The Journal of CPRI,
Vol. 9, No. 3, September. 2013 pp. 381–392

Review of Power Transformer Mechanical Condition Assessment Techniques

Shubhangi Patil*, B E Kushare**

Today's trend of global electricity market has created a competitive environment in power industry. To reduce operational cost, optimize usage of critical equipments, to improve reliability and customer service, fast and enhanced diagnostic techniques are being developed and utilized in power industry. In recent years, transformer fault diagnosis has become an interesting research area.This paper presents the literature review done in the area of power transformer designs, failure causes and effects and on existing and new diagnostic techniques to generate the baseline for the development of mechanical condition assessment system. The survey has included the 90technical reports and papers from CIGRE, IEEE transactions and conferences along with standards and books based on power transformer conditioning and monitoring. In this paper an attempt has been made to analyze, generate real data based approach for development of enhanced and automated diagnostic system for mechanical faults detection.

Keywords: *Artificial intelligence, neural networks,neuro-fuzzy, equivalent circuit modeling, estimation approach, power transformer modeling, SFRA, automated interpretation algorithm.*

1.0 INTRODUCTION

Power transformers are major and critical power system equipment. Under the deregulation policy of electric systems, due to the challenging and competitive energy market, utilities always tend to operate the transformers harder, longer, and closer to their capabilities in order to reduce cost to generate the most amount of profit and to prevent accidental loss. Transformers are more likely to fail under stress condition besides regular aging, insulation deteriorating processes and due to fault events. Being most expensive equipment in substation, preventingtransformer mechanical failures has become critical. In earlier years, most maintenance of largesubstation transformers was done based on a pre-determined schedule, inspection intervals with its earlier state and relevant performance history. This leads in few cases to catastrophic failures of improperly diagnosed transformers and the over inspection of healthytransformers.

Due to the involved cost of scheduled and unscheduled maintenance, especially at remote sites, the utility industries are interested in investing in instrumentation and monitoring of substation equipment [1-3]. Therefore, utilities are interested in an economical and reliable mechanical fault detection system to help with maintenance and extending the life of their existing assets. Because of such economic incentive, preventive testsenhanceddiagnostic tests and analysis, expert systems and algorithms are proved as benefit to predict incipient fault conditions, to schedule outage, maintenance and life of the transformers [4], [82].

About 30% to 40% of transformer failures in recent years are caused by internal core-winding faults [1], [5]. There are two types of internal winding faults: internal short circuit faults and internal incipient faults. Internal faults should be detected as early as possible to prevent further catastrophic failure. Conventional diagnostic

*Crompton Greaves Limited, Kanjur Marg, Mumbai - 400 042. India. E-mail : patilshubhangi30@gmail.com
**K. K. Wagh College of Engineering Education & Research, Nasik, Maharashtra - 422 003. India. E-mail : be_kushare@rediffmail.com

techniques like magnetizing current measurement, measurement of short circuit impedance (SC), capacitance of winding and dissolved gas analysis (DGA) are able to detect the major faults inside the transformer. Also, sweep frequency response analysis (SFRA) is a well known and proven technique for mechanical condition assessment. In many situations, the other tests give just an indication of fault but the proper identification of internal faults and gradual growth of fault is still a thrust area in transformer failure analysis. SFRA technique can give and provide information about the state of transformer health and warning of developed internal fault and criticality of fault [6-8]. In the interpretation and SFRA analysis process, best of system knowledge with transformer historical data and human expertise are required to reach to final solution. But there can be the possibility of variation in opinions or in criticality of fault by the different human experts. Thus, transformer effective diagnostic system on same interpretation schemes basis has become essential.The application of artificial intelligence techniques (AI) can be the better solution to address. AI techniques are already widely used for development of various expert systems [9-14]. AI applied to SFRA analysis can be the leading step towards the automatic mechanical fault detection of power transformers. This system will be based on data collection and direct substation onsite data.

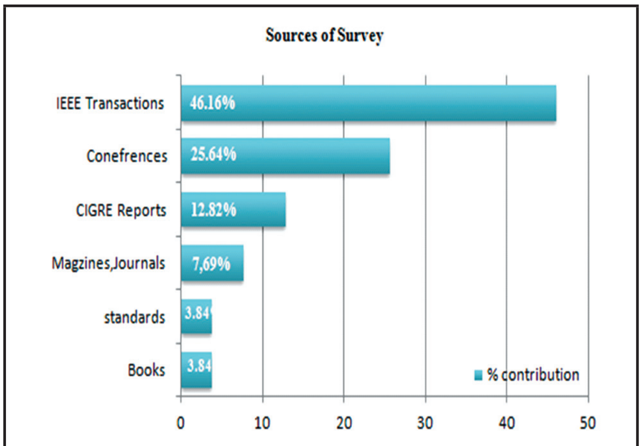

FIG. 1 SOURCES OF LITERATURE SURVEY

In this paper various conventional techniques, new inventions towards internal fault detection methods and applicability of AI techniques like artificial neural network (ANN), Fuzzy logic (FL), hybrid systems neuro-fuzzy, Adaptive resonance theory (ART) to transformer mechanical fault diagnosis are presented. Their usability and characteristics are discussed in detail. The referred technical publications are from IEEE transactions, magazines, proceedings, conferences and standards (Figure 1).

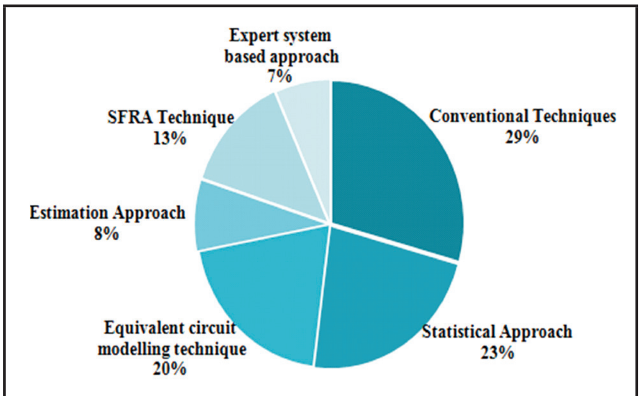

FIG. 2 VARIOUSTRANSFORMER DIAGNOSTIC TECHNIQUES

2.0 CONVENTIONAL TECHNIQUES

With the insufficient short-circuit strength of transformer windings results in mechanical deformations which is one of the main causes to put the transformers out of service. There are also some faults, which are critical but cannot easily detectable like tap related faults. The techniques are improved in recent times to ensure the transformers short circuitwithstand capability, but problems still arise, particularly with older units. Another important factor with older transformers is that significant winding shrinkage can occur with age, leading to a reduction in clamping pressure and short circuits withstand strength. Transformer lowers its short circuit withstand capability after facing every event [4], [8], [77]. Mostly used conventional techniques which are employed by utilities and researchers for detection of such faults are [15]:

A. Short-circuit impedance (leakage reactance)

B. Magnetizing (exciting currents) currents

C. Windingcapacitances

2.1 Leakage field and short circuit impedance

Short-circuit impedance or leakage reactance measurements are probably the most widely accepted method of detecting winding movement. The windings deformations can affect the leakage flux path, which in turn may result in the change of the measured leakage reactance. The authors have discussed the different types of winding arrangements and short circuit measurement parameters with different operating voltages [16], [17]. Further analysis for tap changer related faults resulting in changed volts per turn is demonstrated in paper [16]. 2-D FEM analysis as an effective tool for leakage flux and short circuit impedance evaluation is presented in papers [18-22]. 3D modelingfor various types of transformers has been discussed in [23-27]. At site, impedances are measured with low voltage supplies. There may be the variation in respective three phase results which creates difficulty to detect the exact fault. In case, individual per phase measurements are made to facilitate the detection of faults on comparison basis [28]. Sort circuit impedance extracts as relation:

$$U_R \equiv \sqrt{(U_R^{\ 2} + U_x^{\ 2})} \qquad \text{....(1)}$$

Where, $U_K = (P_K / S) \times 100$ ....(2)

$$Ux = 0.2976 \times \left[(s \times Cx \times Dx) / (V / X) 2 \times Hm 2 x Nb \right] \times Kr (f / 60) \qquad \text{....(3)}$$

Where,

P_K: Load loss (kW); S: Apparent power. And,

N_b: Number of limbs having winding S: Nominal apparent power (kVA)

KR: Rogowsky Coefficient

$$C_x = C_2 + (BOW_1 + BOW_2)/3, \qquad \text{....(4)}$$

$$D_x = DC_2 + (BOW_2 - BOW_1)/3, \qquad \text{....(5)}$$

H_m=H_w: for disc windings and H_w: Height of winding

The technique suffers the disadvantage of difficulty with very small changes about 1% in detection of faults.

2.2 Magnetizing (exciting) current

Exciting current creates a magnetic flux in the core, and the flux in turn induces a voltage in the energized winding that opposes the applied voltage. Consequently, the exciting current is small, usually only a few percent of the rated load current of the winding. The single-phase exciting-current test is useful in detecting the defects in the magnetic core structure, failures in the turn-to-turn insulation, or problems in the tap-changer. These conditions result in a change of the effective reluctance of the magnetic circuit, which consequently affects the current required to force a given flux through the core. Magnetizing current test is not sensitive to winding deformation. Also the results can vary due to residual magnetism. [29-32].

2.3 Winding capacitance

Being the composite insulation system in transformer, dielectric measurements help to indicate the partial conductance of system between two electrodes. It allows detecting gross winding movement faults. The technique is very effective in cases when it is possible to make separate measurements for each phase, when phase by-phase comparisons of results greatly improve the chances of identifying any anomaly, particularly for inter-winding capacitances which should be very similar for each phase [33].

However, in practice the sensitivity of the technique depends on the type of fault involved, and there may be difficulties in interpreting measured values if reference results are not available. Also, in case of autotransformers which are the major population of power transformer in system, the technique is of limited use because it is not possible to measure any main inter-winding capacitances at all.

3.0 RECENT DIAGNOSTIC TECHNIQUES

The various faults of transformer core and winding have been studied analytically and experimentally in literatures. Researchers have done study on applicability and response of techniques like equivalent circuit modeling, estimation approach, statistical approach and special technique like SFRA towards various faults. However, in general various other comparative techniques useful for mechanical fault detection are considered and detailed in further literature review work.

3.1 Methods based on mathematical and statistical approach

Methods based on correlation coefficient (CO), standard deviation (SD) are few new methods have been studied and lies with these methods are in the area of minor fault presented their use for fault diagnosis [34-40]. TF method as a comparative technique is also studied in detail. Disadvantage detection and limitation to transformer core faults detection [41]. Literatures also presented the work considered with design parameters to evaluate fault level [42-50]. But the method has limitation to detect type and location of fault.

3.2 Methods based on Electric Circuit Models

Few researchers have studied the method based on TF measured and described in form of equivalent circuit models [51-53].

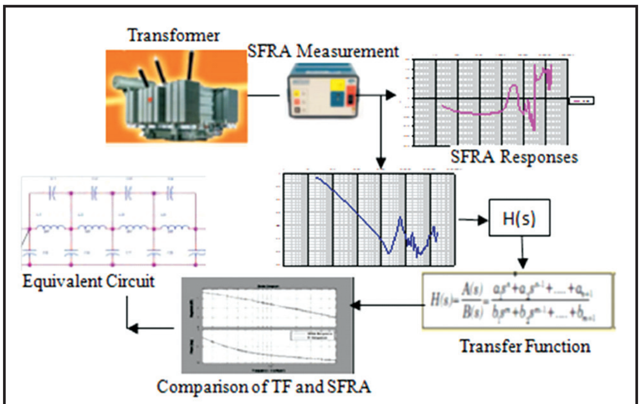

FIG. 3 TRANSFORMER EQUIVALENT CIRCUIT MODELING METHOD [52]

Parameters estimated in model of TF are based on design parameters. Thus, the dependency on design variations, used tolerances can have errors and variations in model parameter approximation. Being larger and complex equations, network parameters needs to be approximate in cases and this can be difficult to detect the exact fault [54-63], [66].

Hybrid model based on travelling wave and multi conductor transmission line (MTL) theories has been studied in detail by researchers. The study is for disc winding type only and can detect the transformer winding deformation faults only [64].

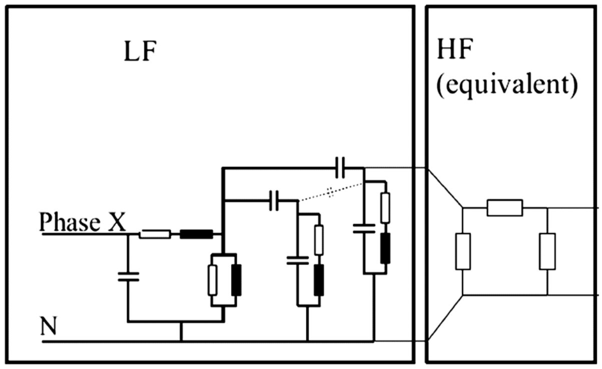

FIG. 4 HYBRID MODEL FOR TRANSFORMER [64]

3.3 Methods Based on Estimation approach

FRSL technique is useful for detection of winding deformation. The unique technique is based on the concept of stray losses measurements. The losses are represented in resistance curves with certain range of frequency. The authors have discussed the better accuracy over impedance measurement system and the method is helpful to detect the axial displacement of winding. The measurement of stray losses has led to the detection of a short-circuit between parallel strands in a winding. It also allows the verification of the quality of the transposition on a winding made up of several parallel strands.

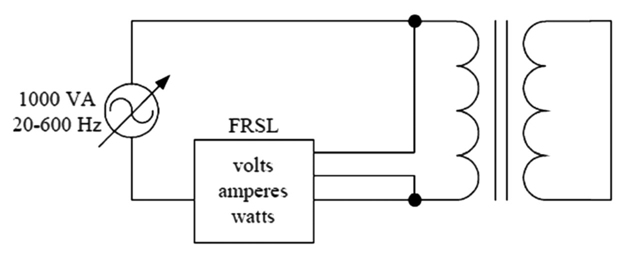

FIG. 5 TEST CIRCUIT FOR FRSL MEASUREMENT [66]

The FRSL diagnosis is based on comparison of curves. The comparison can be established with a similar transformer or with a previous test performed on the same transformer and results can be interpreted based on a comparison between the three phases of the transformer. The method has advantage of capability to sense the disappearance of insulation parts which is not possible with impedance measurement. The paper has work done for fault detection by stray loss measurements. But the stray losses are non uniform throughout the transformer area. It is dependent on tank size and availability. Thus the repeatability of such method is an issue for better and faster fault detection process [65].

Vibration analysis combined with frequency response has been studied in detail [66]. It is a new method for fault detection. But the factors influencing the vibrations inside the transformer are varying and this makes the limited application of method towards the winding failures. Factor average absolute deviation (AAD) is proposed to detect the deviation and fault [56].

$$AAD = \frac{\sum_{fs}^{fe}\left[\frac{abs(A_1(f)-A_0(f))}{\max(A_0(f),A_1(f))}\right]}{N}\times 100\% \quad ....(6)$$

With the severe damage inside, the method is most effective and useful.

3.4 Sweep Frequency Response Analysis (SFRA)

SFRA is the powerful, non-destructive and well proven mechanical condition assessment technique [68-69]. It is the only sensitive technique to mechanical condition of transformer. The SFRA measurement provides diagnostic information, in the form of a transfer function, related to the RLC network of specimen under test. The RLC network is integrally related to the physical geometry and construction of the test specimen. Physical changes within the test specimen alter the RLC network, and in turn can alter the transfer function. The transfer function behavior can reveal a wide range of mechanical or electrical changes in the test specimen. Different transformer failure modes can have different effects on the network admittances, mayalter the transfer function. However, because of thesensitivity of the test, a primary benefit of FRA is the potential for detection of defects in the mechanical or electrical integrity of the transformer that are not apparent with other electrical tests [70-76], [81]. SFRA technique is basically a comparison based approach and any significant difference in low, high frequency region, shift of existing resonance, creation of new resonance, and change in shape of plot would potentially indicate internal damage with the winding and core of Transformer [6], [72], [82]. However, the ability to interpret such ‘differences’ when comparing the SFRA responses is of a great challenge for detection of minor and growing internal faults and then expertise to further analysis of the plot for classification of fault is very limited today for the users who are not very familiar with SFRA and need experts for the conclusions and findings. For better and reliable performance of transformer, it is desirable to check the mechanical integrity at regular time intervals or periodically during their service life to provide the early warning of growing faults.

The application of electrical tests and other comparative methods to fault diagnosis have sensitivity towards few or a particular fault type. The conventional techniques suffer from disadvantages of less sensitivity and lack of reference results for comparison. The non-linearity of transformers makes it exceedingly difficult to create analytic models that provide a high level of accuracy. In addition, the many subsystems (thermal, mechanical, electrical, fluid) present in a transformer make the system modeling very complex. It is not feasible to determine the physical principles that inter-relate the subsystems and accurately formulate a model system. The key advantage of SFRA over all these above techniques are proven sensitivity towards core and winding faults and flexibility of failure analysis in phases comparison basis in case of lack of reference results. For this reason, various artificial intelligence techniques have become more popular for transformer diagnostics. Hence, there is a need for the expert system based tools to standardize the test method, to characterize the various responses patterns with respective fault and to assist in the analysis of SFRA results. Knowledge based interpretation analysis along with artificial intelligence approach for SFRA signatures can play important role in development of exact and effective fault detection system. Currently, the utilities are using the SFRA technique on criticality basis with the need of human experts. An attempt has made to use the proposed system with utilized automated described expertise for SFRA analysis.

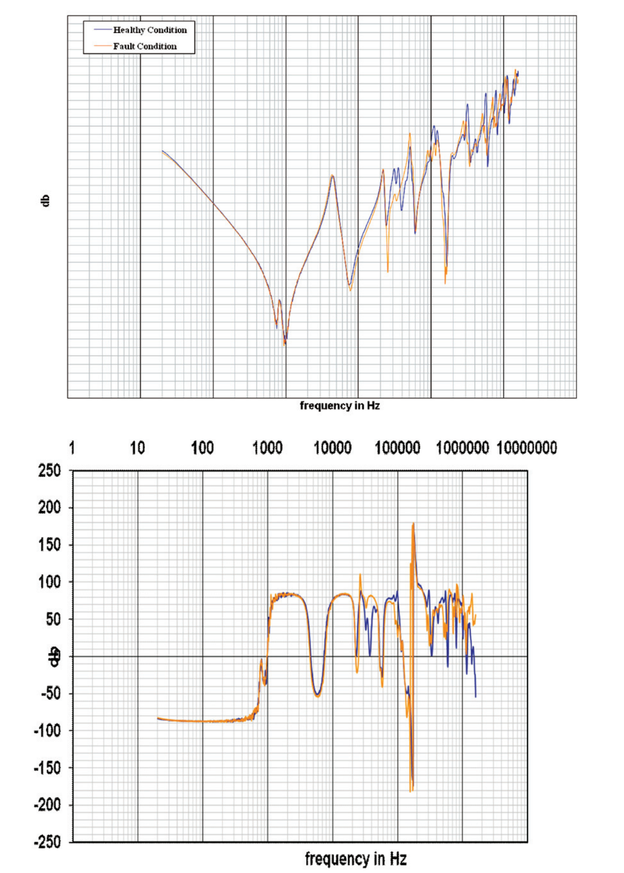

FIG.6 SFRA RESPONSES CONSIDERED FOR ANN BASED SYSTEM FOR SFRA ANALYSIS

The case study considered for the methodology is of 315 MVA, 420 kV three phase transformer. The SFRA responses are shown in Figure 6. The transformer was diagnosed with winding fault and this fault condition is considered for ANN based SFRA analysis. The system results have shown good correlation with actual findings.

3.5 Proposed System Methodology

The knowledge required for the fault detection system varies greatly with the type of technique used. The modeling techniques above require significant knowledge about the system. To make successful and accurate such systems, there must be information available about the inner workings of the transformer system. Application of artificial intelligence is based on black box modeling approach. It does not require knowledge of the inner workings of the system. The artificial intelligence trains itself to the system and provides diagnostic information based on a set of inputs and outputs [77-79]. In this case, the artificial intelligence is solely be used or a hybrid of knowledge-based and artificial intelligence techniques also can be used [80]. The most common forms of artificial intelligence used for transformer diagnosis are neural networks and fuzzy logic. Due to the complexity of the numerous phenomena, it is difficult to formulate a precise relationship relating the different contributing factors.

One of the weaknesses of the artificial neural network approach is the tendency to find only a local minimum in its training due to improper initial value. In this case, the algorithm based method is used to optimize the initial value and thus increased the accuracy of the neural network training. ANN model based on adaptive nature algorithms can be the future step for online monitoring system development.

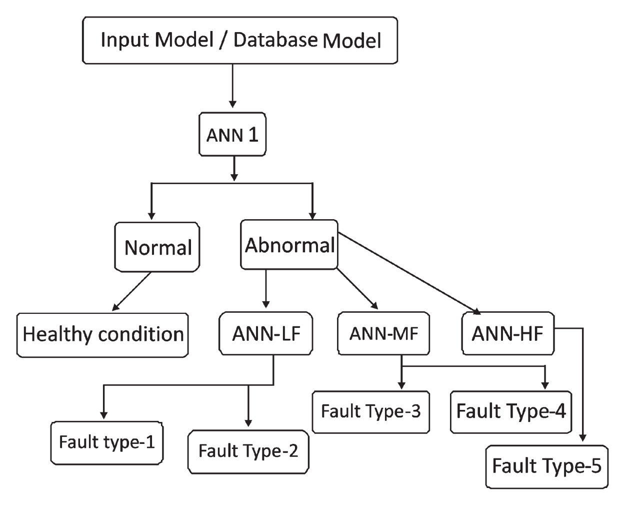

FIG.7 PROPOSED AUTOMATED SFRA DIAGNOSTIC SYSTEM BASED ON ANN

ANN models developed for SFRA responses are based on three steps, creation and initialization of network, Training of network and computation of results. The ANN models are developed using MATLAB command given below:'

$$Net = newff\,(PR,[S_1,S_2.....S_{nl}][TF_1,TF_2,......TF_{nl}]BTF) \quad (7)$$

Where, PR is the values for S1, S2 layer sizes and TF are the activation functions. The detailed proposed methodology is shown in Figure 7.

4.0 CONCLUSION

The methods and techniques suggested by researchers focus on mainly for mechanical fault detection. SFRA technique is the most sensitive technique for mechanical faults. Considering the factors like human experts need, variation in opinion between experts, proposed technique of an automated expert system can be the better option for transformer core and winding related faults detection. In expert system, proper suitable algorithm selection is possible for different faults diagnosis. In order to evaluate and validate the proposed method, number of samples with various winding structures and design variables along with different depending electrical test parameters are examined. Future work includes the improvement of model accuracy and extending this approach to

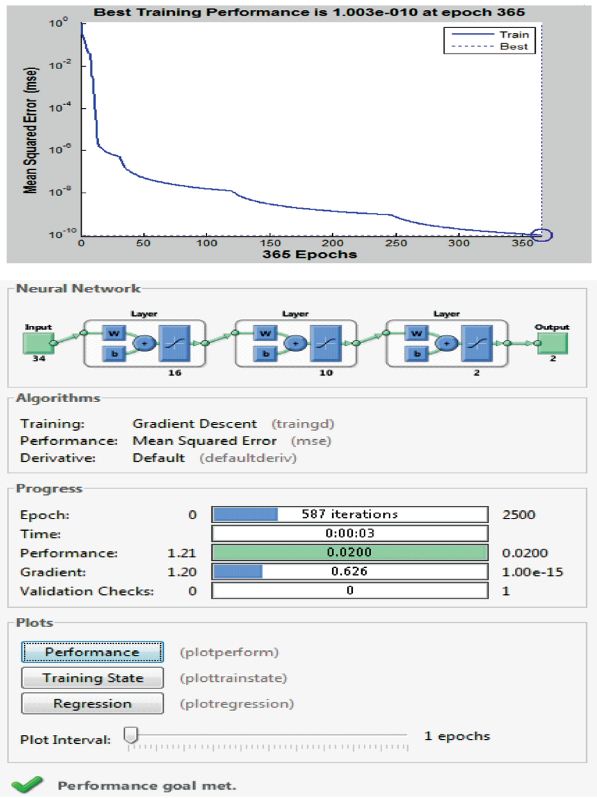

FIG.8 RESULTS OF ANN FAULT DETECTOR SYSTEM

cover the full range of interest. The combination of an expert system with neuro-fuzzy techniques and an integration of an artificial neural network with an expert system can be effective futuristic approach for power transformer diagnosis.

5.0 REFERENCES

[1] CIGRE, C. Bengtsson, "Status and trends in transformer monitoring", IEEE transactions on power delivery, Vol 11, no. 3, july 1996

[2] CIGRE A2-209,"Condition assessment of medium power transformer using diagnostic methods", 2008

[3] CIGRE WG A2.18, "Life management of power transformers" June 2003

[4] CIGRE WG 209, 2002, "The short circuit performance of power transformers".

[5] CIGRE: H. Borsi, S. Suindarmann, "Enhanced Diagnosis of Power Transformers using On- and Off-line Methods:Results, Examples and Future Trends", 2000

[6] CIGRE 2009, Kreatege Kruger, Viljeen Dierks, " FRA Sensitivity for Fault Detection", 2008

[7] J. Lapworth, Doble, "Transformer Condition Assessment by SFRA" 2003

[8] CIGRE WG A2.26 (342),"Mechanical Conditrion Assessment of Transformer Windings using Frequency Response Analysis", 2008

[9] Ronaldo R. B. de Aquino, R.R.B.; Lira, M.M.S.; Filgueiras, T.; Ferreira, H.; Neto, O.N.; Silva, A.M.S.; Asfora, V.K, "A fuzzy system for detection of incipient fault in power transformers based on gas-in-oil analysis", IEEE International Conference on Fuzzy systems, 2010

[10] Msiza, I.S.; Szewczyk, M.; Halinka, A.; Pretorius, J.C.; Sowa, P.; Marwala, T, "Neural networks on transformer fault detection evaluating the relevance of the input space parameters", IEEE Power Systems Conference and Exposition (PSCE), 2011.

[11] Rahmat Allah Hooshmand, Moein Parastegari and Zohreh Forghani, "Adaptive Neuro-Fuzzy Inference System Approach for Simultaneous Diagnosis of the Type and Location of Faults in Power Transformers", IEEE – DEIS Electrical Insulation Magazine, 2012

[12] Geo, Ning, "Diagnosis of DGA based on fuzzy and ANN method", IEEE conference of Electrical insulating materials, Beiging, China, 1998.

[13] Yanming Tu, Zein, Qian, "DGA based insulation diagnosis of power transformer via ANN", 6th International conference on properties and applications of dielectric materials, 2000

[14] A. Akbari, A. Setayeshmehr, H. Borsi, I. Fofana and E. Gockenbach," Intelligent Agent-Based System Using Dissolved Gas Analysis to Detect Incipient Fault in Power Transformers", IEEE DEIS Insulation Magzine, Vo. 26, no. 6 Nov-Dec. 2010

[15] Aradhana ray, "Application of signal processing techniques to condition monitoring of electrical equipment", Sept. 2009

[16] J. A. Ebert, "Application considerations for variable volts per turn power transformers," IEEE Trans. Power Del., vol. 9, no. 1, pp.240–248, Jan. 1994.

[17] Mehdi Bagheri, Mohammad Naderi, Tone Phung, "FRA vs. Short Circuit Impedance Measurement in Detection of Mechanical Defects within Large Power Transformer", IEEE, 2012

[18] X. Cui and G. Zhang, "Automatic design of impedance in shell-form power transformer," IEEE Trans. Magn., vol. 36, no. 4, pp. 1822–1825, Jul. 2000.

[19] A. Lindblom, J. Isberg, and H. Bernhoff, "Calculating the coupling factor in a multilayer coaxial transformer with air core," IEEE Trans Magn., vol. 40, no. 5, pp. 3244–3248, Sep. 2004.

[20] L. Xiaosong, W. Suping, Z. Yusheng, H. Gui, and L. Guzong, "Influence of high temperature superconducting transformer geometry on leakage magnetic field," IEEE Trans. Magn., vol. 44, no. 4, pp. 492–496, Apr. 2008.

[21] V.Behjat, A. Vahedi, "Numerical modeling of transformers interturn faults and characterizing the faulty transformer behavior under various faults and operating conditions", IET Electrical Power Application, pp 415-431, April 2011

[22] Yu-Sheng Quan, Jiang Shan, "Research on deformation of transformer windings based on the analysis of short circuit reactance", IEEE national basic research program, 2011

[23] A. G. Kladas, M. P. Papadopoulos, and J. A. Tegopoulos, "Leakage flux and force calculation on power transformer windings under shortcircuit: 2D and 3D models based on the theory of images and the finite element method compared to measurements," IEEE Trans. Magn., vol. 30, no. 5, pt. 2, pp. 3487–3490, Sep. 1994.

[24] L. Xiaosong, W. Suping, Z. Yusheng, H. Gui, and L. Guzong, “Influence of high temperature superconducting transformer geometry on leakage magnetic field,” IEEE Trans. Magn., vol. 44, no. 4, pp. 492–496, Apr. 2008.

[25] M. Djurovic and C. J. Carpenter, “3-dimensional computation of transformer leakage fields and associated losses,” IEEE Trans. Magn., vol. 11, no. 5, pp. 1535–1537, Sep. 1975.

[26] K. Zakrewski and M. Kukaniszyn, “Three-dimensional model of oneand three-phase transformer for leakage field calculation,” IEEE Trans. Magn., vol. 28, no. 2, pp. 1344–1347, Mar. 1992.

[27] M. A. Tsili, A. G. Kladas, P. S. Georgilakis, A. T. Souflaris, and D. G. Paparigas, “Advanced design methodology for single and dual voltage wound core power transformers based on a particular finite element model,” Electric Power Syst. Res., vol. 76, pp. 729–741, 2006.

[28] O. Biro, “Computation of the flux linkage of windings from magnetic scalar potential finite element solutions,” Proc.Inst. Elect. Eng., Sci.Meas. Tech., vol. 149, no. 5, pp. 182–185, Sep. 2002.

[29] J. Rosenlind, H. Tavakoli and P. Hilber,” Frequency Response Analysis (FRA) in the Service of Reliability Analysis of Power Transformers”, CIGRE conference CMDM-151, 2011

[30] Masashi Kitayama, Miyuki Nakabayashi, “A New approach for inrush current discrimination based on transformer magnetizing characteristics”, PSCC, Session 42, Sevilla, June 2002

[31] Doble Engineering, “Transformer excitation current principles and diagnostics”, Section 7, DTT-PT2-2009

[32] Alberto Avalos Gonzalez, Jaime Cerda Jacobo, Servando Sanchez Ruíz, “Incipient fault detection in power transformers by frequency response analysis”, WCEC, Proceedings of the World Congress on Engineering and Computer Science Vol II, October 2012, San Francisco, USA

[33] Vazquez, D. C., Lopez, E. O., and Albores, R. M. Insulation Power Factor Measurement Options in Oil-Filled Power Transformers, Proceedings of the Annual International Conference of Doble Clients, 1995

[34] K. Jong-Wook, P. ByungKoo, J. Seung, K. S. Woo, and P. PooGyeon, “Fault diagnosis of a power transformer using an improved frequency-response analysis,” IEEE Trans. Power Delivery, vol. 20, no.1, pp. 169–178, 2005.

[35] S. A. Ryder, “Transformer diagnosis using frequency response analysis: results from fault simulations,” in Proc. IEEE Conf. Power Engineering Society Summer Meeting, July 2002, pp. 399–404.

[36] S. A. Ryder, “Diagnosing transformer faults using frequency response analysis,” IEEE Electrical Insulation Magazine, vol. 19, no.2, pp. 16- 22, 2003.

[37] P. M. Nirgude, D. Ashokraju, A. D. Rajkumar, and B. P. Singh, “Application of numerical evaluation techniques for interpreting frequency response measurements in power transformers,” IET Sci. Meas. Technology, vol. 2, no.2, pp. 275–285, 2008.

[38] P. M. Joshi, S. V. Kulkarni,”Transformer winding diagnosis using deformation coefficient”, IEEE conference, 2008

[39] Huang, Sy-RuenR. Feng. Chia., Univ.,Taichung,Taiwan Chen, Hong-ai; Wu, Chueh-Cheng, Guan, Chau-Yu, Cheng, Chiang, “Distinguishing Internal Winding Faults From Inrush Currents in Power Transformers Using Jiles-Atherton Model Parameters Based on Correlation Coefficient”, IEEE Transactions on Power Delivery,April2012);Vol:27, Issue: 2

[40] Kennedy G. M., McGrail A. J., Lapworth John, “Using cross correlation coefficients to analyze transformer sweep frequency response traces”, IEEE power engineering

society conference and exposition in Africa, 2007

[41] J. R. Secue, and E. Mombello, “Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers,” Electric Power Systems Research, vol. 78, no.6, pp. 1119-1128, 2008.

[42] J. Gui, W. Gao, K. Tan, and S. Gao, “Deformation analysis of transformer winding by structure parameter,” in Proc. Int. Conf. Properties and Applications of Dielectric Materials, paper no. P2-47, 2003.

[43] P. Karimifard, and G. B. Gharehpetian, “A new algorithm for localization of radial deformation and determination of deformation extent in transformer windings,” Electric Power Systems Research, vol. 78, no.10, pp. 1701-1711, 2008.

[44] R. Wimmer, S. Tenbohlen, M. Heindl, A. Kraetge, M. Krüger, and J. Christian, “Development of algorithms to assess the FRA,” in Proc. Int

[45] Symp. High Voltage Engineering, paper no. T7-523, 2007.

[46] E. Rahimpour, and D. Gorzin, “A new method for comparing the transfer function of transformers in order to detect the location and amount of winding faults,” Electrical Engineering, vol. 88, no.5, pp. 411-416, 2005.

[47] Ebrahim Rahimpour, Mehdi Jabbari, “Mathematical comparison methods to assess the transfer functions of transformers to detect different types of mechanical faults”, IEEE Trans. Power delivery, Vol. 25, No. 4, October 2010.

[48] M. Wang, A. J. Vandermaar, and K. D. Srivastara, “Evaluation of frequency response analysis data,” in Proc. Int. Symp. High Voltage Engineering, 2001, pp 904–907.

[49] Badgujar, K.P.; M.; Kulkarni, S.V, ”Alternative statistical techniques for aiding SFRA diagnostics in transformers”, Generation, Transmission & Distribution, IET 2012

[50] S. Ab Ghani, Md Thayoob, Y.Z. Yang Ghazali, and I. Sutan Chairul, “Evaluation of transformer core and winding conditions from SFRA measurement results using statistical techniques for distribution transformers”PEOCO, IEEE International 2012

[51] S. K. Sahoo, and L. Satish, “Discriminating changes introduced in the model for the winding of a transformer based on measurements,” Electric Power Systems Research, vol. 77, no.7, pp. 851-858, 2007

[52] Shubhangi Patil, A. Venkatasami, H. A. Mangalwadekar,”Realization ofTransformer Winding Network from Sweep Frequency Response DataIEEE International conference of condition monitoring and diagnosis, Beijing, China 2008

[53] Shubhangi patil, Anbarasan. N, A. Venkatasami,”Equivalent circuit modeling technique for SFRA analysis of power transformer”, Trafotech 2010.

[54] Steven D. Mitchell, and James S. Welsh,” Modeling Power Transformers to Support the Interpretation of Frequency-Response Analysis”, IEEE Transactions On Power Delivery, Vol. 26, No. 4, October 2011

[55] Ebrahim Rahimpour, Jochen Cristian, Hossein Mohseni, “Transfer function method for axial and redail deformation of transformer windings”, IEEE transactions on Power delivery, Vol. 18, No. 2, April 2003

[56] Ebrahim Rahimpour,Mehdi Jabbari, and Stefan Tenbohlen, “Mathematical Comparison Methods to Assess Transfer Functions of Transformers to Detect Different Types of Mechanical Faults”, IEEE Transactions On Power Delivery, Vol. 25, No. 4, October2010.

[57] K. G. Nilanga B. Abeywickrama, Yuriy V. Serdyuk and StanislawM. Gubanski, “Exploring Possibilities for characterization of Power Transformer Insulation by Frequency Response Analysis (FRA)”, IEEE Transactions On Power Delivery, Vol. 21, No. 3, July 2006

[58] Zongdong Wang, Jie Li, D. Sofian, ”Interpretation of Transformer FRA Responses Part I: Influence of Winding Structure”, IEEE Trans. Power delivery, Vol. 24, No. 2, April 2009.

[59] Zongdong Wang, Jie Li, D. Sofian, “Interpretation of Transformer FRA Responses Part I: Influence of Winding Structure”, IEEE Trans. Power delivery, Vol. 25, No. 4, October 2010.

[60] K. Ragavan, and L. Satish, “Localization of changes in a model winding based on terminal measurements: experimental study,” IEEE Trans. Power Delivery, vol. 22, no.3, pp. 1557-1565, 2007.

[61] CIGRE, F. Devax, J. Prins, Z. D. Wang, A. W. Darwin, ”Experience with HF modeling for electrical transients and its application to FRA modeling”, 2008

[62] H.Akcay, S.M.Islam and B.Ninness, “Identification of Power Transformer Models from Frequency Response Data”, IEEE Transactions on Instrumentation and Measurement, vol-48, No.3 pp 700-704, June 1999

[63] Moosa M.Al, Asma Ml “RLC Realization of Transfer Function”, Electrical Engg. dept. Kuwait University IEEE publications, 2003.

[64] T. Y. Ji. W. H. Tang, Q. H. Wu, “Frequency response analysis of power transformer winding deformation based on hybrid model”, IEEE transactions, Aug 2011

[65] CIGRE, R. J. Demer, L. Bolduc,”Detection of transformer winding displacement using FRSL”, 2000.

[66] CIGRE K. Feser, J. Christian, Sundarmann, “The transfer function method for detection of winding displacements on power transformers after transport, short circuit of 30 years of service”.2000.

[67] Belén García , Juan Carlos B. and Ángel Matías A.,” Transformer Tank Vibration Modeling as a Method of Detecting Winding Deformations — Part I: Experimental Verification,” IEEE Transactions On Power Delivery, Vol. 21, No. 1, January 2006

[68] Tony McGrail, “SFRA Basic concepts”, Doble 2003

[69] Andrey A. R. and Valery D.,” Case Studies of Factors Influencing Frequency Response Analysis Measurements and Power Transformer Diagnostics”, IEEE Electrical Insulation Magazine, 2011

[70] Ramesh Yadav, Shubhangi Patil, ”Sweep Frequency Response Analysis as a technique to diagnose the physical condition of transformers”, Doble international conference, 2007

[71] Nilanga A., Yuriy V. Serdyuk, and Stanislaw M. Gubanski,” Effect of Core Magnetization on FRA of Power Transformers IEEE Trans. On Power Delivery, Vol. 23, No. 3, July 2008

[72] Shubhangi Patil, Kirankumar Munji, “Fault diagnosis of OLTC through SFRA and Routine tests”, IEEE international conference of condition monitoring and diagnosis, Beijing, China 2010

[73] Shubhangi Patil, A. Venkatasami, “SFRA Analysis using Transformer Equivalent Circuit Modeling Technique”, IEEE international conference of condition monitoring and diagnosis, Beijing, China 2010

[74] Shubhangi Patil and Sushil Chaudhari, “An attempt to investigate the transformer failure by using DGA and SFRA analysis”, ICPADM, 2013

[75] Shubhangi Patil1, Athikkan Venkatasami,”An Effective Transformer Condition Assessment using SFRA”, International Conference on Condition

Monitoring & Diagnostic Engineering Management of Power Station/Substation Equipment" CPRI, January 2009 Bangalore, India

[76] Victor Sokolov, Boris Vanin, "Experience with detection and identification of winding buckling in power transformers", ZTZ Company, BuinoMak group publications, 2002

[77] Hikki Koivo, "Neural Network basics using MATLAB neural network toolbox", MATLAB 2008

[78] Mark Hudson Beale, Martin T. Hagan, Howard B. Demuth"Neural Netwotk toolbox-starting guide", MATLAB 2012

[79] Andriana R. Garcez Castro, Vladimiro Miranda, "Transformer fault diagnosis based on autoassociative neural networks", Technical conference, Portugal University, 2009

[80] Msiza, I.S.; Szewczyk, M.; Halinka, A.; Pretorius, "Neural networks on transformer fault detection evaluating the relevance of the input space parameters ", Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES.

Standards

[81] Guide for the Application and interpretation of SFRA for oil immersed Transformers, IEEE C57.149 (Draft copy-Not yet published)

[82] Power Transformers – Part 18: Measurement of Sweep Frequency Analysis (SFRA),IEC 60076-18, 2009.