Available online at www.elixirpublishers.com (Elixir International Journal)

Electrical Engineering

Elixir Elec. Engg. 41 (2011) 5827-5831

ISSN: 2229-712X

Frequency response analysis using high frequency transformer model

A.Abu-Siada

Curtin University, Perth, Australia.

ARTICLE INFO

Article history:

Received: 20 September 2011;
Received in revised form:
18 November 2011;
Accepted: 6 December 2011;

Keywords

Index Terms,
Power Transformer,
Condition Monitoring,
FRA.

ABSTRACT

The concept of Frequency Response Analysis (FRA) has been successfully used as a diagnostic technique to detect winding deformation, core and clamping structure for power transformers. The main problem about FRA techniques is to interpret the observed evolution of the frequency response in order to identify failures. Transformer high frequency computer modeling is proposed in this work to be used with the practical FRA measurements. The physical meaning of the model parameters allows the identification of the problem inside the transformer. Two high frequency transformer models based on lumped and distributed parameters approaches are investigated. A comparison of both models is conducted using their transfer function plots, and hence based on the amount of information revealed from the plots, a distributed model is chosen for further analysis. The model validation is carried out through the comparison of the simulation and field results. Mechanical and short circuit faults are simulated into the model to compare the differences in the frequency response of healthy and deformed transformer signatures. The advantage of this technique is that the FRA measurements can be obtained from meaningful parameters that can aid interpretation and classification of FRA signatures.

Introduction

POWER transformers are critical links within a power network and hence any failure can potentially cause long interruptions and costly repairs. They are subjected to heavy loading often in a very hostile environment which can lead to considerable damage to property, environment and potential risk to human life. Traditionally, routine preventative maintenance programs combined with regular testing were used [1, 2]. The increased need to reduce maintenance costs and equipment inventories has led to a reduction in routine maintenance. Hence instead of doing maintenance at regular intervals, it is now carried out only if conditions of the equipment require it [3, 4]. One mode of transformer failure is winding deformation. Winding deformation may be caused by the mechanical forces exceeding the winding withstand capability during short circuit faults [5]. This can occur either when the force is beyond the design limits such as tap-changer failure or the capability is reduced due to a loss of clamping pressure caused by ageing of the winding insulation [6]. The latter is of a great concern since most of the transformers in the power system network have been operational for about 30 to 40 years with the exclusion to the new installations arising due to the ever increasing power demand. Small winding deformations need to be identified because although the transformer may still be capable of normal service, the short circuit withstand capability is probably reduced. Every transformer has a unique transfer function which is considered as a “finger print” or “signature” that can be used to analyse the internal structure without dissembling the equipment [7].

The concept of Frequency Response Analysis (FRA) has been used for detecting winding deformation that can be caused by several fault conditions in a transformer [6-15]. A transformer represents a nonlinear system and its electrical equivalent circuit is very complex network of distributed resistive, capacitive, inductive elements and conductors between high voltage and low voltage windings. Hence, the frequency response of a transformer is dependent on the formulation of complex series and parallel resonant circuits. Deformation results in relative change to the inductance and capacitance of the winding structure, which can be detected externally by FRA method. The tests are conducted off-line by measuring the input/output relationships as a function of frequency in a typical range of 2 MHz to provide a current state wave form of the transformer [16], which is then compared with the signature wave form. Any change in the parameters of the transformer will show the effect of these changes in the transfer function plot. Resonant frequency shifts in the FRA measurement are the key parameters to indicate winding deformation. This method is capable of diagnosing several other faults such as partial discharge, ground leakage, displacement, local breakdown and many more [17]. In this paper a comparison of two transformer models for FRA studies is investigated. The model validation is carried out through the comparison of the simulation and experimental results. Simulation of winding deformation and interpretation of the differences in the healthy and deformed winding FRA signatures is also presented.

Transformer model

The practical application of any diagnostic technique to detect mechanical damage in a transformer depends on its sensitivity to any change in the distributed inductances and capacitances. Transformer can be modelled by a string of inductances to earth and shunted by their stray capacitances between windings. The equivalent circuit is useful in modelling the sensitivity of FRA to winding changes. It also can be used for the localization of partial discharges [18]. A change in response could be related to a calculated amount of winding deformation. FRA results can be used to construct models of transformer winding. These models can be used to relate

Tele:
E-mail addresses: a.abusiada@curtin.edu.au

frequency response data to the transformer mechanical structure and to quantify significant winding changes. High frequency transformer models are based on lumped or distributed circuit approaches where elements of transformer including windings, core, etc are represented by electrical parameters that can be measured or calculated. The selection of these parameters determines the accuracy of the model. The two transformer models are investigated in the following subsections.

Lumped parameter approach

Constant power frequency models provide a good basis for the development of a high frequency model. However, there are three major shortcomings:

(i) They fail to recognize the insulation systems of the transformer as electrical entities.

(ii) They fail to consider the changing effects of the core with respect to frequency.

(iii) They fail to account the effects of varying frequency on transformer parameters.

Fig. 1 shows a transformer equivalent circuit that was proposed by Douglass [19].

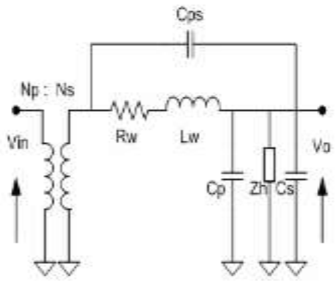

Fig. 1. Transformer lumped parameters equivalent circuit

In the model shown in Fig. 1, the following parameters are in their lumped form and all referred to the secondary side:

(i) an ideal transformer for ratio purposes only.

(ii) C_p and C_s represent the primary and secondary winding capacitances to ground respectively. C_{ps} is the mutual capacitance between primary and secondary windings.

(iii) L_w is the equivalent leakage inductance of the primary and secondary windings.

(iv) Z_h is the core exciting impedance (resistance and inductance in parallel). Z_h has been moved to the load side to include all circuit parameters in the transfer function.

The transfer function of the circuit shown in Fig. 1 can be written as:

$$\frac{V_o}{V_i}=\frac{\frac{C_{ps}}{C_{eq}}s^2(s+\frac{R_w}{L_w})}{s^3+s^2(\frac{R_w}{L_w}+\frac{1}{R_hC_{eq}})+s\frac{1}{C_{eq}}(\frac{1}{L_h}+\frac{R_w}{L_wR_h}+\frac{1}{L_w})+\frac{R_w}{L_hL_wC_{eq}}} \quad (1)$$

Where $C_{eq}=C_s+C_p+C_{ps}$

The design data of the transformer is used to compute the parameters of equation (1) [20].

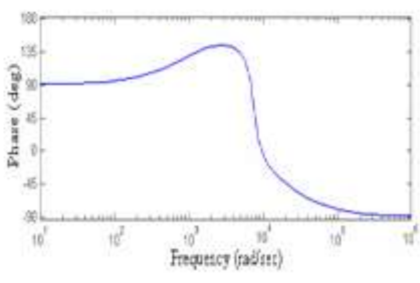

Figure 2. Phase plot of the model TF

It can be observed from the transfer function phase plot shown in Fig. 2 that at low frequencies, the influence of capacitance is neligible and the winding behaves as an inductor and then at high frequency as capacitor. This is due to the fact that at low frequency range, flux penetration of the core is significant and hence Z_h, the core excitation impedance, is included. As the frequency increases, the circuit capacitances dominate and tend to shunt the winding inductance. The core will likely have some effect at the lower frequencies and skin effect will become a factor at higher frequencies.

To conduct FRA test, a sweep frequency voltage of low amplitude is applied to a transformer terminal and the response voltage is measured across another transformer terminal with reference to the tank. The FRA response is the ratio between the amplitudes of the response signal V_o and the source voltage V_i as a function of the frequency expressed in dB. The input, response and reference coaxial cables are tapped together near the top of the bushing. A ground extension is run along the body of the bushing down to the flange to connect the cables shields to the tank. To validate model accuracy, experimental end-to-end FRA test using 50-Ω input impedance was performed on a transformer rated 15 MVA 22/0.415 kV power transformer (vector group dY11). The test conditions were oil winding temperature 25ºC, ambient temperature 22ºC and relative humidity 46%. The test configuration is shown in Fig. 3. The same principles can be applied to all other transformer winding systems. In Fig. 3, the signal is applied to one end of each winding in turn and the response signal is measured at the other end. This configuration is most commonly used for FRA because of its simplicity and the possibility to examine each winding separately.

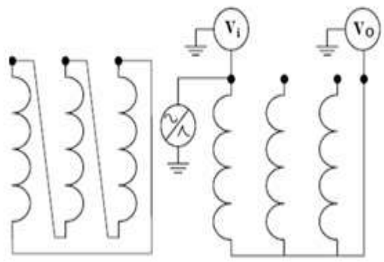

Figure 3. FRA test configuration

Fig. 4 shows a comparison of the frequency response of the model and the actual FRA signature measured using sweep frequency response analyzer. The experimental FRA signature reveals that the frequency range less than 10 kHz, the response is characterized by resonance at 7 kHz which is corresponding to the half-wave space harmonics in the winding due to the low impedance terminations of the measuring circuit. In the low frequency range the transformer winding response is dominated by inductance. As the frequency increases more space harmonics are built up in the winding. In the medium frequency range multiple resonances can be observed over the entire frequency range. In the low frequency range the oscillation is most likely to be affected by coil configuration, in the middle range by layer and section effects and at higher frequencies by individual turns [3]. As can be shown in Fig. 4, in the high frequency range, the model and experimental responses are correlated to far extent. However, model signature can not reflect all resonance (local minimum points) and anti-resonance (local maximum points) frequencies seen in the practical measurements. Also it can be observed that at low frequency range, the experimental response tends to shift towards left. This may be attributed to the presence of residual magnetism in the core. The model cannot simulate the distortion that appears in the very high frequency range which is most probably caused by tap-changer leads and bushing tails.

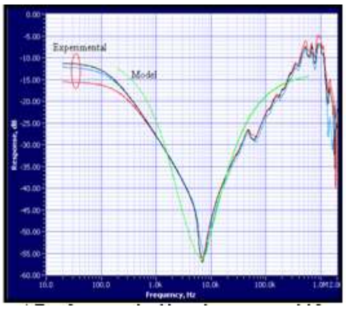

Figure 4. Transformer actual and lumped parameters model frequency responses

Distributed parameter approach

The transformer can be modelled with sufficient accuracy as a distributed analogue R-L-C circuit over a wide frequency range. Miki et al [21] shows that the effect of iron core had minimal role to play in an impulse stressed winding. This agrees well with the fact that in a rapid transient condition the flux lines tend to centre around the conductors rather than penetrating the iron core and for high frequency components of surges the iron core acts effectively as an earthed boundary [4].

Recent studies [12, 22] have neglected the effect of distributed shunt conductance. This will be a valid assumption for impulse voltage distribution analysis in the case of a faultless transformer, but may not be adequate in the case of fault diagnosis. Neglecting shunt conductance in the equivalent circuit will eliminate the study of leakage fault inside a transformer which could have been caused by several reasons such as insulation damage, ground shield or hot spots. The equivalent model (neglecting shunt conductance) could be ideal for verifying measured transfer function for inter-disc, coil short circuit and winding displacements. Hence the model needs some modifications to incorporate the study of leakage faults and partial discharges in the winding. These shortcomings of the computational model can be overcome if parameters which would allow for simulation of ground leakage and void in the insulation are taken into consideration. The distributed transformer model equivalent circuit shown in Fig. 5 has been proposed in this paper. A single transformer winding is divided into cascaded pi-network comprising self/mutual inductances, resistance, series/shunt capacitances and shunt dielectric conductance. For simplicity, it is assumed that the mutual inductances are lumped into series inductances. The overall transfer function of such network shows poles as the resonant frequencies of the winding model. Breakdown between turns or coils of winding under test corresponds to short circuit of one of the local LC network with a shift in resonant pole to another frequency.

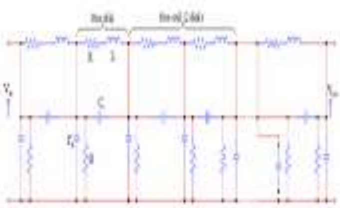

Figure 5. Transformer distributed parameter model

Fig. 6 shows the high and low voltage windings frequency responses of 21 coils of the circuit shown in Figure 5. The number of resonant points is directly related to the intrinsic characteristics of each transformer and hence the concept of “finger print” or “signature”. Unlike the lumped parameter model, more information of the windings can be deduced from the frequency response of a distributed parameters model. The parameters of the model can be calculated/measured using the design data of the transformer [20, 23-26]. The parameters of the transformer under consideration were provided by the manufacturer (ABB, Western Australia) where we have conducted our FRA measurements.

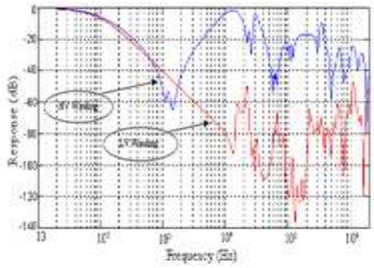

Figure 6. Frequency response of the distributed parameter model

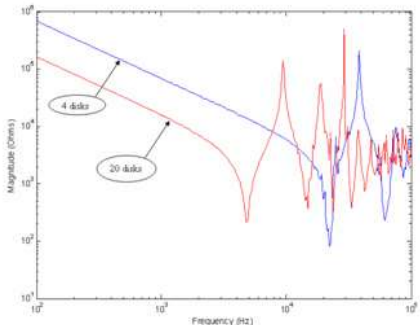

Figure 7. Impedance plot with varying disk numbers

To show the effect of the number of disks taken into account in the model on the frequency response, simulation using 4 and 20 disks has been performed. Fig. 7 shows the impedance plot of the LV winding with a varying sweep frequency up to 100 kHz for each model. As shown in Fig. 7, the starting resonant frequency shifts to the left with increasing number of disks. Also, the number resonance and anti-resonance frequencies increase with increasing the number of disks.

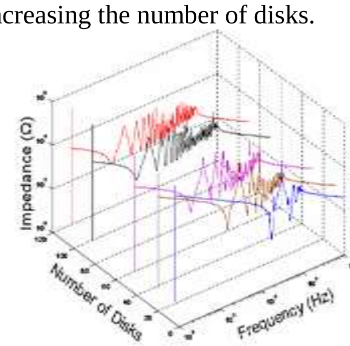

Figure 8. Effect of number of disks on the model frequency response

Fig. 8 shows the frequency response of five models with different number of disks (20, 40, 60, 100 and 120). As have been observed in Fig. 7, the starting resonant frequency shifts to the left and the number of resonance and anti-resonance frequencies increase as the number of disks increases.

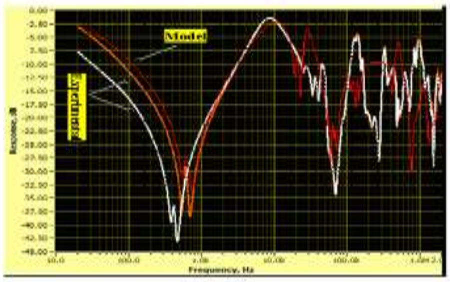

Figure 9. Transformer actual and distributed parameters model frequency responses

The simulation results are compared with the experimental FRA measurements (performed on the 3-phase LV windings) carried out on 250 MVA, 345/16 kV transformer. Fig. 9 shows a good correlation between the model and experimental results. Unlike lumped parameters frequency response, the distributed parameters frequency response reveals most of the resonance and anti-resonance frequencies of the actual response. The shift in resonant frequencies and the difference in the peak amplitudes of the model and experimental frequency responses at higher frequency range are attributed to the accuracy of the parameters values used in the simulation. Moreover, the assumption of the incremental mutual inductance of the distributed model to be lumped into the single series inductance which is widely used in the literatures [27], has affected the results.

Fault analysis

To identify the features of winding deformation and effect of model parameters on FRA signature, some faults such as buckling stress of inner winding, axial displacement and turns short circuits have been simulated. A comparison between the healthy and deformed signatures will help interpreting the actual FRA responses. The advantage of this methodology is that the meaningful physical parameters change can aid interpretation and classification of actual FRA signatures [28].

Buckling stress

Buckling stress will push windings inwards and enlarges the inter-winding distance. As an effect, the inter-winding shunt capacitance will be reduced. This fault type is simulated by reducing the shunt capacitance of disks 19-20 by 20%. A comparison of the impedance plot before and after capacitance change is shown in Fig. 10.

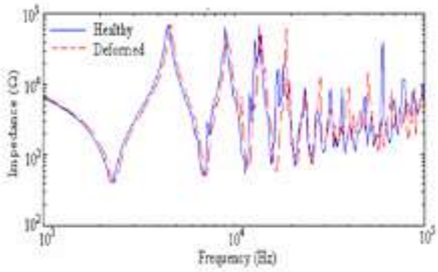

Figure 10. Shunt capacitance effect on FRA signature

As shown in Fig. 10, the effect of reducing the shunt capacitance is pronounced in the regions of frequencies higher than 10 kHz where the amplitude will be slightly changed and resonant frequencies which are the key parameter to indicate winding deformation will shift to the right side.

Axial displacement

Winding axial displacement changes the relative position of the winding and can be simulated by changing the mutual inductance between windings. Fig. 11 shows the effect of inductance change on the frequency response. This fault has been simulated by reducing the inductances of disks 19-20 by 20%. As seen from the figure, this change has no effect on the amplitude. However, resonant frequency locations will be altered and some anti-resonant frequencies will be created. The effect is more pronounced in the low frequency range.

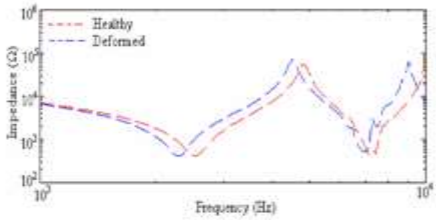

Figure 11. Inductance effect on FRA signature

Turn to turn short circuit

This fault can be simulated by short circuiting series resistors. Fig. 12 shows the effect of short circuiting the resistances of disks 9-10 of the model shown in Fig. 5.

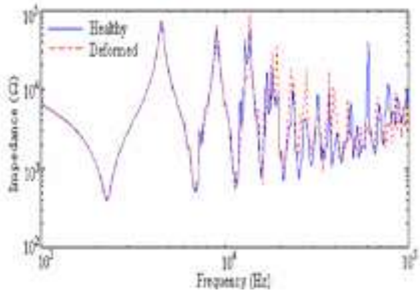

Figure 12. Effect of short circuit fault on FRA

This fault will affect the amplitude in the high frequency range. Also, some of the high frequency resonant points will be shifted due to the fact that the shunt capacitor will be also shorted as can be seen from the circuit model shown in Fig. 5

Conclusion

The main problem about FRA techniques is to interpret the observed evolution of the frequency response in order to identify failures. This paper investigates the transformer high frequency models to be used along with FRA classification and interpretation. Two high frequency transformer models based on lumped and distributed parameters approaches have been investigated. Comparison of the frequency response of the two models with the actual FRA signature has been elaborated. Results show that distributed parameters model can reveal most of resonance and anti-resonance frequencies that exist in the experimental FRA measurement. However, model based on lumped parameters approach fails to correlate with the actual measurements. Various winding deformation are simulated as the change in the electric parameters of the distributed model and a general interpretation of results is done. The physical meaning of the model parameters allows the identification of the problem inside the transformer. The distributed parameters model is very accurate to emulate experimental FRA signature as has been seen in the results and hence it can be used in conjunction with field FRA measurement to help interpretation for its results. The proposed model is easy to implement and can be used as a successful tool for FRA and condition monitoring of power transformer.

Acknowledgement

The authors would like to thank the Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM) for funding this research.

References

[1] T. K. Saha, "Review of modern diagnostic techniques for assessing insulation condition in aged transformers," IEEE

Transactions on Dielectrics and Electrical Insulation, vol. 10, pp. 903-917, 2003.

[2] J. P. Gibeault and J. K. Kirkup, "Early detection and continuous monitoring of dissolved key fault gases in transformers and shunt reactors," 1995, pp. 285-293.

[3] M. Arshad, "Remnant Life Estimation Model Using Fuzzy Logic for Power Transformer Asset Management," PhD thesis, Curtin University of Technology, Australia, 2005.

[4] B. D. Sparling, "Transformer monitoring moving forward from monitoring to diagnostics," Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES, 2002, pp. 1506-1509 vol.2.

[5] M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Transformer winding movement monitoring in service- key factors affecting FRA measurements," IEEE Electrical Insulation Magazine, vol. 20, pp. 5-12, 2004.

[6] K. G. N. B. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "Exploring possibilities for characterization of power transformer insulation by frequency response analysis (FRA)," IEEE Transactions on Power Delivery, vol. 21, pp. 1375-1382, 2006.

[7]A. Abu-Siada and S. Islam, "High frequency transformer computer modeling," in Universities Power Engineering Conference, 2007. AUPEC 2007. Australasian, 2007, pp. 1-5.

[8]S. Birlasekaran and F. Fetherston, "Off/on-line FRA condition monitoring technique for power transformer," IEEE Power Engineering Review, vol. 19, pp. 54-56, 1999.

[9]C. Gonzalez, J. Pleite, R. A. Salas, and J. Vazquez, "Transformer Diagnosis Approach using Frequency Response Analysis Method," in IEEE IECON 2006 - 32nd Annual Conference on Industrial Electronics, 2006, pp. 2465-2470.

[10]C. Gonzalez, J. Pleite, V. Valdivia, and J. Sanz, "An overview of the On Line Application of Frequency Response Analysis (FRA)," in IEEE International Symposium on Industrial Electronics, ISIE 2007., 2007, pp. 1294-1299.

[11]Z. Jin, M. Zhu, and Z. Zhu, "Fault location of transformer winding deformation using frequency response analysis," in Proceedings of 2001 International Symposium on Electrical Insulating Materials, ISEIM 2001, pp. 841-844.

[12]J. Pleite, C. Gonzalez, J. Vazquez, and A. Lazaro, "Power transformer core fault diagnosis using frequency response analysis," in IEEE Mediterranean Electrotechnical Conference, MELECON, 2006, pp. 1126-1129.

[13]D. M. Sofian, Z. D. Wang, and P. Jarman, "Interpretation of transformer FRA measurement results using winding equivalent circuit modelling technique," in Annual Report Conference on Electrical Insulation and Dielectric Phenomena, CEIDP '05. 2005, pp. 613-616.

[14]D. M. Sofian, Z. D. Wang, and S. B. Jayasinghe, "Frequency response analysis in diagnosing transformer winding movements - fundamental understandings," in 39th International Universities Power Engineering Conference, UPEC 2004. pp. 138-142 Vol.1.

[15]P. T. M. Vaessen and E. Hanique, "A new frequency response analysis method for power transformers," IEEE Transactions on Power Delivery,vol. 7, pp. 384-391, 1992.

[16]J. Singh, Y. R. Sood, and R. K. Jarial, "Novel method for detection of transformer winding faults using Sweep Frequency Response Analysis," IEEE Power Engineering Society General Meeting, *2007*. 2007, pp. 1-9.

[17]D. Wenjin, L. Baobin, Y. Li, and Z. Wei, "The application of frequency response analysis in transformer winding distortion inspecting," in Proceedings of the 8th International Conference on Electrical Machines and Systems, ICEMS., 2005, pp. 1759-1762 Vol. 3.

[18]S. M. Islam and G. Ledwich, "Locating transformer faults through sensitivity analysis of high frequency modeling using transfer function approach," in IEEE International Symposium on Electrical Insulation, 1996, pp. 38-41 vol.1.

[19]D. A. Douglass, "Potential Transformer Accuracy at 60HZ Voltages Above and Below Rating and at Frequencies Above 60 HZ," IEEE transactions on power apparatus and systems, vol. PAS-100, pp. 1370-1375, 1981.

[20]K. G. N. B. Abeywickrama, A. D. Podoltsev, Y. V. Serdyuk, and S. M. Gubanski, "Computation of Parameters of Power Transformer Windings for Use in Frequency Response Analysis," IEEE Transactions on Magnetics, vol. 43, pp. 1983-1990, 2007.

[21]A. Miki, T. Hosoya, and K. Okuyama, "A Calculation Method for Impulse Voltage Distribution and Transferred Voltage in Transformer Windings," ,IEEE transactions on power apparatus and systems, vol. PAS-97, pp. 930-939, 1978.

[22]N. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "Effect of Core Magnetization on Frequency Response Analysis (FRA) of Power Transformers," IEEE Transactions on Power Delivery, vol. 23, pp. 1432-1438, 2008.

[23]J. Pleite, E. Olias, A. Barrado, A. Lazaro, and J. Vazquez, "Transformer modeling for FRA techniques," in Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES, 2002, pp. 317-321 vol.1.

[24]N. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "High-Frequency Modeling of Power Transformers for Use in Frequency Response Analysis (FRA)," IEEE Transactions on, Power Delivery, vol. 23, pp. 2042-2049, 2008.

[25]S. M. Islam, K. M. Coates, and G. Ledwich, "Identification of high frequency transformer equivalent circuit using Matlab from frequency domain data," in 32nd IAS Annual Meeting, IAS '97., 1997, pp. 357-364 vol.1.

[26]G. M. V. Zambrano, A. C. Ferreira, and L. P. Caloba, "Power transformer equivalent circuit identification by artificial neural network using frequency response analysis," in Power Engineering Society General Meeting, *2006.* p. 6

[27] Z. Chun, R. Jiangjun, D. Zhiye, L. Shoubao, Y. Yefeng, and Z. Yuanhang,"Calculation of parameters in transformer winding based on the model of multi-conductor transmission line," in *Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on*, 2008, pp. 463-467.

[28]S. Almas, W. Tang, and Q. H. Wu, "Modeling of a Power Transformer Winding for Deformation Detection Based on Frequency Response Analysis," in Chinese Control Conference, CCC. 2007, pp. 506-510.