Chapter

Fuzzy Logic Expert System for Health Condition Assessment of Power Transformers

Teruvai Manoj and Chilaka Ranga

Abstract

In the present chapter, a new fuzzy logic (FL) model is proposed to evaluate the overall health index (OHI) of power transformers. The most significant attributes such as dissolved gases, acidity, 2-furfuraldehyde, water content, breakdown voltage and dissipation factor that influence the health condition of transformers solid and liquid insulations are considered. These attributes are further divided into three different sets. Based on these sets, three different sub fuzzy models i.e. F_1, F_2 and F_3 are designed in order to reduce the possible combinations of fuzzy rules. It results in reducing the complexity issues of the proposed OHI model. In addition, consideration of all significant testing parameters makes the model more reliable and accurate. Further, the proposed fuzzy model helps in initiating appropriate and early action on faulty conditions of the transformers. Conventional fuzzy logic models generally utilize large number of inputs and more number of rules in a single fuzzy model. It makes the models complex and inaccurate. Such shortcomings of existing conventional models are successfully overcame by the present proposed model. Furthermore, the results obtained from the proposed model are compared with the results obtained from expert model proposed by Abu-Elanien et al. This comparison ensures the reliability of the proposed method. Also, it is envisioned that the proposed model can be easily implemented by both the experienced and the inexperienced utility managers.

Keywords: Transformer, insulation, condition monitoring, fuzzy logic, membership function

1. Introduction

Power transformers are vital components of power system. The total service life of power transformers is majorly depends on the life spans of their liquid and solid insulations [1]. The deterioration of the insulation is caused due to the various electrical and thermal stresses present inside the transformers. These stresses accumulate several dissolved gases within the transformer oil, and produce partial discharge, overheating and arcing [2, 3]. Generally, the dissolved gases namely, hydrogen (H_2), acetylene (C_2H_2), ethane (C_2H_6), ethylene (C_2H_4), methane (CH_4), carbon monoxide (CO) and carbon dioxide (CO_2) are induced in the transformer oil. The severity of these gas concentrations identifies the type of faults present in the transformer [4, 5]. Moreover, these gas concentrations are employed to examine the overall health condition (HC) of the transformers. Generally, it is termed as health index (HI). Further, there are some significant attributes that influences the health of transformer solid and liquid insulations. Attributes such as dissipation factor, water content, acidity, breakdown voltage and dissolved gases decide the lifetime of oil insulation [5]. Similarly, solid insulation's life depends on 2-furfuraldehyde. During the operation of transformers, amount of these attributes increase, and lead to excessive deterioration of transformers. Further, it may cause failure of transformers resulting in a huge revenue loss to the customers. To avoid such problems, continuous condition monitoring of power transformers is essential. It is only possible if all the significant tests are performed frequently to obtain attribute values in regular time intervals [6].

Over the past few decades, various fuzzy logic (FL) models are developed by diagnostic experts to evaluate the health condition of transformers [5–7]. These models incorporated the various diagnostic attributes such as furan content, degree of polymerization (DP), dissipation factor (DF), acidity, water content (WC), breakdown voltage (BDV) and total dissolved combustible gases (TDCG) concentration. Using the dissolved gas concentrations, the thermal and electrical criticalities of oil and paper insulations are determined [8]. The recent fuzzy logic models reported in the literature have their own strengths in determining the health index, however, none of them has fully utilized all the significant attributes of the transformers, thereby remain with some backlogs. Hence, these FL models constrained with some limitations [9, 10].

In the present chapter, a new fuzzy logic (FL) model is proposed to determine the overall health index (OHI) of transformer. To validate the efficacy of this model, the test samples and results have been collected from Himachal Pradesh State Electricity Board (HPSEB). For an easy understanding, the present chapter is divided into different sections as follows. The brief explanation of transformer attributes is given in Section 2. Section 3 details about the present proposed fuzzy logic model. Finally, results of the model are discussed in the Section 4. And the complete chapter is concluded in Section 5.

2. Transformer diagnostic attributes

The major deterioration of transformer insulation is caused by attributes such as breakdown voltage, dissipation factor, water content, acidity, dissolved combustible gases and 2-furfuraldehyde. The brief introduction of these attributes is given in this section.

Breakdown voltage (BDV) is defined as voltage at which breakdown occurs between the two electrodes while oil is exposed to an electric field under critical conditions [11]. For insulation system of a transformer, electric strength is the basic parameter which indicates the presence of contaminants like perceptible sludge, moisture and sediment [12]. Dissipation factor (DF) is defined as the sine of loss angle. Also, it is important parameter to test the quality of insulation [13]. Some harmful contaminants such as oxidation products, water and de-polymerization of paper insulation are induced due to high value of DF [14].

The presence of dissolved water in the oil is termed as water content and it is expressed in parts per million (ppm) by weight [15]. The existence of moisture content in the oil is detrimental since it adversely affects the electrical characteristics of oil. Also, excess amount of moisture accelerates deterioration of insulating materials [16]. The measurement of free organic and inorganic acids accumulate in the transformer oil is defined as acidity, and is measured in milligrams of potassium hydroxide. It is required to neutralize the total free acid in one gram of oil [17].

When the influence of abnormal thermal and electrical stresses on transformer oil is not very high, the gases generated as a consequence of decomposition of insulating oil will get enough time to dissolve in the oil. In dissolved gas analysis, the percentage of gas concentrations present in oil is determined and analyzed [18]. These dissolved gas percentages helps in finding out the internal condition of transformer [19]. Solid dielectrics present in the two essential parts of transformer i.e. core and winding which is made of cellulose. Cellulose consists of long chain of molecule structure [20]. During the operation of transformer, these long chains are generally broken into several numbers of minute particles, as per the aging. These furan compounds belong to the fur-furaldehyde group. 2-Furfural is the most predominant among all furfurals compounds. The condition assessment and life estimation of paper insulation is done by using the rate of rise of furfural products with respect to time in oil. Damage in few grams of paper in oil is detected even for a large sized transformer. Therefore, fur-furaldehyde analysis is very sensitive [21]. When the transformer oil is soaked into solid dielectric, furan particles along with gases CO_2 and CO dissolved in the oil due to heat.

3. Proposed fuzzy logic model

Fuzzy logic is a very helpful tool in obtaining accurate output, and easy in implementation [22]. Also, it facilitates more effective and reasonable decision making for transformers in order to ensure maintainability and reliability [23, 24]. The purpose of the proposed FL model is to integrate various diagnostic test results with the experience of transformer diagnosis experts [23]. Different stages of the FL models are discussed in the following sub-sections. The curve which converts the precise (crisp) inputs in to imprecise fuzzy sets with degrees of membership function (DOM) in the range 0 and 1. Generally, membership functions (MFs) have different shapes namely, triangular, sigmoidal or trapezoidal, Gaussian and Gauss2. Trapezoidal MF is widely used MF because of its simplicity [20, 21]. It is shown in **Figure 1**, and given by Eq. (1). The trapezoidal MF consists of a truncated triangular curve and a flat top.

$$\textit{Membership function} = \max\left\{\min\left(\frac{x-a}{c_1-a}, 1, \frac{b-x}{b-c_2}\right), 0\right\} \tag{1}$$

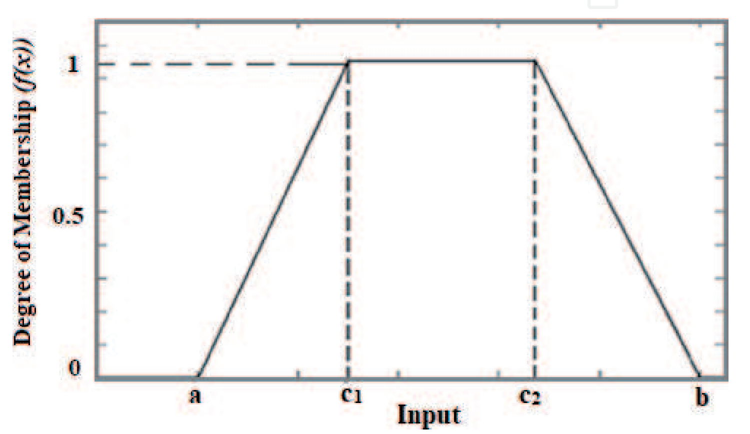

Figure 1.
The trapezoid shaped membership function.

Where, input variable is denoted as 'x', lower and upper limits are denoted as 'a' and 'b', respectively. Similarly, 'c_1' and 'c_2' are the centers of the trapezoidal MF [21]. If the input value lies in between the range of'c_1'and'c_2'of the MFs, then the corresponding MF attains the maximum DOM of unity [25]. Whereas, input values lie between the range of 'a'and'c_1'and between the range of'c_1'and'b', will have DOMs less than unity. Likewise, all the crisp input values (precise) are converted into fuzzy (imprecise) values in fuzzification stage. Where the fuzzy values range lie between 0 and 1.

In the present proposed model, fuzzy logic (FL) is used to determine the overall health index (OHI) of power transformers. The six parameters (Section 2) are considered as inputs in the present proposed model to determine the overall health index (OHI) of transformers. To make the model simple, three sub-fuzzy models viz. F_1, F_2 and F_3 are designed separately. Two parameters namely, water content and acidity are assigned as inputs for F_1, whereas BDV and DF are for F_2. Similarly, DCG and 2-FAL are considered as inputs for F_3. Furthermore, the outputs obtained from these three sub-models are considered as the inputs to a single fuzzy model called F_4. The final output obtained from the model F_4 is OHI of transformers. All the inputs of F_1, F_2 and F_3 used trapezoidal shaped MFs and their limits are assigned in accordance to [1]. These limits for MFs of water content input in F_1 are shown in **Figure 2**. Likewise, MFs are designed with trapezoidal shape for remaining sub models. The values of the six significant attributes have been listed in **Table 1**.

However, input 2-FAL in F_3 consists of 5 MFs as per [1]. These MFs are Very bad, Bad, High-moderate, Low-moderate and Good. The lower and upper limits of these MFs, and their centers are [0 0 0.2 0.2], [0.2 0.2 1 1.5], [1 1.5 3 3.5], [3 3.5 6 7.5] and [6 7.5 10 10] respectively. In case of F_4, the output MFs used in each of the three sub-models was used as input MFs. The corresponding input MFs of water content are same as described in **Figure 2**.

The block diagram consisting of the three sub fuzzy models and a main fuzzy model for transformer sample 12 is depicted in **Figure 3**. The lower and the upper limits along with the two centers of input MFs are specified in **Table 2**. Similarly, the output for each of the four models F_1, F_2, F_3 and F_4 was divided in to four MFs as specified in **Figure 4**.

In fuzzification stage, the input values are converted in to fuzzy values by using the Eq. (1) [26]. Consider transformer sample 12, where the value of acidity is 0.23 mgKOH/g. It lies in the range of Bad (**Table 2**). Therefore, the limits i.e. a, c_1, c_2 and b

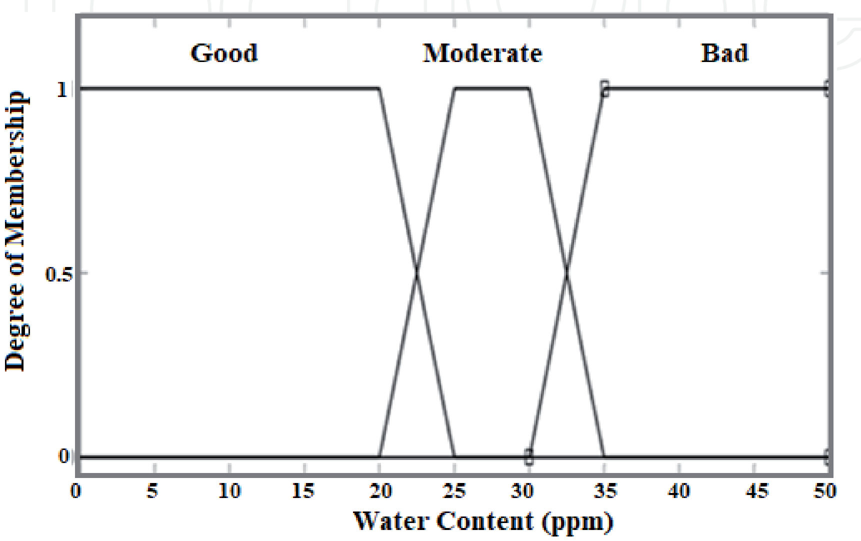

Figure 2.
Membership functions for water content input in F_1.

Sample Number	Acidity	DF	2-FAL	BDV	WC	DCG
1	0.07	0.15	0.52	73	15.4	38
2	0.04	0.18	0.31	64.5	19	8
3	0.02	0.06	1.24	27.9	27.9	501
4	0.14	0.19	7.45	36.5	14	51
5	0.03	0.08	0.85	29	21.3	489
6	0.07	0.66	15.5	29.7	31	32
7	0.04	0.15	0.22	53	13.6	77
8	0.09	0.36	0.21	39.5	27	194
9	0.09	0.89	0.61	56	26.1	292
10	0.06	0.21	0.57	37.2	26.3	25
11	0.07	0.13	5.35	31.4	25.8	321
12	0.23	0.43	5.54	47.7	21.8	215
13	0.13	0.19	9.34	26.6	15.3	76
14	0.06	0.25	0.13	61.5	19.4	61
15	0.17	0.26	0.74	70.5	16.1	147
16	0.11	0.22	0.34	43.8	23.5	33
17	0.08	0.22	0.65	67.2	13	28
18	0.41	0.27	6.62	55.2	17	51
19	0.02	0.12	0.01	73	8	127
20	0.17	0.22	8.56	22.7	15.2	38

Table 1.
Significant attribute values of the 20 test case transformers.

of acidity membership are 0.15, 0.2, 0.3 and 0.3. Substitute the values in Eq. (1) gives the fuzzified value as 1. Similarly, the imprecise values are calculated for all the samples and summarized in **Table 3**.

After fuzzification stage, the inputs are mapped with output by specially designed rules in the fuzzy inference stage. In the present work, a widely used Mamdani maximum–minimum fuzzy inference method is used [21, 25]. Using the fuzzified set of inputs and the designed fuzzy rules, the output is determined in this method. Further, the method truncates the output MF at its minimum DOM value. Initially the inputs are fuzzified using Eq. (1). Further, the truncated output from each of the three models are obtained based on the specially designed expert fuzzy rules and fuzzified inputs. In the present work, the fuzzy rules possible between the inputs of F_1 are designed consisting two inputs each with three MFs generate a total of nine combinations. Similar combinations are also obtained for F_2.

The rule base designed for sub fuzzy model, F_1 is given below:

Rule 1: If Water content is Good and Acidity is Good then output is Excellent.
Rule 3: If Water content is Good and Acidity is Bad then output is Poor.
Rule 6: If Water content is Moderate and Acidity is Bad then output is Worst.
Rule 9: If Water content is Bad and Acidity is Bad then output is Worst.

In case of F_3, the three input MFs in DCG, and five MFs in 2-FAL make a total of fifteen fuzzy rules.

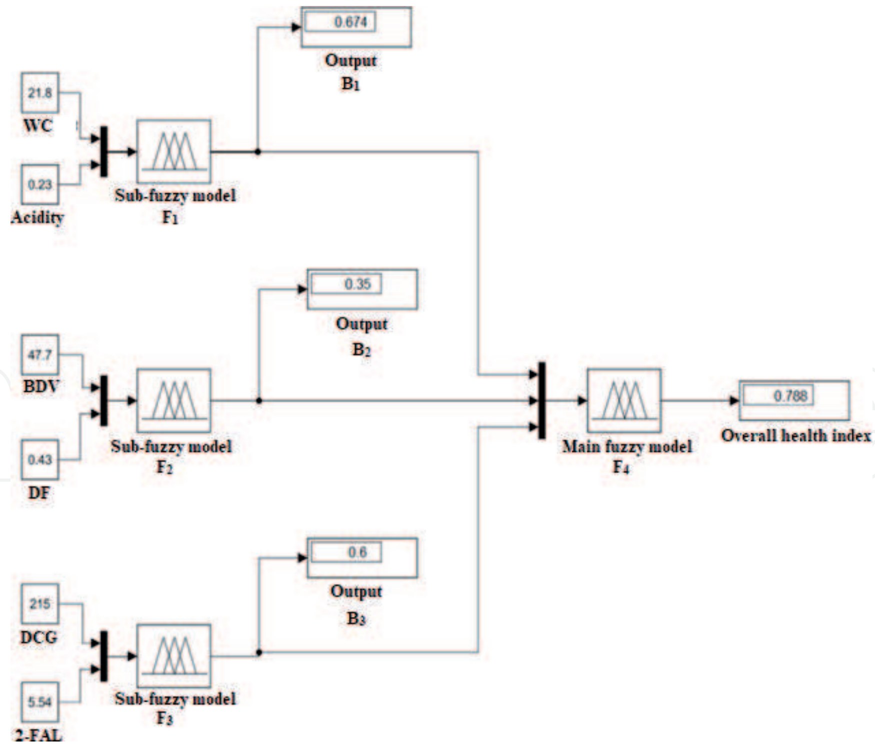

Figure 3.
Block diagram of the proposed fuzzy logic model.

Input MF ranges	Good				Moderate				Bad			
	a	c_1	c_2	b	a	c_1	c_2	b	a	c_1	c_2	b
Acidity	0	0	0.03	0.05	0.03	0.05	0.15	0.2	0.15	0.2	0.3	0.3
DF	0	0	0.05	0.1	0.05	0.1	0.8	1	0.8	1	1.5	1.5
BDV	52	53	75	75	23	24	53	54	0	0	23	24
DCG	0	0	300	400	300	400	1100	1400	1100	1400	2000	2000

Table 2.
Lower and upper limits for MFs of all inputs.

The rule base designed for sub fuzzy model F_3 is given as below:

Rule 1: If DCG is Good and 2-FAL is Very bad then Output is Excellent.
Rule 3: If DCG is Good and 2-FAL is Low-Moderate then Output is Poor.
Rule 6: If DCG is Moderate and 2-FAL is Bad then Output is Worst.
Rule 9: If DCG is Good and 2-FAL is High-Moderate then Output is Good.
Rule 12: If DCG is Moderate and 2-FAL is High-Moderate then Output is Good.
Rule 15: If DCG is Bad and 2-FAL is Good then Output is Worst.

Similarly, the possible combinations (sixty four rules) of input MFs in case of F_4 were generated. The final rule base for main fuzzy model (F_4) with all three inputs (B_1, B_2, B_3) is given below:

Rule 1: If B_1 is Excellent and B_2 is Excellent and B_3 is Excellent then Output is Excellent.
Rule 8: If B_1 is Good and B_2 is Excellent and B_3 is Worst then Output is Poor.
Rule 16: If B_1 is Good and B_2 is Poor and B_3 is Worst then Output is Poor.
Rule 24: If B_1 is Worst and B_2 is Excellent and B_3 is Worst then Output is Worst.

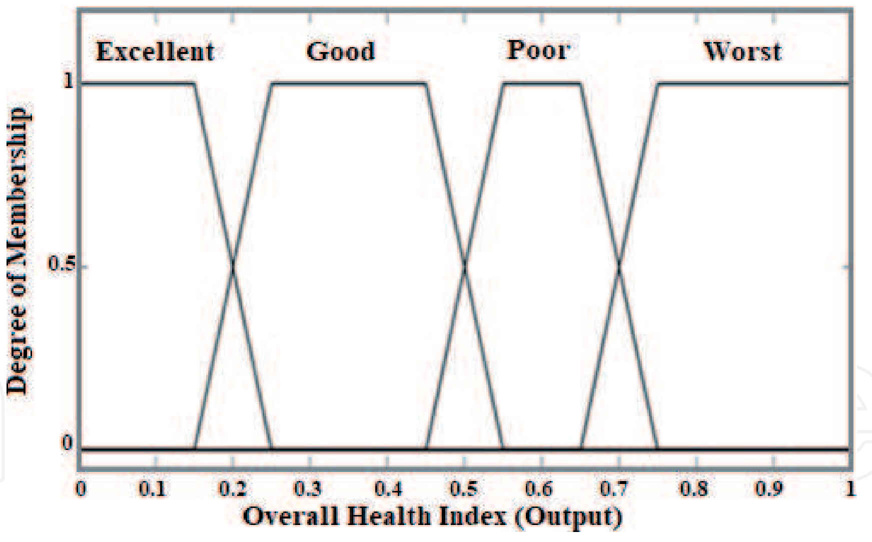

Figure 4.
Membership functions of output F_4.

Sample Number	Acidity	DF	2-FAL	BDV	WC	DCG
1	1	1	1	1	1	1
2	0.5	1	1	1	1	1
3	1	0.8	0.52	1	1	1
4	1	1	0.03	1	1	1
5	1	1	1	1	0.74	1
6	1	1	1	1	0.8	1
7	0.5	1	1	1	1	1
8	1	1	1	1	1	1
9	1	0.45	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	0.79
12	1	1	1	1	0.64	1
13	1	1	1	1	1	1
14	1	1	1	1	1	1
15	0.4	1	1	1	1	1
16	1	1	1	1	0.7	1
17	1	1	1	1	1	1
18	1	1	0.59	1	1	1
19	1	1	1	1	1	1
20	0.4	1	1	1	1	1

Table 3.
Fuzzified values (imprecise) of the attributes obtained in fuzzification stage.

Rule 32: If B_1 is Worst and B_2 is Poor and B_3 is Worst then Output is Worst.
Rule 40: If B_1 is Poor and B_2 is Excellent and B_3 is Worst then Output is Worst.
Rule 48: If B_1 is Poor and B_2 is Poor and B_3 is Poor then Output is Worst.
Rule 56: If B_1 is Excellent and B_2 is Good and B_3 is Worst then Output is Poor.
Rule 64: If B_1 is Excellent and B_2 is Worst and B_3 is Excellent then Output is Good.

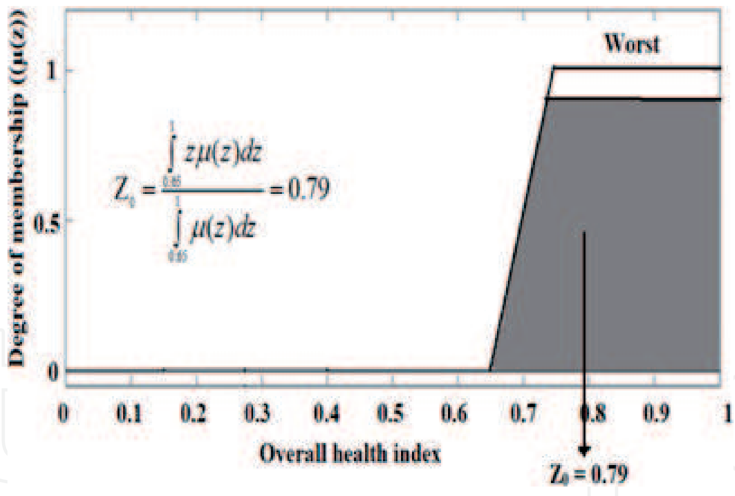

Figure 5.
Center of gravity method applied on transformer sample 12.

The rules are framed according to their severity level deteriorating transformer insulation. Since DCG and 2-FAL are very harmful attributes, the highest priority in determining OHI is given to B_3 (sub fuzzy model F_3). B_1 (sub fuzzy model F_1) has been considered as key factor next to B_3. And, least priority has been given to B_2 (sub fuzzy model F_2) among all the three inputs.

Defuzzification is the last stage of this method where a precise quantitative value from the truncated output MF is determined [27]. Center of gravity is the most popular and efficient defuzzification method [20]. This method is used in the present work. It determines the center of gravity or the centroid (Z_0) of the area bounded by the truncated output MFs [20, 21]. It is obtained by

$$Z_0 = \frac{\int z.\mu(z)dz}{\int \mu(z)dz} \tag{2}$$

Where the output variable is denoted by 'z' and 'μ(z)' is the DOM of the truncated output MF. The crisp output is obtained by using Eq. (2). The centroid representation of the output value (sample 12) is depicted in **Figure 5**. Similarly, the outputs for remaining samples are obtained using the above equation.

4. Results and discussion

For an easy understanding of proposed method, consider sample 12 and its diagnostic values are detailed in **Table 2**. The data related to all diagnostic attributes has been collected from Himachal Pradesh State Electricity Board (HPSEB). In sample 12, 0.23 mgKOH/g of acidity, 0.43 of DF, 5.54 ppm of 2-FAL, 21.8 ppm of water content, 47.7 KV of BDV and 215 ppm of DCG were initially fuzzified in the fuzzification stage. Further, these values are converted into outputs depending upon rule base given in Section 4.

The outputs of sub fuzzy models F_1, F_2 and F_3 are represented by B_1, B_2 and B_3, respectively. After the defuzzification stage, the outputs obtained from F_1, F_2 and F_3 are 0.674, 0.35 and 0.6 using Eq. (2). These three outputs are utilized and converted to inputs for F_4 (i.e. B_4 or RHI). From the F_4 model, the final output for sample 12 is 0.788. Likewise, OHI for all the remaining transformer samples are determined and summarized in **Table 4** (column 2). Also the health indices for each of these transformers were determined in accordance to [1], and are given in the same table (column 4).

Sample Number	HI obtained using Present Proposed Method	HC of Transformers using Proposed Method	HI obtained using Method in [1]	HC of Transformers using the Method in [1]
1	0.25	E	0.3	G
2	0.24	E	0.22	VG
3	0.25	E	0.53	M
4	0.60	P	0.93	VB
5	0.35	G	0.36	G
6	0.84	W	0.94	VB
7	0.24	E	0.3	G
8	0.35	G	0.3	G
9	0.41	G	0.3	G
10	0.27	E	0.3	G
11	0.85	W	0.78	B
12	0.79	W	0.78	B
13	0.62	P	0.94	VB
14	0.11	E	0.3	G
15	0.24	E	0.3	G
16	0.26	E	0.3	G
17	0.25	E	0.3	G
18	0.85	W	0.83	VB
19	0.10	E	0.2	VG
20	0.78	W	0.94	VB

Table 4.
Overall health indices obtained for 20 test case transformers.

Where in **Table 4**, E-Excellent, G-Good, P-Poor, W-worst, VG-Very good, M-Moderate, B-Bad and VB-Very bad.

Four output MFs have been designed in the proposed model, whereas five MFs were considered in Ref. model. The Excellent health condition of proposed model has been compared to the Very good and Good health conditions produced by the reference model [1]. Similarly, Good health condition of proposed model is compared with Moderate condition of reference model. And, comparison has been done Bad with Poor and Very bad with Worst. The overall comparison of all 20 transformer health index by the proposed model and model proposed in [1] is given in **Table 5**.

From **Table 5**, a curious difference has been found out while comparing the test results of proposed model with reference model [1]. It is noted that, out of total 20 test case transformers 11 test results of proposed model are matched with results obtained in [1]. From the comparison, it is observed that the proposed method has better results. To support the statement, consider test sample 12, the HC obtained using model proposed in [1] is Bad. But, the quantities of most influential parameters WC and DCG are 21 and 215 ppm, respectively. These quantities indicate that the transformer insulation is in critical condition and replacement is required. From the test results from proposed model, the HC of sample 12 is worst. It is most suitable condition for the health of transformer. It is proved that the results acquired from the proposed model provide accurate health condition. Also, all the fuzzy models in the proposed model are designed by analyzing the impact of significant diagnostic attributes on transformer insulation. These modifications make the proposed model efficient.

Proposed method/ Method in [1]	Worst	Poor	Good	Excellent	Total
Very Bad	3	2			5
Bad	2				2
Moderate				1	1
Very Good/Good			3	9	12
Total number of transformers					**20**

Table 5.
Comparison of the results obtained from both the methods.

5. Conclusion

In the present chapter, a novel fuzzy logic model has been proposed to find the overall health index of oil-immersed transformers. Parameters that influence the health condition of transformer insulation such as acidity, BDV, DF, DCG, water content and 2-FAL are used to test the HC of transformer. Three sub fuzzy models are created namely, F_1 with water content and acidity as inputs, F_2 with BDV and DF as inputs, F_3 with DCG and 2-FAL as inputs. Further, the individual outputs of three fuzzy models are taken as inputs for the final fuzzy model F_4. All the inputs of sub fuzzy models are designed with three MFs except for 2-FAL which has five. Also, the rule base is formed with nine, nine, and fifteen rules for F_1, F_2 and F_3 sub-fuzzy models, respectively. And, sixty-four rules designed for main fuzzy model F_4. The comparison has been done between the proposed model and fuzzy model designed in [1]. The fuzzy model designed in [1] consists of six inputs and thirty expert rules only. After comparing the two models, it is observed that the results of proposed model are more accurate. In addition, a complete rule base fulfilling all probable situations in determining HI is incorporated in the present model. Hence this model is most efficient, reliable and easily implemented by utilities and industries in order to obtain the health indices of their transformers which is a significant advantage.

Author details

Teruvai Manoj and Chilaka Ranga*
National Institute of Technology, Srinagar, Jammu and Kashmir, India

*Address all correspondence to: chilakaranga@nitsri.ac.in

References

[1] Abu-Elanien B, Salama MMA, Ibrahim M. Calculation of a health index for oil immersed transformers rated under 69kv using fuzzy logic. IEEE Transactions on Power Delivery. 2012;27:2029-2036.DOI: 10.1109/TPWRD.2012.2205165

[2] Jahromi R, Piercy S, Cress J, Wang Fan F. An approach to power transformer asset management using health index. IEEE Electrical Insulation Magazine. 2009;25,20-34. DOI: 10.1109/MEI.2009.4802595

[3] Zeinoddini-Meymand H, Behrooz V. Health index calculation for power transformers using technical and economical parameters. IET Science, Measurement and Tchnology. 2016;10:823 – 830. DOI: 10.1049/iet-smt.2016.0184

[4] Dehghani Ashkezari A, Ma H, Saha TK. Application of fuzzy support vector machine for determining the health index of the insulation system of in-service power transformers. IEEE Transactions on Dielectrics and Electrical Insulation. 2013;20:965 – 973. DOI: 10.1109/TDEI.2013.6518966

[5] Qiu J, Wang H, Lin D, He B, Zhao W, Xu W. nonparametric regression-based failure rate model for electric power equipment using lifecycle data. IEEE Transactions on Smart Grid. 2010;6:955 – 964. DOI: 10.1109/TSG.2015.2388784

[6] Dehghani Ashkezari A, Ma H, Saha T, Cui Y. Investigation of feature selection techniques for improving efficiency of power transformer condition assessment. IEEE Transactions on Dielectrics and Electrical Insulation. 2012;21:836 – 844. DOI: 10.1109/TDEI.2013.004090

[7] Ortiz F, Fernandez I, Ortiz A, Renedo C, Delgado F, Fernandez H. Health indexes for power transformers: A case study. IEEE Electrial Insulation Magazine. 2012;32:7-17. DOI: 10.1109/MEI.2016.7552372

[8] Shaban KB, H. El-Hag A, Benhmed A. prediction of transformer furan levels. IEEE Transactions on Power Delivery. 2016;31(4):1778-1779. DOI: 10.1109/TPWRD.2016.2521320

[9] Pompili M, Scatiggio F. Classification in iso-attention classes of HV transformer fleets. IEEE Transactions on Dielectrics and Electrical Insulation. 2015;22:2676-2683. DOI: 10.1109/TDEI.2015.005252

[10] Wang M, Vandermaar AJ, Srivastava KD. Review of condition assessment of power transformers in service. IEEE Electrical Insulation Magazine. 2002;18(6):12-25. DOI: 10.1109/MEI.2002.1161455

[11] Abu-Elanienand EB, Salama MMA. Asset management techniques for transformers. Electric Power Systems Research. 2010;80(4):456-464. DOI: 10.1016/j.epsr.2009.10.008

[12] Hughes D. Condition based risk management (CBRM)- enabling asset condition information to be central to corporate decision making. CIRED 2005 - 18th International Conference and Exhibition on Electricity Distribution; 6-9 June 2005; Turin, Italy; 2005. DOI: 10.1049/cp:20050884

[13] Singh J, Sood YR, Jarial RK. Condition monitoring of power transformers—Bibliography survey. IEEE Electrical Insulation Magazine. 2008;24(3):11-25. DOI: 10.1109/MEI.2008.4591431

[14] Hughes DT. The use of health indices to determine end of life and estimation remnant life for distribution assets. 17th International Conference on Electricity Distribution; 12-15 May 2003; Barcelona, Spain; 2003.

[15] Hjartarson T, Otal S. Predicting future asset condition based on current health index and maintenance level. ESMO 2006 - 2006 IEEE 11th International Conference on Transmission & Distribution Construction, Operation and Live-Line Maintenance; 15-19 October 2006; Albuquerque; 2006.

[16] Mei D, Min H. A fuzzy information optimization processing technique for monitoring the transformer in neural-network on-line. IEEE International Conference on Dielectric Liquids, ICDL 2005; Coimbra, Portugal; 2005. p. 273-281.

[17] Piercy R, Cress S, Service J, Fan W. An approach to power transformer asset management using health index. IEEE Electrical Insulation Magazine. 2009;25:20-34. DOI: 10.1109/MEI.2009.4802595

[18] BHEL Transformers, 2nd ed. 2003.

[19] http://www.electrical4u.com/dga-or-dissolved-gas-analysis-of-transformer-oil-furfural-or-furfuraldehyde-analysis.

[20] Emsley M, Xiao. X, Heywood RJ, Ali H. Degradation of cellulosic insulation in power transformers. Part 3: Effects of oxygen and water on ageing in oil. IEE Proceedings - Science, Measurement and Technology. 2000;147:115-119. DOI: 10.1049/ip-smt:20000021

[21] Dominelli N. Equipment Health Rating of Power Transformers, Conference Record of the 2004 IEEE International Symposium on Electrical Insulation; 19-22 September 2004; Indianapolis, IN, USA; 2004. p. 163-168.

[22] Arshad M, Islam SM, Khaliq M. Fuzzy logic approach in power transformers management and decision making. IEEE Transactions on Dielectrics and Electrical Insulation. 2014;21:2343 - 2354. DOI: 10.1109/TDEI.2014.003859

[23] Siada A, Hmood S, Islam S. A new fuzzy logic approach for consistent interpretation of dissolved gas-in-oil analysis. IEEE Transactions on Dielectrics and Electrical Insulation. 2013;20:2343-2349. DOI: 10.1109/TDEI.2013.6678888

[24] Tavner P, Ran L, Penman L, Sedding H. Condition Monitoring of Rotating Electrical Machines. The Institution of Engineering and Technology. London, United Kingdom; 2008. DOI: 10.1049/PBPO056E

[25] Hong Lan LT, et al. A new complex fuzzy inference system with fuzzy knowledge graph and extensions in decision making. IEEE Access. 2020;8:164899-164921. DOI: 10.1109/ACCESS.2020.3021097

[26] Kamthan S, Singh H. Hierarchical fuzzy logic for multi-input multi-output systems. IEEE Access. 2020;8:206966-206981. DOI: 10.1109/ACCESS.2020.3037901.

[27] Mei W. Formalization of fuzzy control in possibility theory via rule extraction. IEEE Access. 2019;7:90115-90124. DOI: 10.1109/ACCESS.2019.2928137.