Fuzzy Approach for Residual Life Assessment of Paper Insulation

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***Abstract*—In this paper, an effort has been made to explore the usefulness of DP (Degree of Polymerization) of cellulosic insulation paper (CIP) to monitor the condition of the transformer. The residual life of CIP of the oil-immerged power transformer is determined by detecting the content of dissolved carbon oxide and 2-FAL gases in oil. The proposed work employs Fuzzy Inference System (FIS), which offers preeminent response for calculating extent of degradation of the CIP. Using the FIS the final condition of CIP is categorized as AI (Acceptable Insulation), MD (Moderate Deterioration), ED (Extensive Deterioration) and UR (Urgent Replacement) from correlation between accumulated values of 2-FAL, CO and CO_2 with DP. Furthermore, the best fuzzy membership function has been obtained for the experimental test condition. Finally the results obtained shows that the proposed method accurately monitors the condition of CIP in the oil-immerged power transformers.**

Keywords—: Cellulose; Degree of Polymerization; Oil-immerged transformers;

I. INTRODUCTION

In today's life, the uninterrupted supply of electricity to consumers is in close relation to the consistent function of the transformers. Thus, the major components of the transformers should be maintained to achieve its designed service life span [1]. The life of transformer relies on the life of their insulation system that undergoes a number of stresses, such as electrical, thermal, mechanical and environmental. The transformers are unable to operate for the designed service period [2], due to active participation of such stresses. It is therefore necessary for the utility to have continuous monitoring different insulations used in transformer.

The transformer insulating system, primarily consisting of two special dielectric media; the insulating mineral oil whose ionic conduction varies and the oil impregnated paper (or pressboard), whose life is limited, even under ideal circumstances. The existence of transformer typically depends upon the health condition of its CIP. The fundamental element of pressboard and paper is cellulose, which is polymer of glucose wherein glucose units link to each other in a chain like structure. Chemically cellulose is represented as $[C_6H_{10}O_5]_n$, here '*n*' refers to number of glucose units for each polymeric chain, more specifically Degree of Polymerization (DP); a significant factor of paper degradation. Thus the value of DP specifies the number of monomer unit in the polymer as cellulose is the linear polymer constituent of individual anhydrous glucose units associated with glucosidic bonds. It have been verified that there is direct relationship between mechanical tensile strength of the paper cellulose and the corresponding value of DP. Generally, a fresh cellulose paper has a DP value of 1200 which reduces slightly when subjected to stresses. The cellulose paper life comes to an end when the value of DP approaching to 200.

The Kraft/Cellulose paper losses its tensile strength as it is subjected to ageing and, at some point, does not survive on the short circuit stresses. The mechanism involve in paper deterioration is quite difficult and sturdily influenced by the working environment. Degradation of solid insulation occurs due to schism of the 1, 4-glycoside bonds among two consecutive glucose monomers present in it. As a result of these chain scissions, the DP gets reduced that ultimately lowers the mechanical tensile strength of the paper. During ageing, cellulose is decomposed into various substances including furanic compounds, acids, CO_2 and CO. These by-products are partially soluble in oil and are generally characterized as indicators for cellulose ageing and hence show the end of life of power transformers.

Several authors contributed their research towards deterioration of cellulose under moisture and thermal stress to enunciate the end of life of power transformers using Degree of Polymerization (DP) as a failure index. A mutual stress failure model was developed to perform a chain of thermal aging experiment on kraft paper of power transformer on a laboratory scale [3].Diagnostic and health monitoring approaches based on the value of the ratio of carbon dioxide and carbon Monoxide (i.e. CO_2/CO) gases were also investigated in [4]. Soft computing techniques like Neural Network (NN), Fuzzy Logic (FL), Neural Fuzzy System, Support Vector Machine (SVM) and Wavelet Network [5][6][7]were applied to assess the health condition of CIP. These models used carbon oxide gases to evaluate the degradation of paper cellulose. The main objective of this work is to monitor the condition of CIP using the fuzzy model that correlate the concentrations of CO, CO2 and 2-FAL with the value of Degree of Polymerization (DP). Input to the developed FIS is 2-FAL, CO_2 and CO and output is the value of DP which ultimately decides the residual life of transformers.

II. FUZZY LOGIC BASED TECHNOLOGY

The necessary interpretation of transformer health in terms of its deteriorating insulation can be suitably analyzed through Fuzzy-Logic modeling. The Fuzzy-Logic based transformer condition monitoring codifies the knowledge dependent diagnosis that helps to prepare an improved health estimation

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to assure transformer consistency, accessibility and maintainability.

The main objective of Fuzzy-Logic model for condition monitoring of oil-immerged transformer is to meet following criterion:

- Significant deterioration measurement with specified transformer condition.
- Importance of the parameters used to decide the state of the transformer.
- Suitable range of choice of the measured quantity that comprised of any ambiguity allied with the measurement.

Proposed Fuzzy Inference System (FIS) is developed using GUI tool provided in MATLAB. All inputs are fuzzified into different sets (very low to high) of membership functions. The Fuzzy-Logic based transformers insulation analysis process characterizes a set of rules for transformer health diagnosis mapping fuzzified input to fuzzified output.

A. Membership Functions

The curves which characterize how all the position in space (input) is plotted to a membership value (membership degree) between 0 and 1 are called membership functions of a fuzzy set. The input space, for a while is said to as the universe of discourse. The function might be any random curvature whose outline can be characterized as the function that outfits with the point of view of simplicity, efficiency and convenience.

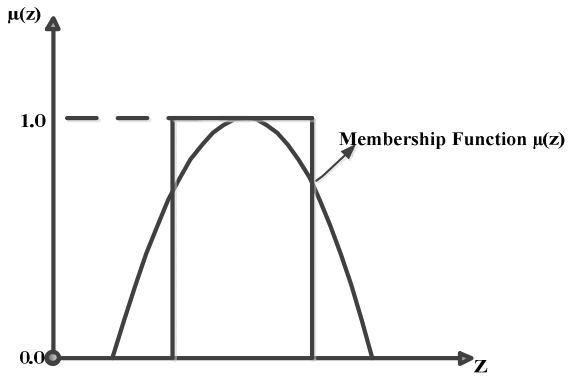

Fig.1. Membership Function of a Fuzzy Set.

The classical set may be given as

$A=\{x \mid x > 7\}$ (1)

A Fuzzy set is an expansion of the classical set. If Z is the universe of discourse whose elements are denoted by z, then a Fuzzy set A in Z is defined as a set of ordered pairs.

$A=\{z,\mu_A(z)|z\varepsilon\ Z\}$ (2)

$\mu_A(z)$ is stated as the membership function of z in A. Membership function assigns every component of Z to a membership value between 0 and 1.

In this work, the Fuzzy models based on different membership functions are prepared mainly to check the status condition of the transformer using the value of DP. Following set of equations defined the various types of membership functions used in the fuzzy models.

(i) y = trapmf (x; a, b, c, d), i.e. the trapezoidal membership curve is the function of vector x, that depends on the four parameters a, b, c and d which is given as

$$f(x;a,b,c,d)=\begin{cases}0, & x \le a\\ \frac{x-a}{b-a}, & a \le x \le b\\ 1, & b \le x \le c\\ \frac{d-x}{d-c}, & c \le x \le d\\ 0, & d \le x\end{cases} \quad (3)$$

Or, more efficiently by

$$f(x;a,b,c,d) = max\left(min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right) \quad (4)$$

The parameters ‘a’ and ‘d’ shows the "feet" of trapezoid while parameters ‘b’ and ‘c’ represent the "shoulders."

(ii) y = trimf(x,[a b c]), the triangular membership curve is the function of vector x, that depends on the parameters a, b, and c, given as

$$f(x;a,b,c)=\begin{cases}0, & x \le a\\ \frac{x-a}{b-a}, & a \le x \le b\\ \frac{c-x}{c-b}, & b \le x \le c\\ 0, & c \le x\end{cases} \quad (5)$$

or, more efficiently by

$$f(x;a,b,c) = max\left(min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \quad (6)$$

The parameters ‘a’ and ‘c’ shows the "feet" of triangle while parameter ‘b’ represents the "peak."

(iii) y = gauss2mf(x,{sig1 c1 sig2 c2}), The Gaussian membership curve depends on the parameters **sig** and **c** given as

$$f(x;\sigma,c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \quad (7)$$

The gauss2mf function is the combination of the two parameters stated above. The first one, specified by sig1 and c1, find out the contour of left most curve. The second one specified by sig2 and c2 gives the contour of the right most curves.

(iv) y = gbellmf(x, params), The gbell membership curve depends on parameters a, b, and c given as

$$f(x;a,b,c) = \frac{1}{1+\left|\left(\frac{x-c}{a}\right)^{2b}\right|} \quad (8)$$

Here the parameter 'b' is taken positive, while the parameter 'c' is the center of curve.

B. Fuzzy Rules

Fuzzy inference system is constructed through the set of linguistic rules. It is developed by "IF-THEN" type rules prepared by a set of knowledge based linguistic rules, called implication, plotted in X-Y surface [8]. The FL so developed is an appropriate way of mapping the input-output space. It gives mathematical strength to the emulation of some perceptual and linguistic attributes connected to human cognition. The principle of fuzzy system offers an inference mechanism under cognitive uncertainty.

The Fuzzy rules are formed with the help of existing relation between carbon oxide gases, 2-FAL and DP [3]. These data are obtained on a laboratory scale through a series of accelerated thermal aging experiment performed on transformer oil impregnated cellulose grade kraft paper.

C. Defuzzification

Defuzzification is the method to bring out the desired result in crisp logic. It is most widely applied using centre-of-gravity principle on account of weighted mean of Fuzzy region [9]. The required output z_o is obtained using the formula given below:

$$z_o = \frac{\int z.\mu_c(z)dz}{\int \mu_c(z)dz} \quad (9)$$

Where $\mu_c(z)$, representing the membership function of the output variable.

In this work, the defuzzification procedure gives the crisp value of DP at the output that basically predicts the condition of paper insulation. From this value the status of insulation is inferred as per predefined range in output membership function and these ranges and corresponding conditions are mentioned in Table 1.

III. Proposed Scheme For Health Monitoring of Paper Insulation in Oil Immersed Transformer

In this work, an FIS model is shaped, to correlate the concentrations of CO, CO_2 and 2-FAL (in ppm) with the value of DP. These carbon oxide gases and 2-FAL released due to thermal degradation of the kraft paper point out the amount of ageing and hence decide end of life of the paper insulation after reaching agreed preventive values. The experimental data is used for verification of developed FIS. Further, the same experimental data set is used to evaluate the performance of the FIS using different membership functions (MF) that helped to choose the best MF for the application. The system's end result was found to be in fine agreement with input parameters.

In [3] it is revealed that DP is having definite relation with CO_2, CO and 2-FAL. The concentration (ppm) ranges of input gases and DP with respect to each linguistic variable are decided as per IEEE C57.104 standard and the experimental data.

Complete experimental range of DP is divided into four status conditions: Acceptable Insulation, Moderate Deterioration (Significant Concern), Extensive Deterioration (Exceedingly Investigable) and End of life (Urgent Replacement) to evaluate the paper deterioration using DP as a failure index. The condition of CIP based on the collected values of 2-FAL, CO and CO_2 is stated as per the IEEE Standard C57.104™ Guide of interpretation of gases dissolved in oil-immerged transformers [10]. To each status state, the ranges of 2-FAL, CO and CO_2 in ppm are specified in Table I:

TABLE I. DP VALUE BASED ON 2-FAL, CO_2 AND CO

2-FAL	CO_2	CO	DP	Condition
A_1=0-0.1	B_1=0-2500	C_1 = 0-350	1200-700	Healthy Transformer/ Acceptable Insulation
A_2=0.1-1	B_2 = 2500-4000	C_2=350-570	700-450	Moderate Deterioration/ Significant Concern
A_3=1-10	B_3=4000-10000	C_3 = 570-1400	450-250	Extensive Deterioration/ Exceedingly Investigable
A_4≥10	B_4≥10000	C_4≥1400	<250	End of Life/ Urgent Replacement

A. Inputs and output of fuzzy expert system

The available experimental data of 2-FAL, CO_2 and CO are fuzzified using membership functions. In fuzzification process, four linguistic variables(very low, low, moderate and high) are considered for each input. Expert rules are so formed that it correlates the different input linguistic variables, assigned to different input gas concentrations, to different output linguistic variables, assigned to DP values, to represent the CIP health status. Further, different membership functions (trapezoidal, triangular, Gaussian) are tried to find out best MF for the considered application.

a) Design of Membership Functions

In MFs, ranges for input and output variable corresponding to consider linguistic variables are decided as per IEEE standard C57.104 and experimental data [3].

(i) Membership functions of 2-FAL: The 2-FAL is considered to be the most significant factor to evaluate the condition of CIP because it directly affects the solid insulation degradation and consequently the end of life of a power transformer. The internal winding temperature and moisture in the solid insulation are main factor for the growth of 2-FAL in the transformer oil. The 2-FAL fuzzified in accordance with four linguistic conditions (very low, low, moderate and high). Very low linguistic variable corresponds to 2-FAL level

between 0-0.1 ppm, low corresponds to the 2-FAL level between 0.1-1 ppm, moderate represents the 2-FAL level between 1-10 ppm and high represent the 2-FAL level exceeding 10 ppm [3].

(ii) Membership functions for CO_2: The evolution of CO_2 in the transformer oil due to thermal degradation of solid insulation also plays a significant role in an attempt to harness the transformer's insulation and hence its life. The concentration of $CO_2$is fuzzified using four linguistic conditions (very low, low, moderate and high).The value of CO_2 lies between 0 ppm – 2500 ppm for very low, 2500 ppm – 4000 ppm for low, 4000 ppm 10000 ppm for moderate and exceeds 10000 for high [10].

(iii) Membership functions for CO: CO is another important factor affecting the transformer health and is produced through oxidation of cellulose insulation. The CO_2/CO ratio for the transformers having healthy cellulose insulation should be between 3 and 11. If DGA results show the value of CO2/CO ratio less than 3, then it is serious concern about transformer as its solid insulation is damaging rapidly. The CO content was also estimated according to four linguistic conditions (very low, low, moderate and high).The value of CO lies between 0 ppm – 350 ppm for very low, 350 ppm- 570 ppm for low, 570 ppm -1400 ppm corresponds to moderate range whereas for high it exceeds 1400 ppm [10].

(iv) Membership functions for the DP (output): The CIP health of the transformer as represented value of DP. The whole range of DP is divided into four linguistic conditions: Acceptable Insulation (AI), Moderate Deterioration (MD), Extensive Deterioration (ED), Urgent replacement (UR). The AI membership functions hold the value from 1200 to 700. The membership functions for the MD covers the value from 700 to 450; ED covers the DP value from 450 to 250 while UR satisfies with the value less than 250.

b) Expert Rules

Four expert rules have been formed for the proposed model to estimate the value of DP which decides the transformer health. The different combinations of 2-Furfuraldehyde content along with CO_2 and CO decide the current status of the oil filled transformers based on the values of DP. When the value of 2-FAL and carbon oxide gases is very low then the DP value of insulation paper is above 1200 which correspond to a healthy transformer. As the evolution of carbon oxide gases increases along with 2-FAL, there is a significant amount of deterioration of insulation paper corresponding to DP in the range of 700-450. As the transformer insulation further deteriorates, the corresponding values of 2-FAL and carbon oxide gases further increases. The DP value decreases between 450-250. When the value of DP decreases less than 250, there is exponential rise in carbon oxide gases and 2-FAL as well. It signifies the end of life of insulation. The expert rules have been listed in the Table II.

TABLE II. FUZZY LOGIC RULES

Rule No.	Rules
1	If 2-FAL is very low, CO_2 is very low, CO is very low; the value of DP refers Acceptable Insulation (AI)
2	If 2-FAL is low, CO_2 is low, CO is low; the value of DP refers Moderately Deteriorated (MD) insulation
3	If 2-FAL is moderate, CO_2 moderate and CO is moderate; the value of DP refers Extensively Deteriorated (ED) insulation
4	If 2-FAL is high, CO_2 is high, CO is high then the value of DP refers Urgent Replacement (UR) of insulation

Various membership functions such as trapezoidal, triangular and Gaussian were used to fuzzify the input and to defuzzify the output variables. It is found that trapezoidal membership function gives best performance satisfying the suitable range as to the IEEE standard. The performance of the proposed FIS is also evaluated using different types of input and output membership functions.

IV. RESULTS AND DISCUSSION

The developed FIS provides the physical state of CIP in terms of DP value. The states of insulation corresponding to DP values are listed in Table I.

TABLE III. TEST RESULT OF VARIOUS SAMPLES USING FUZZY LOGIC

2-FAL	CO_2	CO	DP				
			trap	gbell	gauss	gauss2	tri
3	5315	662	362	378	382	375	375
0.5	3089	405	606	634	661	617	636
0.05	1936	97	986	988	937	966	938
5	5004	935	363	375	375	375	375
0	229	10	978	976	879	906	901
0.1	2500	350	462	456	427	426	428
6	7800	1050	350	366	370	363	363
0.08	1600	145	988	992	998	998	990
0.2	2600	360	495	510	526	519	498
15	12000	1650	116	110	98	96	114
0.06	218	34	1044	1042	998	996	1035
1.72	4150	592	380	368	370	370	375
0.09	877	98	797	824	800	815	810
3.85	4465	1062	280	265	275	279	272
14.17	16500	1750	119	110	114	112	116

Table III shows the test results of developed fuzzy based transformer health monitoring model using different membership functions. The test results shown in Table III,

considered input data points cover all possible combinations as per considered linguistic variables for different inputs. The output of the model gives the crisp value of the DP which can be used to detect the transformer paper insulation condition. Hence at the output of the fuzzy models, the status of CIP of the transformer is obtained. For high values of 2-FAL and carbon oxide gases, the DP values for developed fuzzy models are in the range of less than 250 which demands urgent replacement of the transformer. Likewise the DP values for other status conditions are also shown in Table III. The value of DP associated with each of the status condition is not only in the agreement with the IEEE standard but also in accordance with the obtained experimental results.

TABLE IV. DEVIATION IN THE VALUE OF DP(FIS) W.R.T DP (EXPERIMENTAL)

DP (Experimental)	Deviation				
	trap	gbell	gauss	gauss2	tri
329	33	49	53	46	46
570	36	64	91	47	66
1055	69	67	118	89	117
343	20	32	32	32	32
1024	46	48	145	118	123
484	22	28	57	58	56
296	54	70	74	67	67
965	23	27	33	33	25
465	30	45	61	54	33
146	30	36	48	50	32
1150	106	108	152	154	115
392	12	24	22	22	17
727	70	97	73	88	83
300	20	35	25	21	28
152	33	42	38	40	36

Table IV shows the comparison between experimental results reported in [3] and output of developed fuzzy model. The crisp value of DP obtained at the output of FIS is compared with experimentally obtained DP value. The deviation of FIS output is measured with respect to experimental DP and it is found that the CIP status obtained by fuzzy model built with trapezoidal membership function is closer to the experimental output besides being in agreement with IEEE standards. The insulation status predicted by other FIS also coincides with the IEEE standard.

V. CONCLUSION

In this work, existing correlation between 2-FAL, CO_2 and CO with the value of DP is exploited to access the condition of CIP. This paper is an attempt to monitor the condition of CIP in oil-immerged transformers by means of Fuzzy based model. The model provides the status of the transformer insulation where DP is used as index of failure. The proposed model successfully predicts the value of DP on the basis of concentration of 2-FAL, $CO_2$and CO gases in oil. Performance of the FIS is tested using different membership function. Results of the model are compared with experimental data and comparison shows that the predicted DP values with trapezoidal membership function are having minimum deviation from the experimental values of DP. The information obtained from the model can be used for condition based maintenance of oil-immerged power transformer and in order to enhance its useful operating life.

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