An Intelligent System for Furfural Estimation in the Power Transformers

Md. Manzar Nezami, Hythem Hashem, Md. Danish Equbal, Mohammad Junaid Khan, Md. Fahim Ansari, and Elfatih Elmubarak Mustafa

Abstract Power transformers are supposed to be an expensive and critical component of a power system and so its schedule maintenance is an important aspect near the utilities. The cellulose paper used as the solid insulating material of the transformer deteriorates regularly due to progressive aging. As a result, it produces several degradation by-products of cellulose insulation into the transformer oil. Furfurals are among the major by-product of cellulose and are exploited to estimate the physical state of the transformer's dielectric and the electrical insulation directly and noninvasively. In the present work, an intelligent system is proposed and developed that predicts the level of furfural in the transformer oil. The system makes predictions using easily quantifiable parameters, enabling utilities to avoid suffering financial losses. The proposed system employs the Adaptive Neuro Fuzzy Inference System (ANFIS) technique with temperature and moisture as the input and 2-Furfuraldehyde

Md. M. Nezami (✉)
Department of Electronics and Communication Engineering, GLA University, Mathura 281406, India
e-mail: manzar.nezami@gla.ac.in

H. Hashem · E. E. Mustafa
Department of Computer Science, Faculty of Science and Arts at Belqarn, University of Bisha, 61985, Sabt-Al-Alaya, Saudi Arabia
e-mail: hythemo@ub.edu.sa

E. E. Mustafa
e-mail: eemustafa@ub.edu.sa

Md. D. Equbal
Department of Electrical Engineering, Galgotias College of Engineering and Technology, Greater Noida, India

M. J. Khan
Department of Electrical and Electronics Engineering, Mewat Engineering College (Wakf), Nuh, Haryana, India

Md. F. Ansari
Department of Electrical Engineering, Graphic Era University, Dehradun, India
e-mail: drfahim.ee@geu.ac.in

H. Malik et al. (eds.), *Renewable Power for Sustainable Growth*,
Lecture Notes in Electrical Engineering 1086,
https://doi.org/10.1007/978-981-99-6749-0_20

(2-FAL) as the output. An optimum arrangement of the developed model to find accurate outputs has been achieved by the suitable selection of number and types of the membership functions of the network. Also, an exhaustive study is made to optimize the training data points to achieve the accurate predictions at minimum iterations. The proposed system is validated with nine test conditions of temperature and moisture, and the output thus obtained is verified through existing life models in the literature.

Keywords 2-Furfuraldehyde · Aging · ANFIS · Cellulose · Degradation · Power transformer

1 Introduction

The mineral oil-filled power transformers are considered critical and costly constituent of the power system [1]. The regular power supply is maintained on the cost of transformer's scheduled condition monitoring. Generally, the liquid and solid materials are used to provide the insulation between core and windings. The solid insulation uses the thermally upgraded kraft (TUK) papers made of cellulose. The performance of the transformers is mostly reliant over the condition of insulating cellulosic paper (solid). The transformers undergo successive aging when it confronted to factors like temperature and moisture [2, 3]. These causes hasten aging, create acids and unwanted sludge components that affect the cellulose insulation straight [4]. A continuous negligence in transformer maintenance not only has negative effects on utilities' finances, but also lowers the functionality and dependability of the equipment [5]. For maintenance purposes, a thorough inspection of the transformer provides a better understanding of its condition. Utilities must therefore frequently check on the physical state of the power transformers in order to estimate their valuable lifespan.

The status of the transformer can be readily inferred from how much the insulation made of cellulose paper has decomposed. The cellulose used to manufacture insulating paper is the linear polymer comprised glucose (monomer) units that are linked up all together to form a chain structure [6]. Every polymeric chain's number of glucose units is called the Degree of Polymerization (DP), that is the most reliable parameter to measure the extent of cellulosic insulation decomposition [7]. DP is measured through viscometric technique, and it is an invasive and destructive process of measurement and thereby avoided. The thermal aging of the cellulosic insulation in the company of moisture/water generates few degradation by-products into the transformer oil [8–11]. They most likely include carbon oxides and furfurals. Furfurals have referred to a family of six heterocyclic compound, that includes 2-Furfuraldehyde (2-FAL), 5-Methyl-2-Furfuraldehyde, Furfuryl Alcohol, 2-Furoic Acid, 5-Hydroxymethyl-2-Furfuraldehyde, and 2-Acetyl Furan [12]. The 2-FAL dissipates in transformer oil in large proportion and it is thermally more stable than the other furanic derivatives and thereby considered as the more reliable and prominent aging indicator of the cellulosic insulation [13].

In accordance with the transformer paper insulation's DP value, numerous research studies have been conducted to evaluate the transformer health. But, the DP measurement required intrusion into the transformer to cause a severe outage that will not economical near the utilities. On the other hand, several empirical models have been found in the literature to calculate the value of DP based on the concentration of 2-FA, such as Chendong, Stebbin, De-Pablo, and Pahlavanpour. These models take the 2-FAL concentrations (ppb or ppm) and estimate the value of DP, based on which current physical state of cellulosic insulation is identified. However, numerous soft computing techniques, including support vector machines, wavelet networks, fuzzy logic, neural fuzzy systems, and neural networks, have been documented in the literature to evaluate the health of transformers based on different parameters (especially, DP), and 2-FAL computation has not yet been attempted [14–21]. In this work, an Adaptive Neural Fuzzy Inference System (ANFIS) has been exploited to implement the utility of easily measurable parameters to estimate the molecules (in ppm) of 2-FAL in the transformer insulating oil. The system takes temperature and moisture as the inputs to estimate the value of 2-FAL which ultimately give the DP values and hence the status of the cellulose. The proposed method facilitates the utilities for developing a web-based real-time health assessment system. This not only makes the distribution transformers to complete their designed life but also overcomes the revenue losses for the utilities. The system has also an advantage that it avoids the destructive measurement for the transformer's health assessment and thus the severe outages.

The paper is organized in the chronological order. The first section is the introduction part followed by ANFIS system description in the second section. The proposed methodology and development of the system are detailed thereafter. Finally, the result and discussion and conclusion are included in the last section.

2 ANFIS

The ANFIS employed hybrid input–output mapping technique that utilizes the benefits of neural network's capability for learning within framework of FIS. The ANFIS's generalized structure, which consists of nodes connected by directional links, is represented in Fig. 1. ANFIS structure consists of five layers, each having such nodes that can be either static or adjustable. The output obtained at the adaptive square nodes relies at the parameters that are used to create them, whereas spherical nodes responded as the stationary one and their output is reliant over the outcomes of preceding layers. The one-to-one linkage offers conduit the signal without altering its form [22, 23]. Here, Layer 1 is made up of the four nodes A_1, A_2, B_1, and B_2. These nodes stand for a particular fuzzy set which maps the input toward the output as per that how firmly it bears a resemblance to the define fuzzy sets. The shape of circular nodes in Layer 2 indicates its fixed nature. These circular-shaped nodes provide an output by multiplying the input signals by the product. Nodes that formed Layer 3 conduct the normalizing function for Layer 2's output. Nodes in the Layer 4 are

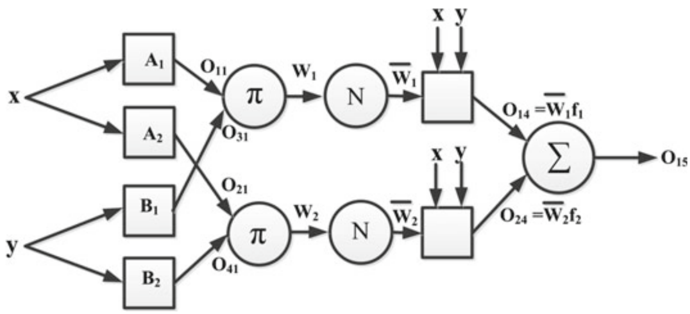

Fig. 1 Generalize five-layered ANFIS structure

of adaptive type, meaning that their output relies on node's ensuing parameter. The results for the layer, therefore, integrate the results of the prior layer. To create the concluding output, the Layer 5 applies the summing function of incoming signals.

3 Proposed Intelligent System for 2-FAL Estimation

The kraft paper is used to provide the insulation inside the transformers and made usually of cellulose ($C_6H_{10}O_5$). The cellulose is polymer of glucose monomers in linear structure which breakdowns under successive aging. Due to overloading condition in the transformers, the temperature rises and distresses the cellulosic insulation [24–27]. The presence of moisture in the transformer accelerates this distress and thereby produces cellulose degradation by-products. The furanic derivatives and carbon oxides are released into transformer oil as the aging (due to decomposition of cellulose) by-products of the cellulosic paper breakdown. Among furanic derivatives, 2-FAL is dissipated in oil in large proportion and thermally stable and thereby predicts the cellulose condition accurately. The ANFIS model proposed here estimates the concentration of 2-FAL as the straight function of moisture and the temperature (ambient). The design of the proposed structure is depicted in the block diagram of Fig. 2.

The proposed ANFIS system takes temperature and moisture as the inputs and estimates 2-FAL as the output. The values of temperature were lying in the range from 90 to 130 °C and moisture (%) varies from 1 to 3%. A dataset which comprises 100 input–output points has been given to the system for the training. To obtain an optimal ANFIS system, different types and number of membership functions have been attempted. Trapezoidal membership function is found to be the best membership function with least error of 0.0024. The model is tested and validated for ten samples comprised different temperature and moisture values.

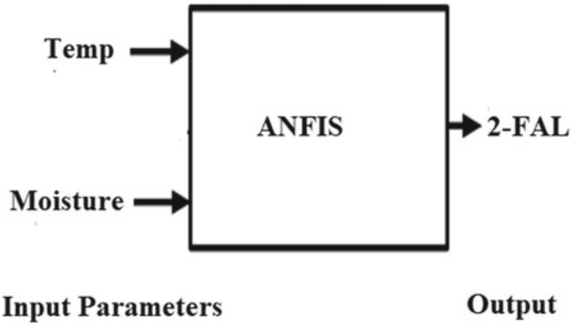

Fig. 2 Schematic of proposed ANFIS-based intelligent system

4 Result and Discussion

The ANFIS structure is designed and implemented using the MATLAB environment to estimate the concentrations of 2-FAL against easily measurable parameters. The optimal ANFIS model has been found using hit-and-trial method, i.e., by varying the type and number of the membership functions. The external experimental data available in literature are then tested using the optimal ANFIS model [11]. Table 1 displays the experimental data points used to evaluate the ANFIS model's performance. Observing Table 1, one can conclude that the rise in temperature directly affects the evolution of 2-Furfuraldehyde in the transformer's insulating oil. However, the increase in the moisture accelerated the 2-FAL generation more rapidly. As a result, the proposed ANFIS model was found to be more accurate for the detection of transformers' cellulose degradation product more appropriately.

Table 1 Estimated output of the developed ANFIS system as the function of temperature and moisture

Input		Output
temperature (°C)	Moisture (%)	2-Furfuraldehyde (2-FAL) ppm
90	1	0.11
90	2	0.32
90	3	1.99
110	1	2.50
110	2	2.93
110	3	2.92
130	1	2.44
130	2	2.95
130	3	2.84

5 Conclusion

The paper successfully implemented the ANFIS model for 2-Furfuraldehyde (2-FAL) estimation. The model employs the parameters like temperature and moisture to measure the 2-FAL. The parameters used to develop the system are easily measurable and thereby make the system more economical for the utilities. The ANFIS structure easily correlates the input and the output by appropriately tuning the membership function. The system has been tested and validated with the available data in the literature and found to estimate more precise and accurate outcomes. As a result, the ANFIS model offers us a productive substitute for measuring the values of DP with the help of diagnostic parameters while restricting the intrusive measurements approach.

References

1. Wu S, Zhang H, Wang Y, Luo Y, He J, Yu X, Zhang Y, Liu J, Shaug F (2022) Concentration prediction of polymer insulation aging indicator—alcohols in oil based on genetic algorithm—optimized support vector machines. Polymers 4:1449
2. Yoo J, Kang S, Lee J et al (2023) Electrical characteristics of high-performance ultrasonic transducer for non-destructive testing. Trans Electr Electron Mater. https://doi.org/10.1007/s42341-023-00432-0
3. Fan X, Liu J, Lai B, Zhang Y, Zhang C (2021) FDS measurement-based moisture estimation model for transformer oil-paper insulation including the aging effect. IEEE Trans Instrum Meas 70:1–10
4. Pradhan MK (2006) Assessment of the status of insulation during thermal stress accelerated experiments on transformer prototypes. IEEE Trans Dielectr Electr Insul 13:227–237
5. Kherif O, Benmahamed Y, Teguar M, Boubakeur A, Ghoneim SSM (2021) Accuracy improvement of power transformer faults diagnostic using KNN classifier with decision tree principle. IEEE Access 9:81693–81701 (2021)
6. Kachler AJ, Hohlein I (2015) Aging of cellulose at transformer service temperatures. Part 1: influence of type of oil and air on the degree of polymerization of pressboard, dissolved gases, and furanic compounds in oil. IEEE Elect. Insul Mag 21:15–21 (2015)
7. Saha TK, Darveniza M, Yao ZT, Hill DJT, Yeung G (1999) Investigating the effects of oxidation and thermal degradation on electrical and chemical properties of power transformers insulation. IEEE Trans Power Del 14:1359–1367
8. Feng DW, Yang LJ, Liao RJ, Zhou LW, Lin YD (2018) Effect of moisture content on the production and partitioning of furfural in oil-paper insulation. IEEE Trans Dielectr Electr Insul 25:2389–2397
9. Unsworth J, Mitchell F (1990) Degradation of electrical insulating paper monitored with high performance liquid chromatography. IEEE Trans Electr Insul 25:737–746
10. Ali M, Emsley AM, Herman H, Heywood RJ (2001) Spectroscopic studies of the ageing of cellulosic paper. Polymer 42:2893–2900
11. Mandlik M, Ramu TS (2014) Moisture aided degradation of oil impregnated paper insulation in power transformers. IEEE Trans Dielectr Electr Insul 1:21
12. Nezami MM, Wani SA, Khan SA, Khera N, Sohail S (2018) An MIP-based novel capacitive sensor to detect 2-FAL concentration in transformer oil. IEEE Sens J 18(19):7924–7931
13. Nezami MM, Wani SA, Khan SA, Khera N, Sohail S (2020) A comb type capacitive 2-FAL sensor for transformer oil with improved sensitivity. IEEE Trans Instr Meas 69(7):4524–4532

14. Ghunem RA, Assaleh K, El-hag AH (2012) Artificial neural networks with stepwise regression for predicting transformer oil furan content. IEEE Trans Dielectr Electr Insul 19:414–420
15. Nezami MM, Equbal MD, Khan SA, Sohail S, Ghoneim SSM (2021) Classification of cellulosic insulation state based on smart life prediction approach (SLPA). Processes 9:981
16. Chaturvedi D, Satsangi PS, Kalra PK (1999) Flexible neural network models for electrical machine. J. Inst Engg 80:53–58
17. Abu-Elanien AEB, Salama MMA, Ibrahim M (2012) Calculation of a health index for oil-immersed transformers rated under 69 kV using fuzzy logic. IEEE Trans Power Deliv 27:2029–2036
18. Talpur N, Abdulkadir SJ, Alhussian H et al (2023) Deep neuro-fuzzy system application trends, challenges, and future perspectives: a systematic survey. Artif Intell Rev 56:865–913
19. Nezami MM, Equbal MD, Khan SA, Sohail S (2021) An ANFIS based comprehensive correlation between diagnostic and destructive parameters of transformer's paper insulation. Arab J Sci Eng 46:1541–1547
20. Nezami MM, Wani SA, Khan SA, Khera N, Khan MA (2017) Fuzzy approach for residual life assessment of paper insulation. In: 3rd International conference on condition assessment techniques in electrical systems (CATCON), pp 26–30, Ropar, India (2017)
21. Goyal D, Choudhary A, Sandhu JK, Srivastava P, Saxena KK (2022) An intelligent self-adaptive bearing fault diagnosis approach based on improved local mean decomposition. Int J Interact Des Manuf. https://doi.org/10.1007/s12008-022-01001-0
22. Khan SA, Equbal MD, Islam T (2015) A comprehensive comparative study of DGA based transformer fault diagnosis using fuzzy logic and ANFIS models. IEEE Trans Dielectr Electr Insul 22(1):590–596
23. Forouhari S, Abu-Siada A (2018) Application of adaptive neuro fuzzy inference system to support power transformer life estimation and asset management decision. IEEE Trans Dielectr Electr Insul 25(3):845–852
24. Ahmad MW et al (eds) (2022) Intelligent data analytics for power and energy systems. Springer, Singapore, p 22, 641, ISBN: 978-981-16-6081-8. https://doi.org/10.1007/978-981-16-6081-8
25. Tomar A et al (eds) (2022) Proceedings of 3rd international conference on machine learning, advances in computing, renewable energy and communication: MARC 2021, vol 915. ISBN: 978-981-19-2830-7. Springer, pp 15, 781. https://doi.org/10.1007/978-981-19-2828-4
26. Heywood RJ, Emsley A, Ali M (2000) Degradation of cellulosic insulation in power transformers. Part 1: factors affecting the measurement of the average viscometric degree of polymerization of new and aged electrical papers. IEE Proc Sci Meas Technol 147(2):86–90 (2000)
27. Mian T, Choudhary A, Fatima S (2022) Vibration and infrared thermography based multiple fault diagnosis of bearing using deep learning. Nondestr Test Eval. https://doi.org/10.1080/10589759.2022.2118747