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Condition assessment of power transformers status based on moisture level using fuzzy logic techniques

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Abstract

Power transformers are one of the most expensive components; therefore the focus on their status and its continuous operation is the primary task. In the power systems, condition assessment of performance and reliability is based on the state of components, measurements, testing, and maintenance as well as their diagnosis. Hence, condition assessment of power transformer parameters is important regarding their status and finding incipient failures. Among many factors, the most factors that affect the safe operation and life expectancy of the transformer is the moisture in oil. It is known that the low moisture oil in power transformers causes many problems including electrical breakdown, increase the amount of partial discharge, decreases the dielectric withstand strength and other phenomena. Thus, knowledge about the moisture concentration in a power transformer is significantly important for safe operation and lifespan. In this study, moisture level in oil is estimated, and its status classification is proposed by using fuzzy logic techniques for the power transformer monitoring and condition assessment. Moreover, the goal of the study is to find methods and techniques for the condition assessment of power transformers status based on the state of moisture in oil using the fuzzy logic technique. These applied techniques increase the power system reliability, help to reduce incipient failures and give the better maintenance plan using an algorithm based on logic rules. Also, by using the fuzzy logic techniques, it is easier to prevent failures which may have consequences not only for transformers but also for the power system as a whole.

Keywords: Moisture in oil; power transformers; fuzzy logic techniques; failures; condition assessment; measurements.

I. Introduction

Power transformers are key components for transmission and distribution infrastructure that transfer electricity from the substations to consumers. Forced component outages caused by failures may collapse the electrical power systems, interrupt the electricity consumption and give an environmental impact. The transformer could fail due to electrical failures, mechanical or thermal stresses. Such defects are sometimes catastrophic and can be lead to an unscheduled outage of the component, therefore causing the need of repairment and replacement. Assessment of power transformer condition is the basis for reliable operation and optimal repairs schedule. Generally, there are four main aspects of transformer condition monitoring and assessment, includes thermal dynamics, dissolved gas, partial discharge, and winding deformation [1]. Continuous monitoring of oil insulation characteristics has become an important task to avoid deterioration of its characteristics under working conditions. Several efforts have been made over the past years to study the electrical, physical, and chemical of insulating oils [2].

Methods for evaluating the status and monitoring of transformer parameters create a possibility of diagnosis and analysis to define accurate measures for necessary steps that should be taken into consideration. Various methods have been explained [3], such as using Fuzzy Logic techniques or the Neural Network methods. The combination of these techniques will improve diagnostic decision-making under the uncertainty inherent in diagnostic information, and it can also capture gradual system degradation [4]. The techniques for condition assessment, measurement,

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and interpretation of gases have been developed [5]. However the assessment technique should be extended to other parameters such as moisture concentration in oil.

Furthermore, through such techniques, a more detailed look at the predictions of failures based on the statistics for transformers is not needed. Faults in different parts of transformer winding or other parts during impulse tests generate distinct signatures in the time-frequency spectrum. Thus, such signs are difficult and impossible for the human eyes to identify; this complex task can be successfully handled and developed by modern classification algorithm such as fuzzy logic [6]. The main objective of this paper is to design a model or technique for condition assessment of the moisture in oil of the power transformers.

The assessment of parameter conditions through fuzzy logic techniques also makes a significant contribution to the recognition of transformer status as well as its ranking according to the conditions and quality of parameters in the case of moisture in oil. The model includes the design of the algorithm, which the given inputs are the conditions of moisture in oil (five conditions), and oil level (defining oil by standards). Those inputs are processed by logic rules IF, AND, THEN, to finally results in the condition assessment of the moisture in oil, monitoring measures, diagnosis, and preventive measures. The condition assessment through this logic is also compared with the statistical database.

II. Failure analysis in a power system and assessment methods

In a power system, unplanned outages, faults, and hidden failures are difficult to track down and to model because those are obviously hidden [7]. The reliability of the power system is classified into adequacy and security. The adequacy is related to the existence of sufficient generation of the electric power system to comply the consumer demand. Meanwhile, the security is related to the ability of power system to respond to the transients and disturbances that occur in the system [8]. Failure is an inability of a part or equipment to carry out its specified function. Meanwhile, a fault has broader meaning than a failure in specific equipment and its related features that needed for proper operation of the equipment [9].

A power transformer condition monitoring focuses mainly on the detection of incipient faults inside the transformer that are generated from the gradual deterioration. Some of these incipient faults may be detected during routine maintenance; however other faults may cause numerous problems before the regular maintenance cycle.

Markov method is a stochastic process in which future states are conditional only on the present state and independent of previous states [10]. The Markov process in which there is the number of finite states $S_1, S_2, S_3, \dots, S_n$ that may exist at any given time. The probability of the process moving from S_i to S_j is denoted by the transition probability $-P_{ij}$ and the probability of the process remaining in the same state is denoted by the probability $-P_{ii}$ [11]. Markov method is widely used for reliability and simulation analysis [12].

A system is made of a number of components n, which at any given time may be operating successfully or not. The successful operation of the entire system depends on the operation or failure of its components. Therefore, the system may exist in one of two states as follow:

1. An operating state, where the system is operating even if some of its components have failed. A fully operational system is one in which no components have failed.
2. A failed state, where the system is not operating because of the failure of one or more of its components [12][13].

Previous researches have discussed the topic of condition assessment of transformers in several contexts. One method is fault identification at the defective condition, commissioning test, and trend analysis [14]. The power transformer monitoring process evaluation starts from the beginnings of incipient failures, their diagnosis, and the final actions of the measures to prevent the defects or failures are presented in Figure 1.

Another method is a linear regression that consists of finding a linear function $f(x) = (w \circ x) + b$ that gives the best interpolation of a set of training points labeled from $Y = \subseteq R$. Geometrically this corresponds to a hyperplane fitting of the given points. This technique is known as a method of least squares [15]. Therefore, the training process of a neural network involves tune of the value of the weights and the biases of the networks to optimize network performance, as defined by the network performance function [16].

$$F = mse = \frac{1}{N}\sum_{i=1}^{N}(e_i)^2 = \frac{1}{N}\sum_{i=1}^{N}(t_i - \alpha_i)^2 \qquad (1)$$

In the Equation (1), α is network outputs, t target, and mse is the mean square error. By comparing the data in their input, and processing by combining the data, it is possible to obtain results that enable the recognition of the conditions of the transformer operation according to the parameters that had been taken into account [17]. In some condition, assessment methods can be confirmed or automated with the use of electronic performance support systems such as statistics based systems, expert systems, and algorithms [18].

III. Problem formulation using fuzzy logic

Probability and fuzziness are related to different concepts. Fuzziness is a type of deterministic

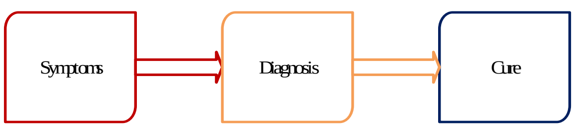


Figure 1. Process evaluation of power transformer monitoring

uncertainty. It describes the event class ambiguity, so fuzziness measures the degree in which an event occurs. A linguistic variable can be regarded as a variable of value, either a fuzzy number, or a variable. Fuzzy logic of fuzzy set theory provides a basis for mathematical modeling and language to express quite sophisticated algorithms in a precise manner [19].

The Fuzzy techniques consist of several phases and processes, which are analyzed according to the defined conditions in the assessment range. Through the building concept of the model, inputs, and outputs; the database is processed according to the numerical values of the membership that are allocated to the respective sets. The output is obtained through the set of inputs rules.

The implementation of the fuzzy logic technique to a real application requires the following three steps:

a) Fuzzification – convert classical data into fuzzy data or membership functions,
b) Fuzzy Interference Process – combine membership functions with the control rules to derive the fuzzy output, and
c) Defuzzification – use different methods to calculate each associated output to put them into a table or graphical structure [20].

The most popular fuzzy logic systems are Mamdani and Sugeno which use crisp data as inputs. As an extension of the Mamdani model in order to work with interval inputs, the fuzzy sets are represented by triangular fuzzy numbers [21]. The processes and steps of operating conditions assessment and their status according to fuzzy logic are also included.

Determining the membership functions of inputs means that the data populations as well as the assessment of transformers parameters are inputted at certain time periods or on a continuous basis. The membership functions of the outputs are determined by members and their impact on the status of power transformers. For different cases involving aspects of issues evaluation that have an impact on specific parameters, such as temperature, state of gases, moisture in oil, paper, tap changer, hot spot partial discharge, and load factor. Therefore, this structure of fuzzy logic operation is built by populating the data at certain time periods in the online or offline mode.

$$i(0,a,b,c,d)=\begin{Bmatrix} 0<x<a \\ a<x<b \\ c<x<d \\ d<x \end{Bmatrix} and,\quad j(0,e,f,g,h)=\begin{Bmatrix} 0<x<e \\ e<x<f \\ f<x<g \\ x>h \end{Bmatrix} \qquad (2)$$

In Equation (2), the logic technique for defining the inputs and outputs parameters is depicted. This includes the membership determination by the levels and numbers belonging to the sets, which based on the respective measurements, and their comparison is made to reach the most accurate conclusions. Structuring the rules of fuzzy logic includes a set of rules (range of data) that are created according to the classification of transformer occurrences. The entirety of the failures causes is processed according to the logic operators, IF, AND, THEN. Through the processing of the causes, their ranking according to the assessment results is derived from the outputs. It constitutes a logical method of data processing and obtaining results that can be helpful in monitoring and diagnosis of transformers during continuous operation. In this study, a problem of condition estimation of the power transformers that are installed in the transmission system of Kosovo is addressed. The transformers conditions are estimated based on moisture content in the oil using fuzzy logic. Simulation results are compared with real measurements results, and a ranking of the power transformers conditions is presented.

IV. Condition assessment model of power transformer parameters

Condition assessment of electrical, thermal, and mechanical parameters is one of the fundamental elements for determining the operational continuity of transformers. Fuzzy logic may be applied for condition assessment and status classification of the transformers which emphasize the main parameters such as oil temperature, winding temperature, dissolved gases, moisture in oil, and partial discharge.

Oil insulation is an important form of the power transformer insulation system. The remaining life of the transformer largely depends on the oil insulation status. Aging degree and moisture content are two important factors of insulation state assessment. Thus, accurate assessment technique to evaluate the condition of oil in the power transformers insulation has become a popular research topic. A lot of valuable research about oil insulation condition assessment and the influence of moisture have been done, such as; Spectroscopy, Polarization and depolarization Current, and Recovery Voltage Measurement [22].

This paper proposes a fuzzy model which involves two fuzzy input variables, i.e., moisture in oil and moisture level, and transformer condition status as the fuzzy output. The moisture in oil is divided into five functions: Condition 1 (Con1), Condition 2 (Con2), Condition 3 (Con3), Condition 4 (Con4), and Condition 5 (Con5). The moisture level is also divided into five functions: Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH). The transformer condition status is divided into six functions: Very Good (VG), Good (G), Medium (M), Alarm 1 (A1), Alarm 2 (A2), and Alarm 3 (A3). Figure 2 illustrates the proposed fuzzy model. The model includes an algorithm where the two fuzzy inputs are given and processed by logic rules (IF, AND, THEN) to produce a condition assessment.

This fuzzy model links the two fuzzy input variables with a transformer condition status. This model provides a clear view of a transformer conditions status and necessary measurement according to the fuzzy output. Figure 3 and Figure 4 show the functions of the fuzzy input and output variables, respectively.

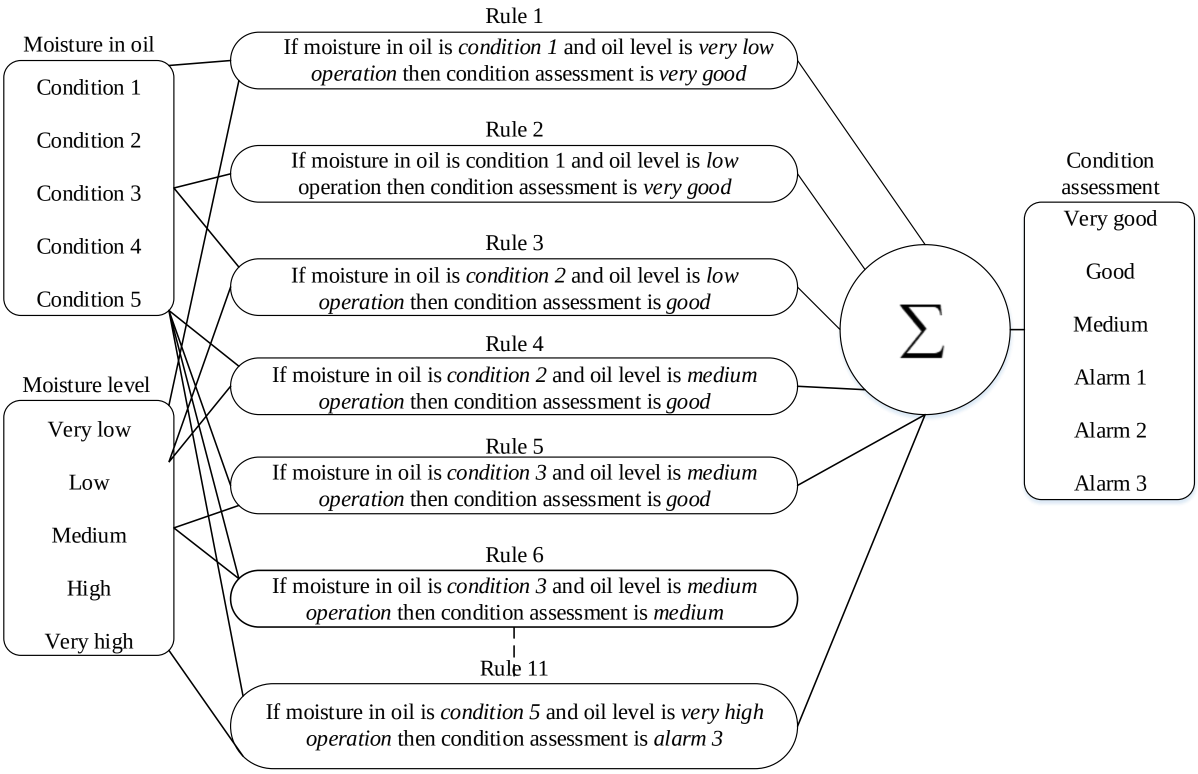
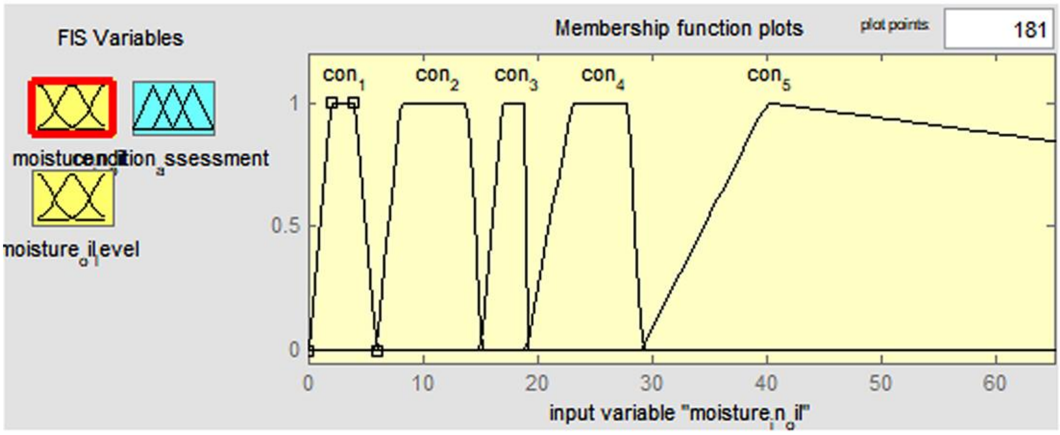
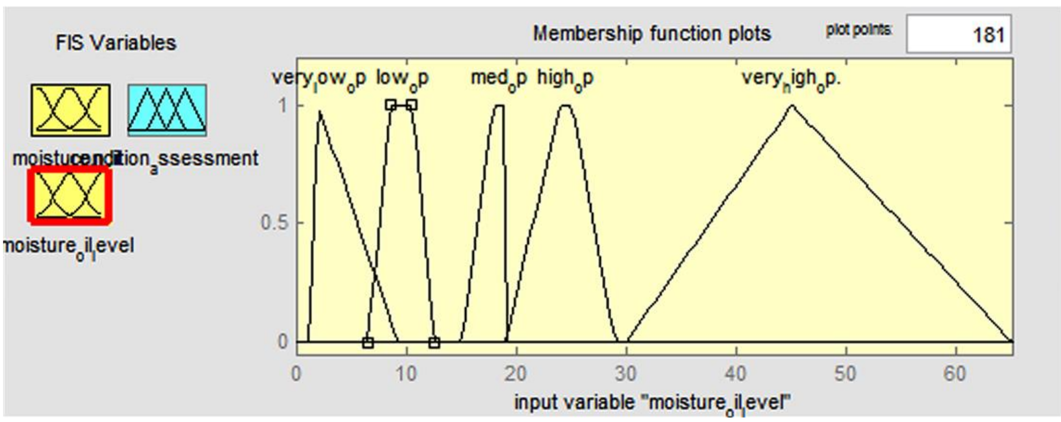


Figure 2. Fuzzy logic model for condition assessment



(a)



(b)

Figure 3. The functions of fuzzy input variables; (a) moisture in oil; (b) moisture level

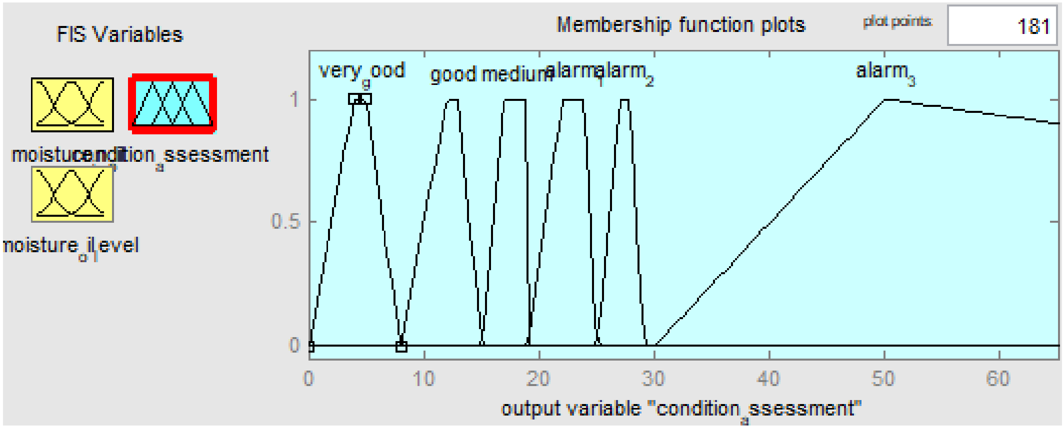


Figure 4. Output and membership functions

According to oil moisture ranges in the standard of power transformer operation condition, the universe of discourse (UOD) of fuzzy input variables is expressed in Equations (3) and (4), whereas UOD of fuzzy output variable is expressed in Equation (5) [23].

$$moisture\ in\ oil = \begin{cases} condition1 & 0 \le a < 6 \\ condition2 & 6 \le b < 15 \\ condition3 & 15 \le c < 20 \\ condition4 & 20 \le d < 29 \\ condtion5 & e \ge 30 \end{cases} \quad (3)$$

$$moisture\ level = \begin{cases} very\,low & 0 \le a < 8 \\ low & 8 \le b < 15 \\ medium & 15 \le c < 20 \\ high & 20 \le d < 29 \\ very\,high & e \ge 30 \end{cases} \quad (4)$$

$$condition\ \ assessment = \begin{cases} very\ good & 0 \le a < 8 \\ good & 8 \le b < 15 \\ medium & 15 \le c < 20 \\ alarm1 & 20 \le d < 25 \\ alarm2 & 25 \le e < 29 \\ alarm3 & e \ge 30 \end{cases} \quad (5)$$

This fuzzy rule refers to the standard regarding power transformer condition status [24]. Eleven fuzzy rules are proposed in this study and listed in Table 1.

Table 1.
Fuzzy rule base (11 Fuzzy rules)

Condition Status		Moisture in oil				
		Con 1	Con 2	Con 3	Con 4	Con 5
Moisture Level	VL	VG				
	L	VG	G			
	M		G	G+M	M	
	H				M+A1	A2
	VH					A3

Figure 5 and Figure 6 illustrate 11 fuzzy rules that link each relevant fuzzy input variable with the corresponding fuzzy output variable using logic operators (IF, AND, THEN) in Matlab®/Simulink® environment.

Figure 7 shows three dimensional form of the parameter levels extension according to the level of moisture in oil, output to the Z axis through measured samples, and data processing based on the rules of fuzzy logic. The standards or codes recommend the counter measures or actions to be done for each power transformer conditions status [25]. Table 2 summarizes the appropriate measure according to the standards/codes.

V. Results and discussion

Monitoring and diagnosis of the status of transformers in the operator transmission system of Kosovo were conducted from July to August 2017. The fuzzy logic model of transformer condition assessment includes 65 transformers from 20 up to 400 MVA power capacity.

The Kelman TRANSPORT X – mobile labs was used to measure moisture in oil and its level. Measurement of moisture in oil and moisture level was conducted manually. Manual diagnostics were conducted by mapping values of the manual measurements to the condition status according to the power transformer assessment code. Simulated diagnostics were carried out by inputting the same values of measurement to the fuzzy logic model to obtain the corresponding transformer condition status. Figure 8 presents the assessment results of the power transformers. Transformer condition status is shown as

Table 2.
Recomended measures / actions according to standard

Status	Recommended Action
VG	No need any action to make a diagnosis
G	No need any action to make a diagnosis
M	Should be under monitoring from time to time
A1	Should be under continuous monitoring
A2	Need any action to make diagnosis and analysis
A3	Should be out of operation for deep analysis

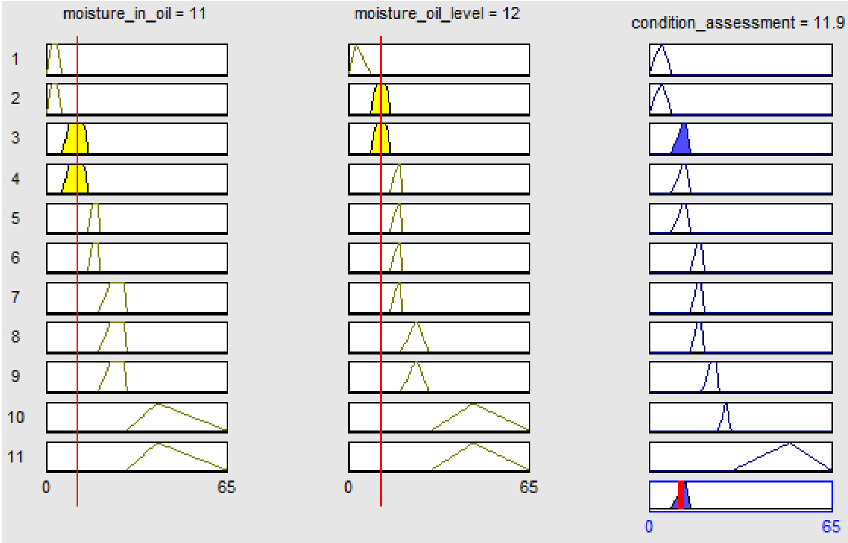


Figure 5. Assessment model by the fuzzy logic method

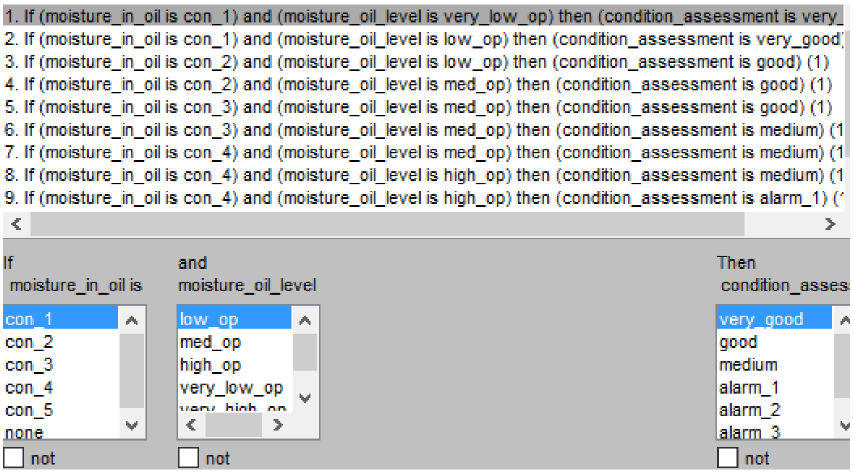


Figure 6. Definition of the structure rules

the result of manual diagnostics and simulated diagnostic using fuzzy logic. The same results are listed in Table 3. The error is calculated by subtraction the manual diagnostic value from the corresponding fuzzy logic diagnostic value. From the error values, it can be calculated that the mean error is zero and the root mean squared error (RMSE) is 1.62.

Explanation of the first raw in Table 4 is as follows: 1st condition assessment; moisture in oil = 3 ppm; moisture level = 7 ppm; and condition assessment = 4.07 ppm. From the data, the result only emerges the 1st rule, where according to this rule, it can be concluded that IF the moisture in oil is condition 1 AND the moisture level is in very low operation THEN the condition assessment is very good, that means the transformers are in *very good* condition and do not need any diagnosis or analysis. Other raws in Table 4 have a similar explanation.

Discussion of the cases related to the status of the power transformers parameters such as moisture in oil is helpful in achieving results for defining the transformer status during their work. It is also

Table 3.
Condition assessment results

Status	Number of Transformer		Error
	Fuzzy Logic Diagnostic	Manual Diagnostic	
VG	2	4	-2
G	55	53	2
M	7	5	2
A1	0	2	-2
A2	0	0	0
A3	1	1	0
Total	65	65	0

Table 4.
Examples of some diagnostics using fuzzy logic

CA	Moisture in oil (ppm)	Moisture level (ppm)	CA (ppm)	Effective Rule	Status
1st	3	7	4.07	1	VG
2nd	16	18	14.0	5	G
3rd	20	19	17.2	5	M
4th	24	24	20.3	9	A2
5th	35	35	47.0	11	A3

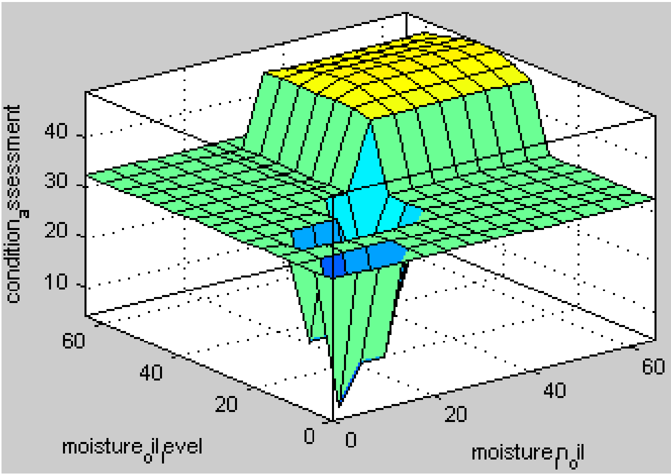


Figure 7. Three-dimensional graphic of the moisture level in the oil

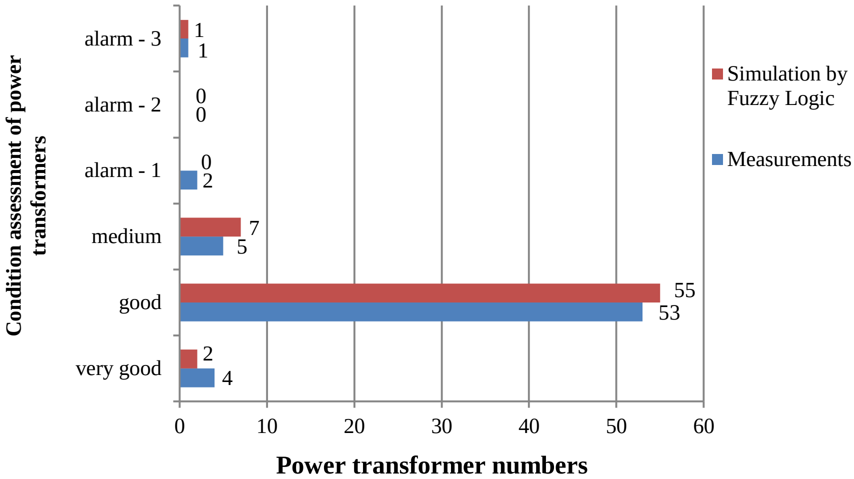


Figure 8. Condition assessment monitoring of the moisture in oil to the power transformers

important to perform other analysis. Through the fuzzy logic model, condition assessment or diagnosis of the power transformers can be carried out automatically. Measurements values of moisture in oil and moisture level are fed to the fuzzy logic model, and the transformer condition status is automatically obtained.

VI. Conclusion

A fuzzy logic model for transformers condition assessment was designed based on moisture content. The fuzzy logic model was applied to 65 transformers condition assessment in order to classify them into 5 statuses, i.e. Very Good, Good, Medium, Alarm 1, Alarm 2, and Alarm 3. The simulation result using the fuzzy logic model was compared with the manual assessment result based on the standard/code. The error between the simulation result and the manual assessment result was calculated. The mean value of error was zero, and the root means square error (RMSE) was 1.62. These results demonstrated that the proposed fuzzy logic model had provided good assessment performance. It can be assumed that fuzzy logic technique constitutes an efficient method for understanding transformer status over the key parameters. It also reflects the connectivity between on-line measurements and time to time measurements in a function to achieve the most accurate and reliable results.

Acknowledgement

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