Reliability Improvement of Transformers by Dissolved Gas Analysis and Machine Learning: A Review of Literature

Pankaj Chawla[1], Vineet Dahiya[2]

[1]Research Scholar, School of Engineering and Technology, K R Mangalam University, Sohna Road, Gurugram, Haryana, India
Email: *pankajerda[at]yahoo.in*

[2]Associate Professor, School of Engineering and Technology, K R Mangalam University, Sohna Road, Gurugram, Haryana, India

Abstract: ***Reliability of Power Transformers not only affects the supply of energy but also affects the utility due to loss of economic operation. This review paper provides a current state of the reliability of transformers using dissolved gas analysis and machine learning. This paper presents the historical review of the literature, advancements in the field by using the machine learning algorithms, data analytics and their improvement in maintain the reliability of power supply by power transformers. The paper also highlights the benefits and limitations of different approaches used by conventional approaches to rule based systems to machine learning algorithms. The aim of review of this literature is to have valuable insights in to the reliable operation of transformers to ensure the reliable supply of electrical supply and a power industry as a whole.***

Keywords: Reliability, Power Transformer, Dissolved Gas Analysis (DGA), Machine learning, incipient faults

1. Introduction

Reliable operation of Power Transformers plays a critical role in the power transmission and distribution. Any malfunction in the operation of power transformer can lead to serious power outages and damage to power transformers. In conventional approaches, the reliable operation of power transformers is ensured by visual examination, electrical testing and other manual testing methods specified by different specifications and standards which may be costly and time consuming and not always effective in detection of incipient faults in the Power Transformers for reliable operation. Dissolved Gas Analysis is widely used for the detection of incipient faults in the Power Transformers. DGA results interpretation is complex and should be done with care. Power transformers are major power system equipment. Their reliability not only affects the electric energy availability of the supplied area, but also affects the economical operation of a utility. For example, the fault of a distribution transformer may leave thousands of homes without heat and light, and the fault of a step-up transformer in a power generation plant may cause the shutdown of the attached generation unit. Under the deregulation policy of electric systems, each utility is trying to cut its cost, and the prevention of accidental loss is much more important than before. The capital loss of an accidental power transformer outage is often counted in million dollars for output loss only, not to say the costs associated with equipment repair or replacement [Myers98]. Because of this economic incentive, preventive tests and on-line monitoring are of benefit to predict incipient fault conditions, and to schedule outage, maintenance and retirement of the transformers. The major concern of power transformer incipient faults is that they may decrease the electrical and mechanical integrity of the insulation system. This may progress to a point that the insulation cannot withstand transient overstresses caused by through-fault current (mechanical forces on windings) and electrical over voltages (temporary, switching or lightning). Incipient fault diagnosis is therefore closely related to insulation condition assessment.

2. Insulation Condition Assessment

Insulation condition assessment test refers mainly to off-line routine tests, including measurement of insulation resistance (IR), dielectric loss factor (DLF), interfacial polarization (IP) using anomalous IR and frequency dispersion of capacitance, turns ratio (TR), winding resistance (WR), core ground resistance (CGR), and some excitation tests [C57.125, Darv 3]. These tests are applied to the whole transformer and thus are bulk measurements of the insulation condition. They can reveal some severe problems but may not find the incipient ones. Other tests examine paper or pressboard samples taken from transformers (and which must be replaced if the transformer is to be returned to service). These tests include measurement of the 2 degree of polymerization (DP) and tensile strength (TS). Some relatively new methods, such as high performance liquid chromatography (HPLC) furan analysis, interfacial polarization spectra (IPS) using return voltage (RV) measurement, and analytical chemical techniques [Darv97], are also used for the same purpose. These intrusive techniques are usually not favorable because the sampling process may damage the integrity of the insulation system, but may be necessary for very old transformers. The most favorable tests for power transformer insulation assessment are on-line types, including partial discharge (PD) monitoring and dissolved gas-in-oil analysis (DGA) [Chu 4]. These online tests are also the major incipient fault diagnosis methods.

3. Dissolved gas-in-oil analysis (DGA)

A more successful technique for on-line incipient fault diagnosis is dissolved gas-in-oil analysis (DGA). By “on-line” we mean the transformer does not need to be de-energized. This type of analysis includes the conventional

DGA, which is based on routine oil sampling, and the modern technology of on-line gas monitors. Conventional DGA has been in practice for about thirty years, and has gained tremendous success compared to other techniques [Kemp95]. The main reason for this success is that the sampling and analyzing procedures are simple and inexpensive, and easy to be standardized. Many experiences have been gained from the process and several DGA standards have been set up [IEC599, IEC599r, C57.104]. Major diagnostic gases have been identified as hydrogen (H2), ethane (CH4), methane (C2H6), ethylene (C2H4), acetylene (C2H2), carbon monoxide (CO) and carbon dioxide (CO2). An important problem with conventional DGA methods, however, is over reliance on experts. Since transformers of different size, structure, manufacturer, loading and maintenance history may have different gassing characteristic, they need to be considered differently in most cases. DGA is thus often referred to as “art” instead of “science” [Ding 5, Zhang 6]. On-line gas-in-oil monitors appeared soon after the introduction of the DGA technology [Lyke7]. Several research prototypes and commercial products were introduced later. Some of the monitors concentrated on hydrogen (H2) only [Gold 8, McDe 9, Bel 10, Inoue 11], while others are of multi-gas type [Tsu 12, Lind 13, Ger 14, Glodjo 15, Liao 16, Birlase 17]. An advantage of these on-line monitors is the continuous measurement of one or more gases, so that any gassing trend, which is critical information for incipient fault screening, can be easily obtained. Problems with these monitors are related to selectivity and durability of the gas molecule screening membrane, field calibration, measurement range and resolution. Selectivity refers to the membrane allowing certain kinds of gases to pass but preventing the rests. Poor selectivity lowers measurement accuracy. Membranes with poor durability deteriorate faster, especially under field conditions where temperatures vary greatly between summer and winter, or even between day and night. Since the inputs of the monitors are non-electrical quantities, while the readout device of the monitors contains electronic circuits that are subject to offset and characteristic shift due to factors like temperature and humidity, field calibration of the device could be a big problem. Generally, the measurement range and resolution of on-line monitors are far behind that of laboratory tests. With the new generation of monitors being developed, the gap is becoming narrower. For all these reasons, on-line monitors are usually used as screening tool to identify possible abnormal units. Detailed fault diagnosis is then left to conventional DGA. Networking capability and diagnostic intelligence are also important requirements for on-line monitors. The former has been incorporated in some approaches [Glodjo98]. The latter is not yet available, probably because no machine intelligence is yet good enough to replace the work of a human expert, and it is too risky to implement an immature technology. Combining the use of DGA and acoustic methods often leads to successful diagnosis and location of PD type fault [Hayes 18, Austin 19, Berent 20]. The procedure is to identify the PD fault first using DGA, and then find the location of PD using acoustic method.

4. Review of Literature

Balint Nemeth [21] describes realistic method for power transformer using readily available data. The method considers practical limitation in obtaining data and possible constraint on the parameter utilize IEC, IEEE criteria. The calculation considers test result along with other parameter like tap changer, bushing condition, load history, maintenance work order, age. The calculation includes rating by using Fuzzy logic. They have shown how a fuzzy based approach of DGA can be applied for a certain problem.

D. R. Morais and J. G. Rolim [22] developed and implement a tool for detection of fault in power transformer using fuzzy logic. The computational approach is based on combined use of some traditional methods, artificial neural network and fuzzy logic system. The result shows that, the result obtained by hybrid system reaches higher degree of reliability with respect to each technique individually. For evaluating the tool presented in a previous data of DGA was obtained from different transformers. The performance was satisfactory and more than 80 % cases identified correctly.

Hongzhong Ma, Zheng Li, P Ju [23] proposed a fuzzy based three ratio method. Among the conventional ratio method, IEC three ratio methods are widely used to detect incipient fault in transformer. It is considered that IEC three ratio method shows drawback when ratio crosses the coding boundary, but in reality boundary should be fuzzed. On this assumption they suggested the fuzzy based three ratio method. The result shows that these proposed methods overcome the drawback of conventional three ratio method. It enhances the diagnosing accuracy in case of multi fault. The result shows that accuracy of conventional three ratio method is 65 % and that of proposed fuzzy three ratio method is 90 %.

Hong Tzer, Chiung [24] enhances the fault diagnosis abilities for DGA by proposing a novel adaptive fuzzy system for the recognition of incipient fault. They have suggested a fuzzy reasoning a logarithm to establish fuzzy based diagnosis system. In the evolutionary optimization a logarithm is developed to fine tune membership function and if then rules to enhance the accuracy of diagnosis method, the system is compact by filtering out insignificant or redundant rule. The method is verified by analyzing data collected from Taiwan Power Company.

Jitka Fuhr [25] explained that the reliability of all H V apparatus is strongly depend upon the ability of insulating system to withstand electrical stress without damage during lifetime. By using dissolved gas analysis, the detection of incipient fault is done by specialist. DGA is general method to detect the location of fault on additional advanced methods must be used to identify and localized the source of fault gases dissolved in oil. They have shown that it is possible to identify and localize the reason for alarm by application of conventional and advanced methods. Defect caused by electric stresses are detected by advanced PD measuring system. Defect caused by thermal stress are detectable by polarization effect.

K Tomsovic, M. Tapper, J. T. Ingvar son [26] shown that various methods used for fault detection in transformer require some experience to correctly interpret fault. Researcher have applied Artificial intelligence concept only to a single technique and have failed to manage the inherent uncertainty in various method. They have suggested theoretic fuzzy information model. A framework is established that allow various diagnostic method to be combined in systematic way. For encoding of the proposed system the programming style should allow simple modification and easy implementation. Traditional programming has some drawback therefore they have strongly suggested object oriented programming (OOP) techniques. The rule and fault are stored in database. This allows simple modification to the knowledge base.

Er. Lee Wai Meng [27] discusses a procedure for monitoring the functioning the mineral oil of used in transformer. When mineral oil is subjected to high electrical and thermal stress it decomposes and generated gases. Different type of fault produced different types of gases and chemical analysis of these gases through DGA (dissolved gas analysis) help to identify type of fault in transformer. The causes of gas generation are breaking of chemical bonds between atoms and hydrocarbon modules are formed. The fault in transformer produces energy that breaks chemical bonds. When mineral oil contains normal values gas no incipient fault in transformer. DGA method is a chemical rather than an electrical method. It is powerful tool in preventive maintenance of transformer.

M. Duval, J Dukarm [28] explained how the reliability of transformer improved is by using gas-in-oil analysis. There is some degree of inaccuracy in DGA at low gas concentrations. Proper allowance for this inaccuracy improves transformer condition assessment. The paper shows how proper for this inaccuracy can improve transformer condition assessment by DGA. Simple statistical calculations improve the accuracy of diagnosis by associating correction factor (CF) with each diagnosis.

M. Wang [29] published that life of transformer can be as long as 60 years with appropriate maintenance. When transformer is new it has sufficient electrical and mechanical strength to withstand stresses. To prevent failure preventive maintenance is carried out by using traditional diagnostic techniques for detection of incipient fault in transformer. The most widely tests are oil test and power factor test.

Michel Duval [30] has review of fault detectable by gas in oil analysis in transformers. He reviews the DGA results in a more user friendly graphical form. The specific case of on load tap changers is reviewed much more extensively and separately. Particular attention is given to DGA related to PD and low temperature thermal faults. One hundred and more cases of faults in transformer service, identified by visual inspection have been examined. Application of DGA to load tap changer has examined.

Michel Duval [31] shows that dissolved gas analysis is very efficient tool monitor in service behavior to avoid outage and losses of production. The main gases formed as a result of electrical and thermal fault in transformer ax H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO and CO_2, whose relative concentration depends upon fault. The IEC- IEEE ratio method is most widely used to detect fault. He suggested developing expert system.

N. A. Muhamad and S.A.M. Ali [32] use lab view with fuzzy logic controlled and built a simulation system to diagnose fault in transformer. The front panel of the system is designed using lab view. Fuzzy logic was used as expert system that process all information keyed at front panel and predict condition of transformer. The output of fuzzy logic displayed at front panel of lab view. Fuzzy logic was used as expert system to predict types of fault for dry type and oil immersed transformer. In this project to monitor dry type of transformer current and voltage analysis method was used. The system has advantage that the designed program is user friendly.

Q. Sui [36] has developed fuzzy logic tool for transformer fault diagnosis. Various fault occur in transformer are diagnosed by dissolved gas analysis (DGA). When there are more than one fault conventional IEC /IEEE ratio code method cannot determine fault in many cases. This paper proposed a fuzzy logic tool to diagnosis multiple faults in power transformer. When there is multiple fault fuzzy logic give accurate diagnosis. By using fuzzy logic method there is an improvement over conventional IEC ratio method.

Q. Su [33] presents a fuzzy logic technique which can diagnose multiple faults in a transformer and indicate severing of fault. A new method has developed to employ fuzzy boundaries between different IEC codes. The FIK method developed successfully used for the diagnosis of transformers. It has been found that larger is the fuzzy component, the more dominant and severe the fault.

R. Naresh, V. Sharma, M, Vashith [34] have developed an integrated neural fuzzy approach for detection of fault in transformer using DGA. They have proposed a method which translate problem of higher dimension into lower dimensions by using Neural Fuzzy model. Rule base for identification of fault is designed by subtractive clustering method. As compare to traditional fuzzy and neural fuzzy method, integrated fuzzy approach method has superior performance.

R.R. Rogers [35] has developed ratio technique to interpret fault in power transformer by Dissolved Gas Analysis (DGA). This method proved beneficial for smaller utility, without the need for extended statistical and laboratory investigation, to apply the technique to reduce the overall costs for maintaining power transformers in service.

R. Samsudin, A. Qisti Ramli [36] demonstrate that life of transformer depends upon condition of paper insulation. Degradation of paper is due to electrical fault. Electrical fault in transformer by DGA. But DGA alone is not able to detect the fault therefore acoustic partial Discharge technique is additionally used. They proved that DGA analysis method was unable to detect OLTC oil contamination in main Tank. The analysis of DGA depends on design of main Tank.

Sukhabir Singh, M.N. Bandyopadhyay [37] have done bibliographic survey over the last 40 on research and development and on procedure of evaluating fault in power transformer by Dissolved Gas Analysis (DGA). They have permissible concentration of gases in oil with operations time of a Healthy Transformer.

Sayed M. Islam, Muhammad Arshad [38] have developed a novel fuzzy based technique for estimation of remaining life of transformer. Most of transformer are operating beyond their expected life. Therefore, reliability on transformer cannot be assured. The forced outage of transformer has serious impact on blackout, revenues. The prediction of remaining life of transformer help to take decision on replacement or relocation of asset. Tapan Kumar Saha [39] addresses the issue of DGA interpretation with very limited data. He has proposed a maintenance decision making procedure using IEC 60599-2007 and Duval's Triangle scheme. He has also highlighted limitation and future possible development.

V. Duraisamy, N. Devarajan [40] have developed Neuro fuzzy scheme for fault detection in power transformer. IEC/IEEE ratio method and gas concentration values for the fuzzy diagnosis Neural network system. The fuzzy system is analyzed with different membership function. The neural network is trained to classify transformer fault. The result of both methods is compared.

M. Hui Wang [41] has developed a novel extension method for fault diagnosis of paper transformer based on the matter–element model and extended relation functions. Because of this the incipient fault in power transformer can be directly identified by degree of relation.

Wilfedo C. Flores, Enrique Mombello [42] have developed expert system for insulation condition assessment based on type -2 Fuzzy system by using Duval's Triangle and gas Ratio the condition of transformer assessed by DGA. Second step based on survey. The results are fed to first Type-2 Fuzzy Logic System based on only DGA result. The output of this first -2 FLS is as input to second T2-FLS to assess condition of paper-oil System. The output of second T2-FLS is given in terms of words understandable by maintenance person.

Y.C. Huang, H T Yang, C L Huang [43] have proposed evolutionary programming based (EP) fuzzy system to identify incipient fault in power transformer. Using IEC DGA criteria first fuzzy based framework is built. Then proposed FP based system employed to automatically modify the fuzzy If –then rules and membership functions. As compare to conventional methods and ANN methods this method has shown superior performance to find out fault cases. Proposed method has tested on previous diagnosis record.

Z. Qian and Z. Yan [44] proposed fuzzy synthetic method for life assessment of power transformer. Fuzzy theory is applied to assess the degree of ageing and whether it is normal or abnormal. Then a synthetic evaluation model is developed to identify ageing condition step by step. The simulation result shows that this model is effective for evaluating condition of insulation whether is normal or abnormal and helps to predict remnant life of power transformer.

5. Conclusion

Reliable operation of Power Transformers plays a critical role in the power transmission and distribution. Any malfunction in the operation of power transformer can lead to serious power outages and damage to power transformers. In conventional approaches, the reliable operation of power transformers is ensured by visual examination, electrical testing and other manual testing methods specified by different specifications and standards which may be costly and time consuming and not always effective in detection of incipient faults in the Power Transformers for reliable operation. Dissolved Gas Analysis is widely used for the detection of incipient faults in the Power Transformers. DGA results interpretation is complex and should be done with care.

Power transformer plays a very important role in power system, its long-term operation will cause various kinds of faults. Accurate identification and timely elimination of transformer faults are the basis of safe operation of power grid. As one of the most commonly used fault diagnosis methods, dissolved gas analysis (DGA) technology is used to identify fault types through dissolved gas in transformer oil, and its reliability has been proved. In order to analyze these gases and diagnose transformer fault types with the results, many methods have been developed, such as Key Gas Method, Method of Duval, IEC 60599 Method, Method of Dornenburg and Method of Rogers, etc.

In some cases, the accuracy of these traditional methods is reduced and cannot be applied for diagnosis, since they have fixed input features and is not flexible for input combination. In order to achieve the propose of solving this defect, the study will be carried out on network-based DGA method to diagnose the faults and states of power transformers with customized input features. The future work will include the development of a knowledge-based fault detection inference engine, the identification of a multi-layer perceptron (MLP) modular neural network for fault diagnosis, procedures for combining the outputs of knowledge-based and neural network-based diagnosis, and fuzzy logic methods and other machine learning tools for transformer condition assessment and maintenance recommendations.

References

[1] C. Myers, "Transformers –Condition monitoring by Oil Analysis, Large or Small; Contentment or Catastrophe", Proceedings of the 1998 1st IEE/IMeChE International Conference on Power Station Maintenance – Profitability through Reliability", pp.53-58.
[2] [C57.125] IEEE PES Transformers Committee, "IEEE Guide for Failure Investigation, Documentation, and Analysis for Power Transformers and Shunt Reactors", IEEE Standards Board, C57.125-1991
[3] [Darv, M. Darveniza, T.K. Saha, D.J.T. Hill, T.T. Le, "Investigation into Effective Methods for Assessing the Condition of Insulation in Aged Power Transformers", IEEE PES WM 1997, PE-343-PWRD0-11-1997
[4] [Chu99] Donald Chu, Andre Lux, "On-Line Monitoring of Power Transformers and Components: A Review of Key Parameters", IEEE Electrical Insulation Conference & Electrical Manufacturers and Coil Winding Exposition, Cincinnati, Ohio, Oct 25, 1999.
[5] Ding, X. Ding, E. Yao, Y. Liu, P. J. Griffin, "ANN Based Transformer Fault Diagnosis Using Gas-in-oil

Analysis", Proceedings of the 57th American Power Conference, April 1995, Chicago IL.

[6] Zhang Yuwen Zhang, An Artificial Neural Network Approach to Transformer Fault Diagnosis, Thesis of Virginia Tech, 1996

[7] Lyke, A.J. Lyke, A.P. Vitols, "Automated Monitoring of Dissolved Gas-in-oil for Large Power Transformers", Minutes of Fourty-Fourth International Conference of Doble Clients, 1977, Section 10-601

[8] Gold, T.W. Goldsborough, J.F. Millward, "On-Line Hydrogen-in-oil Monitoring", Minutes of Fiftieth International Conference of Doble Clients, 1983, Section 6-601

[9] McDe W. McDermid, J.F. Millward, "On-Line Hydrogen-in-oil Monitoring (A Progress Report)", Minutes of Fifty-Second International Conference of Doble Clients, 1985, Section 6-701

[10] Bel, G. Belanger, "Field Testing of HYDRAN® 101 and 201 for Dissolved Hydrogen in Transformer Oil", Minutes of Fifty-Second International Conference of Doble Clients, 1985, Section 6-801

[11] Inoue, Y. Inoue, K. Suganuma, M. Kamba, M. Kikkawa, "Development of Oil-Dissolved Hydrogen Gas Detector for Diagnosis of Transformers", IEEE Trans., Vol.PD-5, No.1, Jan 1995, pp.226-232

[12] Tsu, H. Tsukioka, K. Sugawara, "New Apparatus for Detecting Transformer Faults", IEEE Trans., Vol.EI-21, No.2, Apr 1986, pp.221-229

[13] Lind, S.R. "Transformer Fault Gas Analyzer – Update", Minutes of Sixty-Second International Conference of Doble Clients, 1995, Section 5-3.1

[14] Ger, P. Gervais, J. Aubin, "On-Line Monitoring of Key Fault Gases in Power Transformers and Shunt Reactors", Minutes of Sixty-Second International Conference of Doble Clients, 1995, Section 5-2.1

[15] Glodjo, A. Glodjo, "A Field Experience with Multi-Gas On-Line Monitors", Minutes of Sixty-Fifth International Conference of Doble Clients, 1998, Section 8-12.1

[16] Liao 16, R. Liao, C. Sun, W. Chen, C. Wang, "On-Line Detection of Gases Dissolved in Transformer Oil and the Fault Diagnosis", Proceedings of 1998 International Symposium on Electrical Insulating Materials, in conjunction with 1998 Asian International Conference on Dielectrics and Electrical Insulation, Toyohashi, Japan, Sept 27-30, 1998, pp.771-774

[17] Birlase S. Birlasekaran, G. Ledwich, "Use of FFT and ANN Techniques in Monitoring of Transformer Fault Gases", Proceedings of 1998 International Symposium on Electrical Insulating Materials, in conjunction with 1998 Asian International Conference on Dielectrics and Electrical Insulation, Toyohashi, Japan, Sept 27-30, 1998, pp.75-78

[18] Hayes, T.W. Hayes, "Investigation to Determine the Location of a Low-Energy, Audible Electrical Arcing in a Power Transformer", Minutes of Fifty-Third International Conference of Doble Clients, 1986, Section 6-301.

[19] Austin, P.L. Austin, "Use of DGA and Acoustic Devices to Detect and Locate Faults in a 588 MVA Generator Step-Up Transformer", Minutes of Fifty-Ninth International Conference of Doble Clients, 1992, Section 1-18.1

[20] Berent, D. Berent, "Acoustic Monitoring and Gas-in-oil Analysis for Transformers", Minutes of Sixty Second International Conference of Doble Clients, 1995, Section 8-3.1

[21] Balint Nemeth, Szilvia Laboncz, Istvan kiss, "Condition Monitoring of Power Transformers using DGA and Fuzzy Logic", Electrical Insulation Conference, 2009, EIC 2009 IEEE

[22] D. R. Morais and J. G. Rolim, "A hybrid tool for detection of incipient faults in transformers based on the dissolved gas analysis of insulating oil," IEEE Transactions on Power Delivery, vol. 21, no. 2, pp. 673–680, 2006.

[23] Hongzhong Ma, Zheng Li, P. Ju, Jingdong Han, and Limin Zhang, Diagnosis of Power Transformer Faults Based on Fuzzy Three-Ratio Method, in The 7th International Power Engineering Conference, IPEC 2005, Nov 2005.

[24] H.-T. Yang, C.-C. Liao, and J.-H. Chou, ''Fuzzy learning vector quantization networks for power transformer condition assessment,'' IEEE Trans. Dielectr. Electr. Insul., vol. 8, no. 1, pp. 143–149, Mar. 2001, doi: 10.1109/94.910437.

[25] Fuhr, Jitka. (2011). Condition based maintenance for power transformers in service: Application of conventional and advanced diagnostic methods. 271-275. 10.1109/ EIC. 2011.5996160.

[26] K. Tomsovic, M. Tapper, T. Ingvarson," A Fuzzy information approach to integrating different transformer diagnostic methods", IEEE Transactions on Power Delivery, vol. 8, no. 3, pp. 1638-1646, July 1993.

[27] Er. Lee Wai Meng, "Dissolved Gas Analysis (DGA) of Mineral Oil used in Transformers" The Singapore Engineer, May 2009, pp 1-4, 2009.

[28] Duval, Michael and James J. Dukarm. "Improving the reliability of transformer gas-in-oil diagnosis." *IEEE Electrical Insulation Magazine* 21 (2005): 21-27.

[29] M. Wang and K. D. Srivastava, "Review of condition assessment of power transformers in service," IEEE Electr. Insul. Mag., vol. 18, no. 6, pp. 12–25 Nov./Dec. 2002.

[30] M. Duval, "A review of faults detectable by gas-in-oil analysis in transformers," IEEE Insulation Magazine, vol. 18, no. 3, pp. 8–17, May/ Jun. 2002

[31] M. Duval and A. de Pablo, "Interpretation of gas-in-oil analysis using new IEC publication 60599 and IEC TC 10 databases", IEEE Electr. Insul. Mag., Vol. 17, pp. 31-41, 2001

[32] N. A. Muhamad and S. A. M. Ali, "Lab view with Fuzzy Logic Controller Simulation Panel for Condition Monitoring of Oil and Dry Type Transformer," Int. J. Electr. Comput. Energy, Electron. Commun. Eng., vol. 2, no. 8, pp. 1685– 1691, 2008.

[33] Su, Qi. "A fuzzy logic tool for transformer fault diagnosis." Power Con 2000. 2000 International Conference on Power System Technology. Proceedings (Cat. No.00EX409) 1 (2000): 265-268 vol.1.

[34] R. Naresh, V. Sharma, M, Vashith "An Integrated Neural Fuzzy Approach for fault diagnosis of Power Transformers", IEEE Transactions on Power Delivery, vol. 24, no. 4, Oct. 2008.

[35] Rogers RR. IEEE and IEC codes to interpret incipient faults in transformers, using gas in oil analysis. IEEE Electr. Insul. Mag. 1978(5):349- 54.
[36] Samsudin, Mohd & Ramli, Ahmad & Berhanuddin, A. & Yang Ghazali, Young. (2010). Incipient fault detection in 33/11kV power transformers by using combined Dissolved Gas Analysis technique and acoustic partial discharge measurement and validated through un tanking. 1 - 6.
[37] S. Sukhbir and M.N. Bandyopadhyay, “Dissolved gas analysis technique for incipient fault diagnosis in power transformers: a bibliographic survey,” IEEE Electrical Insulation Magazine, vol. 26, no. 6, pp. 41-46, 2010.
[38] Naeem, Muhammad & Hashmi, Khurram & Kashif, Syed Abdul Rahman & Khan, Muhammad & Alghaythi, Mamdouh & Flah, Aymen & Ali, Samia & Aboras, Kareem & Ben Dhaou, Imed. (2022). A novel method for life estimation of power transformers using fuzzy logic systems: An intelligent predictive maintenance approach. Frontiers in Energy Research. 10. 977665. 10.3389/fenrg.2022.977665.
[39] Dehghani Ashkezari, Atefeh & Saha, Tapan & Ekanayake, C. & Ma, Hui. (2011). Evaluating the accuracy of different DGA techniques for improving the transformer oil quality interpretation. 1-6. Universities Power Engineering Conference (AUPEC), 2011.
[40] V. Duraisamy, N. Devarajan, D. Somasundareswari, A. A. M. Vasanth and S. N. Sivanandam, “Neuro Fuzzy Schemes for Fault Detection in Power Transformer,” Applied Soft Computing, Vol. 7, No. 2, 2007, pp. 534-539. doi: 10.1016/j.asoc.2006.10.001
[41] Wang, Meng-Hui. (2002). A Novel Extension Method for Transformer Fault Diagnosis. Power Engineering Review, IEEE. 22. 63 - 64. 10.1109/MPER.2002.4312484.
[42] Flores, Wilfredo & Mombello, Enrique & Jardini, J.A. & Rattá, Giuseppe & Corvo, Antonio. (2011). Expert system for the assessment of power transformer insulation condition based on type-2 fuzzy logic systems. Expert Systems with Applications. 38. 8119-8127. 10.1016 /j. eswa. 2010.12.153.
[43] Y.C. Huang, H T Yang, C L Huang, “Fault Diagnosis of Power Transformers Using Computational Intelligence: A Review,” 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of the organizing committee of 2nd International Conference on Advances in Energy Engineering (ICAEE).
[44] Qian, Z., Yan, Z.: ‘Fuzzy synthetic method for life assessment of power transformer’, IEE Proc. Sci. Meas. Technol., 2004, 151, (3), pp. 175– 180.

Author Profile

Er. Pankaj Chawla received his B. Tech degree in Electrical Engineering from Kurukshetra University and ME degree in Power Systems from PEC Chandigarh. His areas of interest include Power System Studies, Energy Management and Auditing. He is Certified Energy Auditor of BEE, Govt. of India. He has more than 25 years of teaching, laboratory and industry experience.

Dr. Vineet Dahiya has completed his M. Tech (Power System & Drives) from YMCAIE Faridabad in 2009. Completed his PhD from Manav Rachna University in 2020 and presently working as Associate Professor in K R Mangalam University. His areas of research include solar energy, renewable energy resources, power system stability.