzzy-Sugeno method, the defuzzification process is carried out by calculating the Weight Average where the value of $WA = \alpha_1 z_1 + \alpha_2 z_2 + \alpha_3 z_3 + \cdots \alpha_n z_n$ and $z_n = \alpha_1 + \alpha_2 + \alpha_3 + \cdots \alpha_n$ Where: WA is an average value, α_n is the value of the rule predicate $n - th$ dan z_n is the output value index (constant) $n - th$.

Input and Output Variables

This study uses six functions of input variables and one output variable. The six dissolved gases are Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Acetylene (C_2H_2), Carbon Monoxide (CO), and Ethylene (C_2H_4). Each gas input variable consists of 4 fuzzy sets: Normal, Caution, Abnormal and Danger. The output variable is the TDCG value, each composed of 4 fuzzy sets: Normal, Repair, Danger, and Fault. Figure 4 shows the FIS model using the Sugeno method. Figure 5 shows the complete MFs modelling of six gas input variables. Figure 6 shows the membership function of the TDCG output variable. Table 3 and Table 4 show the linguistic function and boundary of the Sugeno Fuzzy set of input variables of six gases and output variable TDGC, respectively. The complete MFs for the six gas input variable is shown in Figure 5.

The fuzzy rule base used to determine the TDCG output value is 1920 rules. Figure 7 shows the fuzzy rule base in the order of 1 to 17 rules. Figure 8 shows the fuzzy rule base sequence from 1904 to 1920 rules.

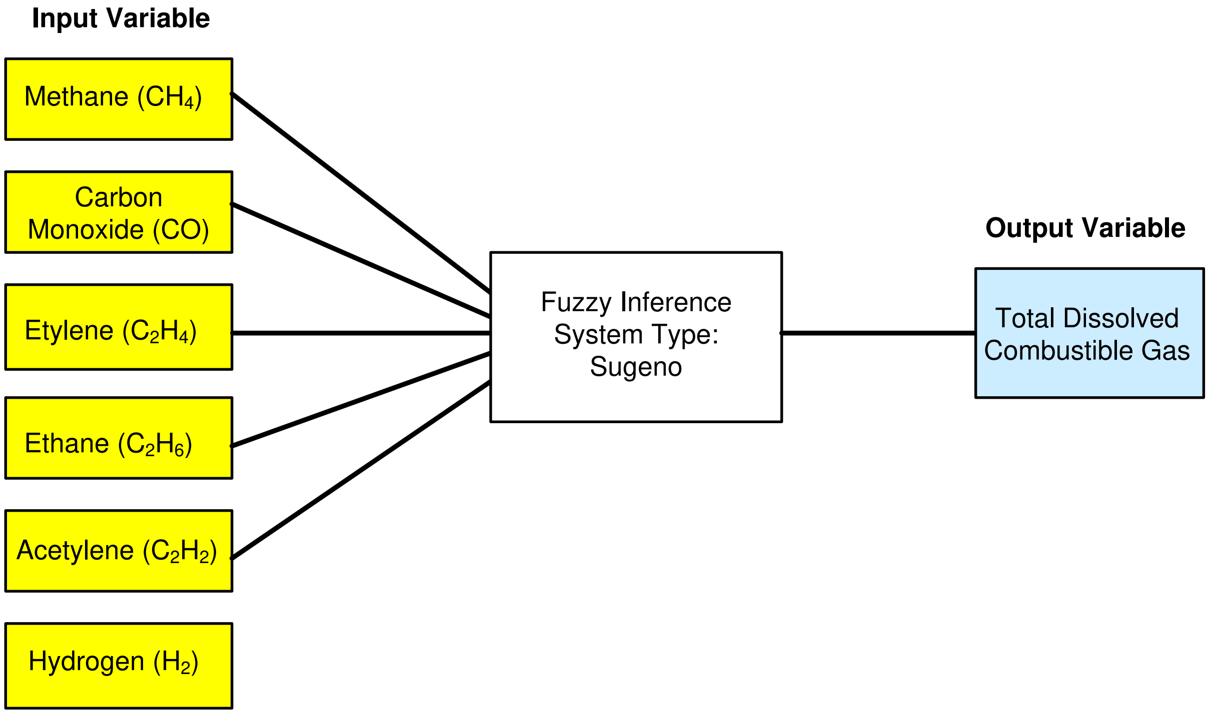

Figure 4. Model of fuzzy inference system-Sugeno

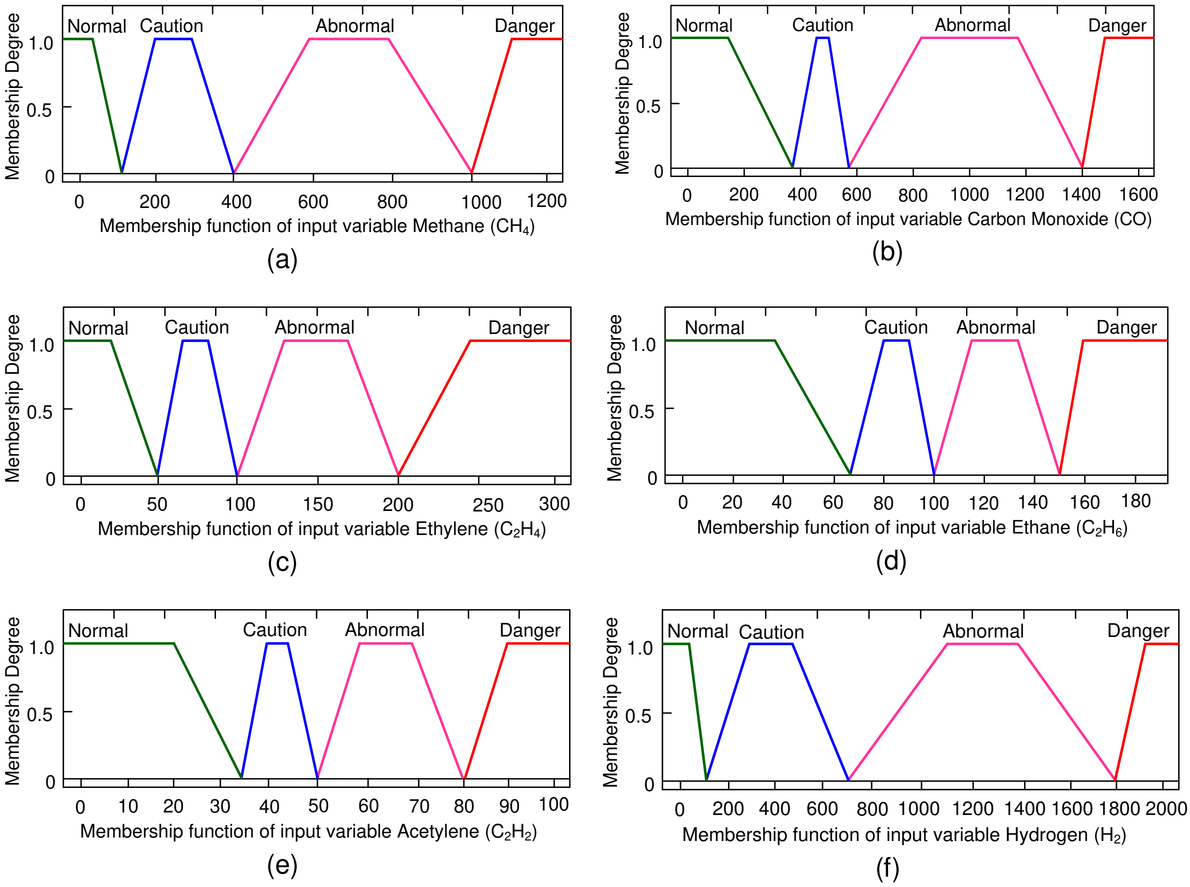

Figure 5. Complete membership functions for gas input variables respectively i.e. (a) Methane (CH_4), (b) Carbon Monoxide (CO), (c) Ethylene (C_2H_4), (d) Ethane (C_2H_6), (e) Acetylene (C_2H_2), and (e) Hydrogen (H_2)

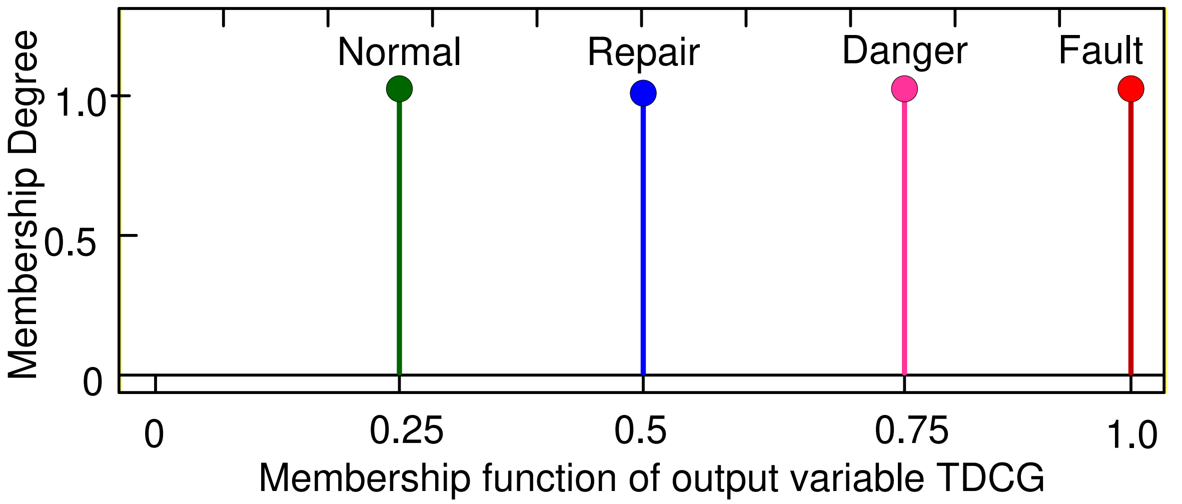

Figure 6. Output variable membership function of TDGC

Table 3. The linguistic function and the boundary of the Sugeno fuzzy set of the output variable TDCG

No.	Output Variables	MFs	Linguistic Functions	Boundaries
1	TDCG	[0,1]	Normal	0.25
			Repair	0.50
			Danger	0.75
			Fault	1.00

Table 4. Linguistic function and boundary of the Sugeno fuzzy set of input variables of six gases

No.	Input Variables	MFs	Linguistic Functions	Boundaries
1	Methane (CH_4)	Trapmf	Normal	0 to 120
			Caution	121 to 400
			Abnormal	401 to 1000
			Danger	1001 to 1200
2	Carbon Monoxide (CO)	Trapmf	Normal	0 to 350
			Caution	351 to 570
			Abnormal	571 to 1400
			Danger	1401 to 1600
3	Ethylene (C_2H_4)	Trapmf	Normal	0 to 50
			Caution	51 to 100
			Abnormal	101 to 200
			Danger	201 to 300
4	Ethane (C_2H_6)	Trapmf	Normal	0 to 65
			Caution	66 to 100
			Abnormal	101 to 150
			Danger	151 to 180
5	Acetylene (C_2H_2)	Trapmf	Normal	0 to 35
			Caution	35 to 50
			Abnormal	51 to 80
			Danger	81 to 100
6	Hydrogen (H_2)	Trapmf	Normal	0 to 100
			Caution	101 to 700
			Abnormal	700 to 1800
			Danger	1801 to 2000

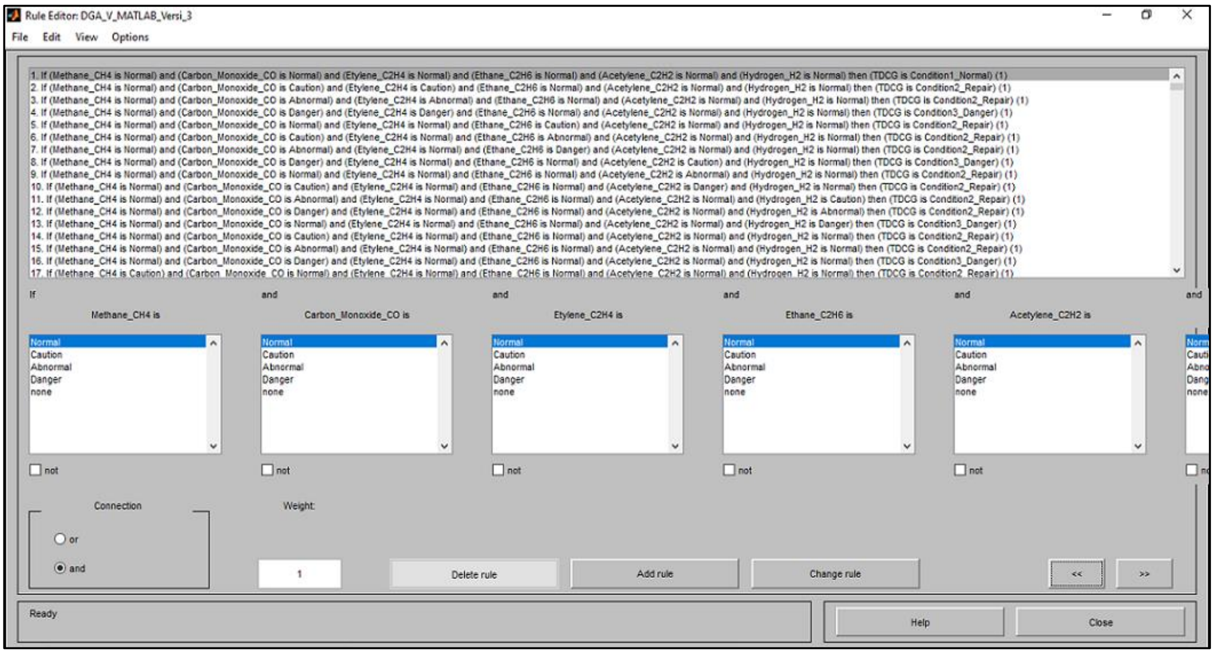

Figure 7. Fuzzy rule base sequence 1 to 17

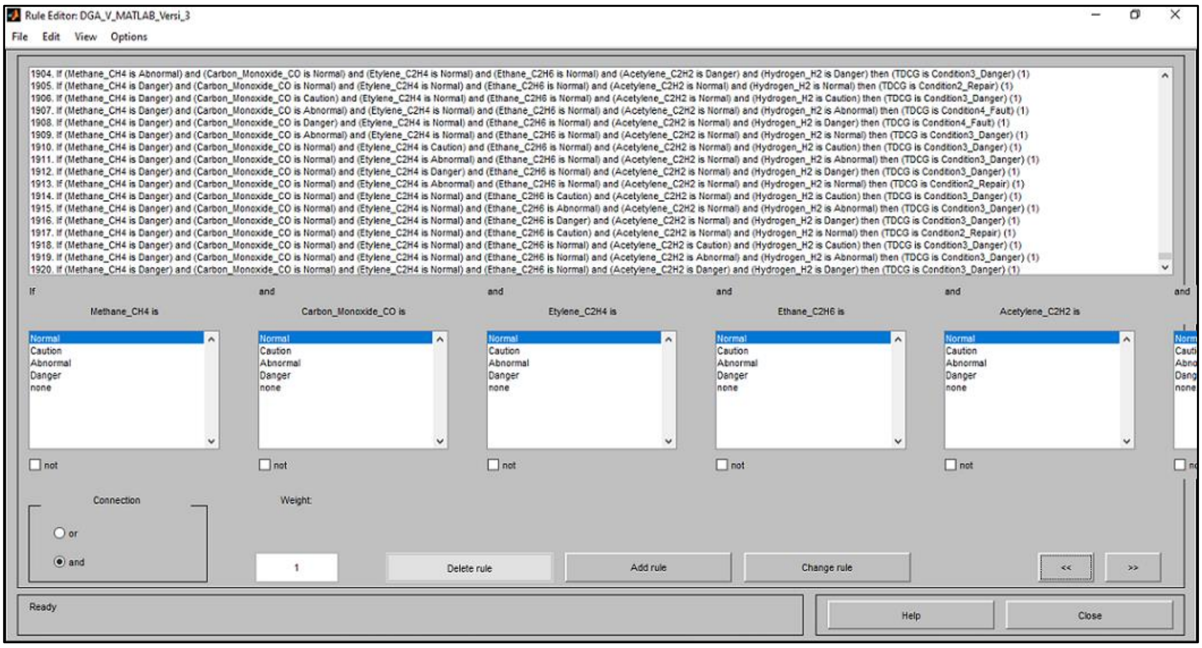

Figure 8. Fuzzy rule base sequence 1904 to 1920

RESULTS AND DISCUSSION

The study used oil samples from 150 kV Transformers Number 1 and Transformers Number 6 at the Buduran Substation. In addition, further oil testing was carried out at PT. PLN UPT Surabaya for the period March to May 2021. Technical specification data and DGA test of oil results for each transformer are shown in Table 5, Table 6, Table 7, and Table 8.

The DGA Nitrogen and Carbon Dioxide values are not included in the input variable because the ppm value of the two gases is greater than the TDCG value, which can interfere with the results obtained from Matlab. So then, the output value of the DGA test is TDCG.

Table 5. Specifications of Transformer 1

Parameter	Data
Phase	RST
Voltage	150
Merk	FUJI ELECTRIC
Type	TR 246018 B
Serial Number	AN 69002 T1-2
Made by	JAPAN
Production Year	1980
Operation Year	23/05/1994

Table 6. Specifications of Transformer 6

Parameters	Data
Phasa	RST
Voltage	150
Merk	BAMBANG DJAJA
Type	PX-001-FOHB
Serial Number	PX17-003
Made by	INDONESIA
Production Year	2017
Operation Year	29/12/2017

Table 7. DGA Test Results of Transformer 1

Date	Gases	Result (ppm)
	Hydrogen	0,00
	Nitrogen	1295,24
	Methane	0,00
	Ethane	20,70
22/04/2020	Acyteline	0,00
	Carbon Monoxide	10,84
	Carbon Dioxide	1495,61
	Ethylene	1,13
	Oxygen	1261,44
	TDCG	32,67

Table 8. DGA Test Results of Transformer 6

Date	Gases	Result (ppm)
	Hydrogen	0,00
	Nitrogen	1254,90
	Methane	0,00
	Ethane	17,55
22/04/2020	Acyteline	0,00
	Carbon Monoxide	8,64
	Carbon Dioxide	964, 09
	Etylene	0,00
	Oxygen	1215,70
	TDCG	26,19

Figure 9 and Figure 10 show the determination of the TDGC value based on the six DGA value input data using the rule viewer on Transformer 1 and Transformer 6, respectively. Figure 11 and Figure 12 show the determination of the TDGC value based on the six input data of dissolved gas in oil using Simulink, respectively, on Transformer 1 and Transformer 6.

Figure 9 shows the fuzzy-Sugeno rule viewer for oil data input and TDGC output on transformer 1. With the input of six DGA parameter values, the Sugeno fuzzy rule viewer produces a TDGC value of 0.25 or normal conditions.

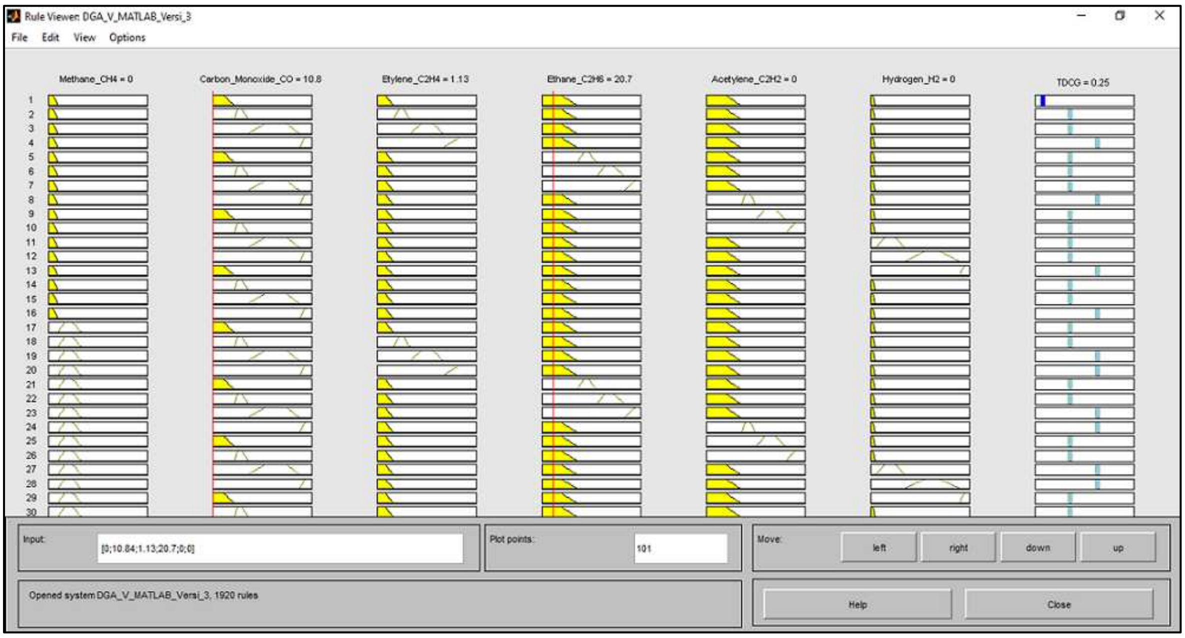

Figure 9. Determination of TDGC on six gas input data using the rule viewer on Transformer 1

Figure 10. Determination of TDGC on six gas input data using the rule viewer on Transformer 6

Figure 10 shows the fuzzy-Sugeno rule viewer for oil data input and TDGC output on transformer 6. With the input of six different DGA parameters, the Sugeno fuzzy rule viewer produces the same TDGC value of 0.25 or normal conditions.

Figure 11 shows that the fuzzy-Sugeno simulation with the input of six values of the DGA test results produces a TDCG output value of 32.67 ppm in Transformer 1. This value indicates that Transformer 1 insulating oil is in condition 1, indicating the gas composition is "Normal". Furthermore, the results of the DGA analysis through the PLN test (UPT Surabaya) in Table 9 also show the condition of the transformer insulation oil is also in condition 1, which means the status is "Normal".

Furthermore, the results of the DGA analysis through the PLN test (UPT Surabaya) in Table 9 also show the condition of the transformer insulation oil is also in condition 1, which means the status is "Normal".

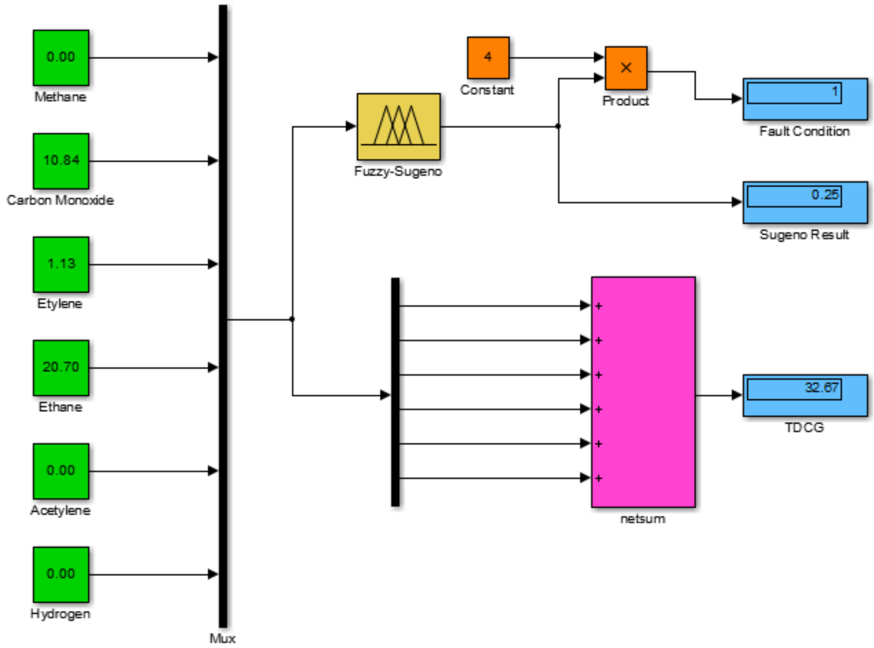

Figure 11. Determination of TDGC and fault status of six gas input data on Transformer 1 using Simulink

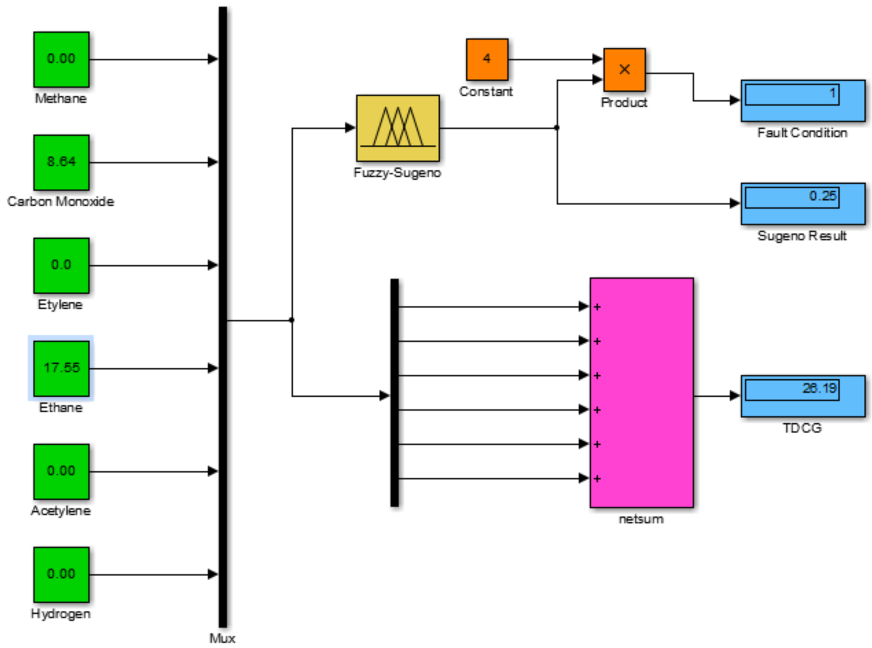

Figure 12. Determination of TDGC and fault status of six gas input data on Transformer 6 using Simulink

Figure 12 shows that the fuzzy-Sugeno simulation with the input of six values of the DGA test results produces the TDCG output value of Transformer 6 of 26.19 ppm. This value indicates that Transformer 6 insulating oil is in condition 1, indicating the gas composition is "Normal". The results of the DGA analysis through PT. PLN (UPT Surabaya) in Table 10 also show the condition of the transformer insulating oil is also in condition 1, which means the status is "Normal".

Table 9. DGA Test Results of Transformer 1

No	Gases	Results (ppm)	Output Sugeno
1	Hydrogen	0.00	
2	Methane	0.00	
3	Carbon Monoxide	10.84	Condition 1 Normal (0.25)
4	Ethylene	1.13	
5	Ethane	20.70	
6	Acetylene	0.00	
	TDCG	**32.67**	

Table 10. DGA Test Results of Transformer 6

No	Gases	Results (ppm)	Output Sugeno
1	Hydrogen	0.00	
2	Methane	0.00	
3	Carbon Monoxide	8.64	Condition 1 Normal (0.25)
4	Ethylene	0.00	
5	Ethane	17.55	
6	Acetylene	0.00	
	TDCG	**26.19**	

Table 11. Comparison of the fuzzy method with the addition of nominal fuzzy rules in the DGA analysis of transformer insulation oil compared to previous studies

Authors	Fuzzy Inference System (FIS)	Nominal Input	Nominal Output	Nominal Fuzzy Rules	TDGC (Fuzzy)	TDGC (Test Result)	Accuracy (%)
[15][16]	Mamdani	7	1	27	487	436	89.5
[17]	Mamdani	7	1	9	82.1	77.9	94.9
[18]	Mamdani	9	1	3	175	250	57.2
[19]	Mamdani	8	4	27	244	244	100
Proposed Method	**Sugeno**	**6**	**1**	**1920**	**32.67 (T1) and 26.19 (T6)**	**32.67 (T1) and 26.19 (T6)**	**100 and 100**

A comparison of the Sugeno Fuzzy Method with the addition of fuzzy rules in the DGA analysis of transformer oil (research method) to the previous research is shown in Table 11. The Fuzzy-Mamdani method to help standardize DGA interpretation consistently and identify critical levels of insulating oil DGA data transformers has been observed by Abu-Siada et al. [16]. The input variable is seven dissolved gases, and the output variable is one, namely TDGC. With 27 fuzzy rules, this method's implementation can produce a TDGC value of 487 ppm. Furthermore, with the TDGC value based on the gas-in-oil test results of 436 ppm, the Fuzzy-Mamdani method produces a simulation accuracy of 89.5%. The Fuzzy-Mamdani method uses DGA data interpretation and diagnoses many types of transformer faults that have been observed [17]. The input variable is seven dissolved gases, and the output variable is one, namely TDGC. With nine fuzzy rules, this method's implementation can produce a TDGC value of 82.1 ppm.

On the other hand, the TDGC value based on the gas-in-oil test results is 77.9 ppm, and the Fuzzy-Mamdani method produces a simulation accuracy of 94.9%. The simulation of transformer oil conditions using DGA data with the Fuzzy-Mamdani method has been investigated by [18]. The input variable is nine dissolved gases, and the output variable is one, namely TDGC. With three fuzzy rules, this method's implementation can produce a TDGC value of 175 ppm. On the other hand, the TDGC value based on the gas-in-oil test results is 250 ppm, and the Fuzzy-Mamdani method produces a simulation accuracy of 57.2%.

The Fuzzy-Mamdani method approach, as one of four methods for DGA analysis, has been studied by Poonnoy et al. [19]. The input variables are eight dissolved gases, and the output variables are 4, one of which is the TDGC value. With 27 fuzzy rules, the implementation of this method and the dissolved gas test produced the same TDGC value of 244 ppm, resulting in a simulation accuracy of 100%. In contrast to the four previous studies, the researcher proposes the Fuzzy-Sugeno method for DGA analysis in determining the TDGC output variable. The input variable is six dissolved gases, and the output variable is one, namely TDGC. The researcher developed a larger nominal fuzzy rule amounting to 1920 rules. The implementation of the proposed method and the dissolved gas test produced the same TDGC value of 32.67 ppm on Transformer 1 and 26.19 ppm on Transformer 6, resulting in a simulation accuracy of 100%. Thus, the development of nominal (number) fuzzy rules using the fuzzy logic method with FIS Sugeno can perform DGA analysis more accurately to determine the quality of power transformer insulating oil.

CONCLUSION

The fuzzy logic method using the FIS-Sugeno with a large nominal of 1920 rules for DGA analysis and determining the quality of insulating oil for power transformers 1 and 6 at the 150 kV Buduran Substation has been proposed. The implementation of this method on Transformer 1 and Transformer 6 shows that with the six input variables from the DGA test, it can produce TDCG output values of 32.67 and 26.19 ppm, respectively. This value indicates that the insulating oil of Transformer 1 and Transformer 6 is in condition 1, indicating the dissolved gas composition is in normal status. The TDCG value, condition, and quality status of the insulating oil are the same as the results of the DGA test by PT. PLN (UPT Surabaya). Thus, the nominal development of fuzzy rules using a fuzzy logic method with FIS-Sugeno can perform DGA analysis more accurately to determine the quality of power transformer insulating oil.

The paper did not include nitrogen (N_2) and carbon dioxide (CO_2) gas elements as input variables. Because the membership function interval value for these two gases has exceeded the TDCG value limit, it requires a longer simulation time. The development of the Fuzzy-Sugeno method with a nominal rule greater than 1920 rules at least equal to the Membership Function interval value for the two gases can be proposed to overcome these weaknesses.

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