Impact of Power Transformer Insulating Mineral Oil Degradation on FRA Polar Plot

Omar M Aljohani, Ahmed Abu-siada
Electrical and Computer Engineering Department
Curtin University
Perth, Australia
omaljohani@hotmail.com and a.abusiada@curtin.edu.au

***Abstract*—Frequency response analysis (FRA) has been employed as an effective tool for the detection of various mechanical winding and core deformations within electrical power transformer. Traditional FRA signature interpretation relies on the magnitude of the FRA plot although all practical frequency response analyzers are able to provide both magnitude and angle of the FRA signal in wide frequency range. Moreover, no attention has been given to the impact of power transformer insulating oil degradation on the FRA signature. This paper presents is aimed at introducing a new interpretation approach of the FRA signature using polar plot which is obtained by incorporating FRA signature magnitude and phase into one plot. The paper also investigates the impact of insulating mineral oil degradation on the proposed polar plot signature. Digital image processing (DIP) technique is developed to automate the interpretation process. In this regard, the physical geometrical dimension of a single-phase transformer filled with insulating mineral oil is simulated using three-dimensional finite element analysis to emulate real transformer operation. FRA polar plot signatures are measured and analyzed for various health conditions of the mineral oil. Results show that insulating mineral oil degradation has an impact on the transformer FRA polar plot signature. The proposed FRA polar plot technique is easy to implement within any frequency response analyzer.**

***Keywords*—power transformer; Mineral insulating oil; Frequency response analysis; Polar plot; Digital Image Processing.**

I. INTRODUCTION

The bulk of global power transformers were commenced into service prior to 1980 and as a result they are approaching or have already exceeded their proposed design life [1-3]. The likelihood of failures is significantly increasing with transformer aging, consequently it is an essential to adopt a reliable diagnostic tool to identify the current health condition and to take timely and proper remedial action to avoid any possible catastrophic failures [2, 4-6]. Various diagnostic techniques are currently used worldwide to detect faults within power transformers [7-10]. Among these techniques, frequency response analysis (FRA) has been widely recognized as the most reliable tool to diagnose mechanical deformation within power transformers [11, 12]. FRA is based on the fact that transformer components including the core, windings and insulation can be modelled as a network of capacitance, resistance, and self and mutual inductances whose values change when internal mechanical deformation takes place within the transformer. This change can be detected externally through the variation in the resonance frequencies of the transformer FRA signature. Transformer insulation dielectric characteristics deteriorate over time due to oil/paper degradation and moisture ingress which may have an impact on the transformer FRA signature as well [13]. FRA testing is conducted by applying a sweep variable frequency AC voltage of low amplitude to one terminal of a transformer winding and measuring the response voltage across the other terminal of the winding with reference to the tank [4, 14]. The measured FRA signature could be in the form of impedance, admittance, or transfer function (V_{out}/V_{input} in dB) as a function of wide frequency range. Because FRA signatures relies on graphical analysis, interpretation process is a highly specialised area that motivated researchers to investigate the impact of various mechanical winding deformations on the FRA signature in order to develop stander codes for FRA signature identification and quantification [15-17]. While transformer FRA signature is provided as magnitude and phase angle of the measured signal, only magnitude is currently used for signal interpretation. Furthermore, no attention has been given to investigate the impact of insulating oil condition on the FRA signature. This paper introduces a new approach for FRA signature interpretation by incorporating both magnitude and phase angle of the measured signal in one polar plot that exhibits most of the measured signal features and facilitate the use of digital image processing (DIP). The new approach is used to investigate the impact of mineral insulating oil degradation on the transformer FRA signature.

II. TRANSFORMER MINERAL OIL INSULATION

The insulation system within power transformers consists of paper insulation immersed in insulating oil which involves different physical, dielectric, and thermal properties. Mineral oil is the most popular fluid used for insulating electrical equipment, such as power transformers [1]. Researchers have attempted to improve the technical attributes of mineral oil to overcome some of its drawbacks which include a lack of eco-friendliness and the expected increase in its price due to the shortage of petroleum products [1, 2]. Various characteristics of mineral oil as a transformer dielectric are listed in Table A-I in the Appendix [1-6]. Due to the high electrical and thermal stresses that in-service transformers exhibit, paper and oil decomposition takes place causing a change in oil dielectric properties such as oil break down voltage, acidity, viscosity, conductivity, and permittivity. Oil deterioration can be simulated by changing some of the oil dielectric characteristics such as conductivity and permittivity. While dielectric permittivity (ε) affects insulation material behavior under transient electrical conditions, electric conductivity (σ) is a vital oil characteristic which specifies the dielectric strength of insulating oil [3]. The electrical conductivity of mineral oil can be assessed to evaluate oil health condition and aging [7]. Because variations in dielectric permittivity and electrical conductivity have a significant effect on the oil capacitance [8], oil degradation/aging is expected to affect the transformer FRA signature particularly in the high frequency range.

III. Finite Element Analysis

Finite element analysis (FEA) has been utilized as a physical environment to emulate different dynamic systems such as power transformer [9]. In this paper, the physical dimension for a single-phase transformer is simulated using FEA, as shown in Fig.1 (all specifications/dimensions are given in Table A-II in the Appendix). The 3D transformer model shown in Fig. 2 is solved in magneto-static and electro-static solvers using Maxwell's equations to extract the inductance, and capacitance matrices of the relevant transformer components. Resistance and conductance calculations are carried out by applying the eddy current, magnetic transient and electric DC conduction solvers.

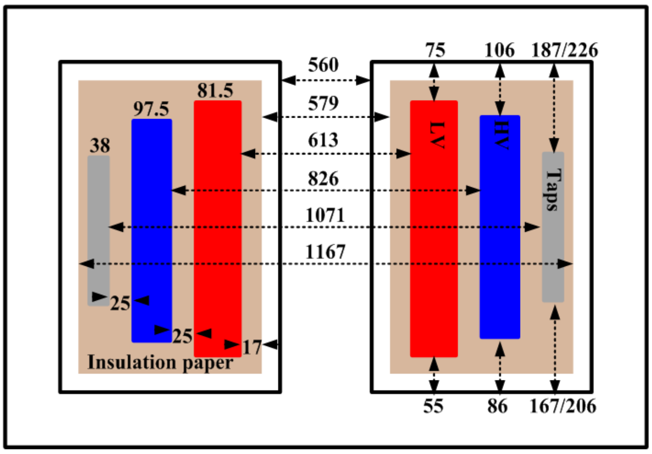

Fig. 1. Schematic diagram of the investigated transformer model (all dimensions are in mm).

Transformer parameters were calculated using FEA and used to simulate the high frequency equivalent electrical transformer model shown in Fig. 3. This model comprises series inductance (L_s), and series resistance (R_s), representing the high voltage (HV) and low voltage (LV) windings. Winding insulation is modeled by shunt capacitance (C_{sh}) and conductance (G_{sh}). Mutual inductances (M) between relevant coils are also simulated. The insulation between the HV and LV windings is modeled by series capacitance (C_{HL}) shunted by dielectric conductance (G_{HL}). Series capacitances (C_{H0}), (C_{L0}) shunted by dielectric conductances (G_{H0}), (G_{L0}), model the dielectric insulation between HV / LV windings and the earthed tank / core, respectively.

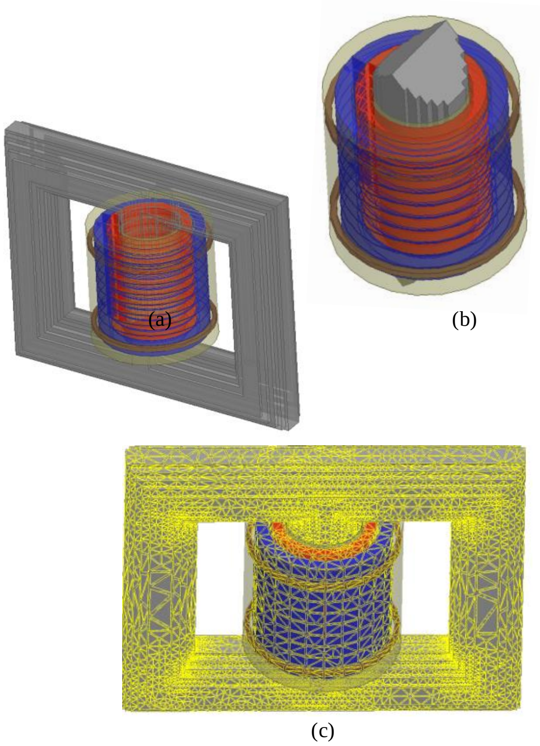

Fig. 2. (a) 3D transformer model, (b) Single leg with coils and insulation paper, and (c) Meshed entire model.

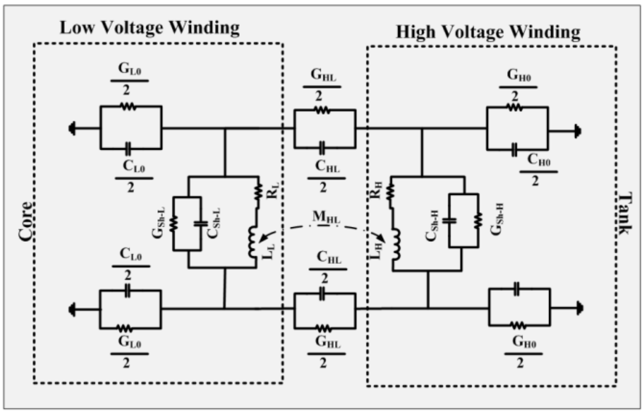

Fig. 3. Transformer distributed parameters model.

Parameters of the transfer function of the transformer model shown in Fig. 3 are obtained using FEA of the 3D transformer model of Fig. 2 as briefly illustrated below:

Capacitive component calculation is carried out using the electro-static solver where voltage v is applied on one conductor, while the voltage level is maintained at a level of zero on the other conductor. The electrostatic field energy (W) between the two conductors can be calculated as follows [10-12]:

$$W_{ij}=0.5\int_{\Omega} D_i \times E_j \, d\Omega \qquad (1)$$

Where W_{ij} is the electrical field energy between conductors i and j, D_i is the electrical flux density of conductor i and E_j is the electrical field intensity of conductor j.

The capacitance C between two conductors i and j can then be calculated as:

$$C = 2\times W_{ij} / v^2 \quad (2)$$

Inductive components are calculated based on the average of the magnetic field energy (W_{ij}) and the corresponding peak current passing through the winding (I_p) as follows [12]:

$$W_{AV} = 0.25 \int_m B \times H\, dm \quad (3)$$

$$L = (4\times W_{AV})/(I_p)^2 \quad (4)$$

where B is the magnetic field density, H is the magnetic field intensity, and m is the conductor volume.

Resistive components are calculated based on power losses (P_{loss}) depending on conductor conductivity (σ) and current density (J) as given in (5) and (6) below [12]:

$$P_{loss} = 1/(2\times\sigma) \int_m J.J\, dm \quad (5)$$

$$R = P_{loss} / (I_{rms})^2 \quad (6)$$

Table A-III in the Appendix lists the calculated transformer equivalent circuit parameters.

IV. Proposed Polar Plot and Digital Image Processing Technique

Fig.4 shows a typical FRA signature which comprises magnitude and phase angle of the transfer function of the HV winding. To capture most of the frequency features and to facilitate the use of DIP, both plots (magnitude /phase) are incorporated into one polar plot as shown in Fig.5. Any point on the polar plot is represented by magnitude (r) and angle (θ), corresponding to a particular frequency[13]. The aim of DIP is to improve the interpretation of pictorial information using electronic devices [14, 15]. Any digital image is represented as a two-dimensional (2D) matrix, $[A]_{X\times Y}$, which consists of a finite number of pixels with a dimension of X×Y. In the polar plot, each point can be written as $a(x_1,y_1)$, where $|a|$ represents image intensity at point a, and x_1,y_1 are the spatial location with respect to coordinates X and Y, respectively[14]. The developed DIP is built in accordance to the following steps:

- Pre-processing the image by resizing it and adjusting the colour format [15].
- Segmentation and edge detection is used to detect a region of interest (ROI) within the processed image [14].
- Feature extraction which is the crux of DIP technique. In this paper, number of pixel (NP) of polar plot signatures is used as the image extracted feature, and is given as:

$$NP = \sum_{x=0}^{X-1} \sum_{y=0}^{Y-1} a_{FRA\text{-}PP}(x,y) \quad (7)$$

- The finial task is comparing the extracted feature of the current condition with the healthy condition to identify any variation in the signature.

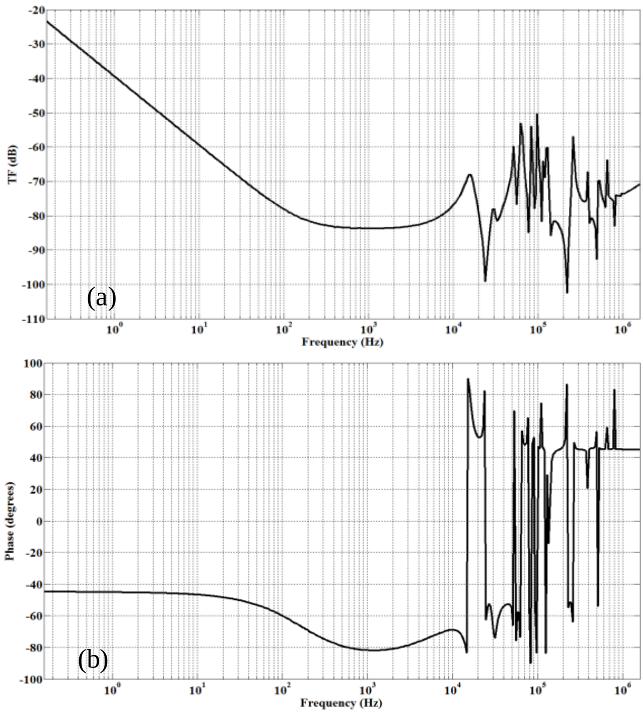

Fig. 4. Typical FRA signature for new oil insulation, (a) magnitude and (b) phase angle

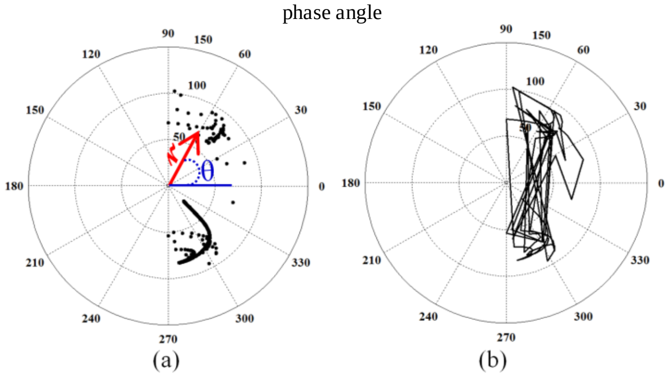

Fig. 5. Polar plot signature for new oil insulation, (a) point and (b) line.

V. Impact of Insulation Oil Degradation on Transformer FRA Polar Plot Signature

Mineral oil with five different levels of degradation is used to perform the analysis. The FRA polar plot signature for each oil health condition is obtained and analyzed. The transformer HV winding polar plot for new mineral oil insulation is shown in Fig. 5 and the extracted NP using the developed DIP technique is found to be 8,264 pixels. The high electrical and thermal stresses within operating transformers deteriorates the dielectric strength of insulation oil [16]. To show the impact of insulating oil degradation on the transformer FRA polar plot signature, the signature of the HV winding of the transformer model shown in Fig. 2 is plotted for five health conditions of transformer oil (incipient, slight, moderate, high and significant deterioration). In the model under study, oil was degraded through changing its permittivity and conductivity. The impact of each insulation oil health condition on the proposed polar plot is shown in Figs. 6 through 10. Table A-IV in the Appendix shows the how those degradation levels are simulated by controlling oil conductivity and permittivity. Results show that, more degraded oil leads to an increase in the NP of the polar plot image as can be shown in Table I and Fig. 11.

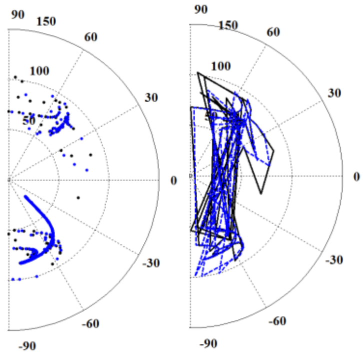

Fig. 6. Incipient oil degradation impact on polar plot signature.

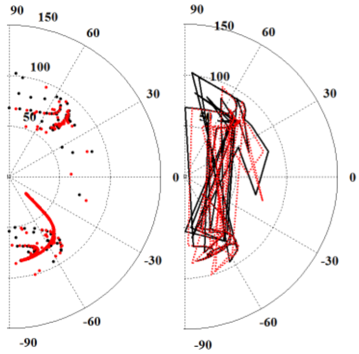

Fig. 7. Slight oil degradation impact on polar plot signature.

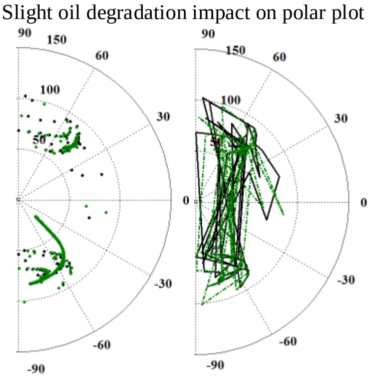

Fig. 8. Moderate oil degradation impact on polar plot signature.

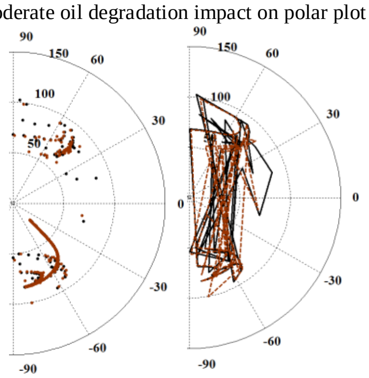

Fig. 9. High oil degradation impact on polar plot signature.

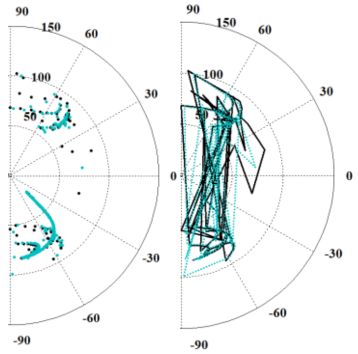

Fig. 10. Significant oil degradation impact on FRA signature.

TABLE I. NUMBER OF PIXELS FOR THE OIL DEGRADATION

Oil degradation level	Number of pixels (NP)
New	8264
Incipient	8342
Slight	8762
Moderate	8823
High	8995
Significant	9513

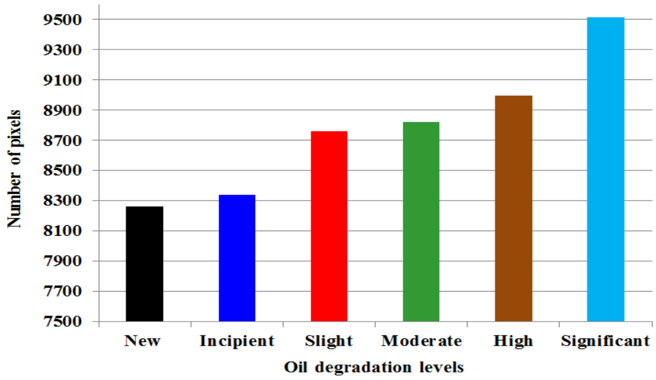

Fig. 11. Bar chart for oil degradation.

The above results show that FRA polar plots have the potential to detect transformer oil aging/degradation. Through using DIM, The effect of oil degradation is noticeable in each level of degradation according to the image number of pixels. The impact is more pronounced with the increase in the oil degradation level.

VI. CONCLUSION

This paper introduces a new approach for frequency response (FRA) signature analysis using polar plot along with digital image processing technique (DIP). The use of polar plot is aimed at comprising most of the FRA signature features in one plot and to facilitate the use of DIP. The new proposed technique is employed to investigate the impact of insulation oil degradation on the FRA polar plot. Results show that transformer oil degradation introduces an increase in the number of pixels (NP) of the transformer FRA polar plot signature. The proposed technique can be extended to identify and quantify other mechanical faults within the power transformer. This technique is simple, reliable and easy to build within the current frequency response analyzers to automate the FRA interpretation process.

VII. APPENDIX

TABLE A-I CHARACTERISTICS OF INSULATION OIL [1, 2, 4, 5]

Parameter	Mineral oil
Dielectric Breakdown, KV	30/85
Relative Permittivity at 25°C	2.5
Viscosity at 0°C, $mm^2.s^{-1}$	<76
Viscosity at 40°C, $mm^2.s^{-1}$	3/16
Viscosity at 100°C, $mm^2.s^{-1}$	2/2.5
Pour Point, °C	-30/-60
Flash Point, °C	100/170
Fire Point, °C	110/185
Density at 20°C, $kg.m^3$	0.83/0.89
Thermal Conductivity, $W.m^{-1}.K^{-1}$	0.11/0.16
Expansion Coefficient, $10^{-4}.K^{-1}$	7/9
Electrical Conductivity, $S.m^{-1}$	1.5×10^{-10}

TABLE A-II SPECIFICATIONS AND DIMENSIONS OF THE 40MVA ONE PHASE THREE-LEGGED CORE TYPE POWER TRANSFORMER MODEL

Classification	Value
Phase	1
Frequency [Hz]	50
Rated power [MVA]	40
Primary/Secondary voltage [KV]	66/11
Primary/Secondary Winding resistance [mΩ]	123.7/12.07
Primary/Secondary Turns [Turn]	1200/200
Impedance [%]	13.79
Height of 1st and 2nd rows of taps [mm]	912/834
Height of HV winding/ LV winding [mm]	1074/1136
Distance of 1st/2nd row taps to yoke [mm]	187/226
Distance of HV/LV winding to upper yoke [mm]	106/75
Distance of HV/ LV winding to lower yoke [mm]	86/55
Insulation thickness between HV/LV windings [mm]	25
Core cross-section diameter [mm]	560
Insulated core cross-section diameter [mm]	579
Inner diameter of HV/LV winding/ taps [mm]	826/613/1071

TABLE A-III TRANSFORMER PARAMETERS VALUE

Transformer parameters	HV	LV
Series inductance (L_s) [μH]	8.91	8.91
Series resistance (R_s) [Ω]	1	0.025
Shunt capacitance (C_{sh}) [pF]	61.196	115.53
Shunt conductance (G_{sh}) [μS]	68.5	0.25
Series capacitance (C_o) [pF]	567.96	333.24
Dielectric conductance (G_o) [μS]	68.5	0.25
Series capacitance (C_{HL}) [pF]	89.283	
Shunted conductance (G_{HL}) [μS]	68.5	

TABLE A-IV MINERAL OIL DEGRADATION LEVEL

Degradation level	Electrical Conductivity,S.m-1	Permittivity
New	1.50×10^{-10}	2.50
Incipient	1.71×10^{-10}	2.75
Slight	1.86×10^{-10}	3.00
Moderate	2.02×10^{-10}	3.25
High	2.17×10^{-10}	3.50
Significant	2.33×10^{-10}	3.75

REFERENCES

[1] S. Mofizul Islam, K. M. Coates, and G. Ledwich, "Identification of high frequency transformer equivalent circuit using Matlab from frequency domain data," in Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS '97., Conference Record of the 1997 IEEE, 1997, pp. 357-364 vol.1.

[2] L. M. Geldenhuis, "Power transformer life management," in Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on, 2005, pp. 1-4.

[3] E. J. Figueroa, "Managing an Aging Fleet of Transformers," in Proceeding 6th Southern Africa Regional Conference, CIGRE, 2009.

[4] A. Abu-Siada and S. Islam, "A Novel Online Technique to Detect Power Transformer Winding Faults," Power Delivery, IEEE Transactions on, vol. 27, pp. 849-857, 2012.

[5] M. A. Stephanie Uhrig, René Hummel, and Michael Krueger, "Advanced Methods for Insulation Diagnostics on Power Transformers," 3 March 2014.

[6] J. Chong and A. Abu-Siada, "A novel algorithm to detect internal transformer faults," in Power and Energy Society General Meeting, 2011 IEEE, 2011, pp. 1-5.

[7] J. A. S. B. Jayasinghe, Z. D. Wang, P. N. Jarman, and A. W. Darwin, "Investigations on sensitivity of FRA technique in diagnosis of transformer winding deformations," in Electrical Insulation, 2004. Conference Record of the 2004 IEEE International Symposium on, 2004, pp. 496-499.

[8] B. Cahyono, A. Pharmatrisanti, Y. Tamsir, Sumaryadi, and R. Siregar, "Thermal monitoring on power transformers," in Condition Monitoring and Diagnosis, 2008. CMD 2008. International Conference on, 2008, pp. 482-484.

[9] W. Ma and F. Cheng, "Research on the influence of microorganism on TAN δ of power transformer oil," in Power Engineering and Automation Conference (PEAM), 2011 IEEE, 2011, pp. 301-304.

[10] K. Kwang-Hwa, S. Jong-Ho, Y. Sang-Hwa, S.-B. Han, and K. Dong-Sik, "Study on the On-line PD Measurement Technology for Power Transformer," in Properties and applications of Dielectric Materials, 2006. 8th International Conference on, 2006, pp. 570-574.

[11] J. A. S. B. Jayasinghe, Z. D. Wang, P. N. Jarman, and A. W. Darwin, "Winding movement in power transformers: a comparison of FRA measurement connection methods," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 13, pp. 1342-1349, 2006.

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

[13] M. Bagheri, M. S. Naderi, T. Blackburn, and B. T. Phung, "Dean-Stark vs FDS and KFT methods in moisture content recognition of transformers," in Power and Energy (PECon), 2012 IEEE International Conference on, 2012, pp. 712-717.

[14] H. Firoozi, M. Kharezi, H. Rahimpour, and M. Shams, "Transformer Fault Diagnosis Using Frequency Response Analysis - Practical Studies," in Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific, 2011, pp. 1-4.

[15] CIGER, "Mechanical-condition assessment of transformer windings using Frequency Response Analysis (FRA)," in Tutorial of Cigre WG A2.26 Convener, ed. Patrick Picher, Canada: CIGER, 2007, p. 21.

[16] S. D. Mitchell and J. S. Welsh, "Modeling Power Transformers to Support the Interpretation of Frequency-Response Analysis," Power Delivery, IEEE Transactions on, vol. 26, pp. 2705-2717, 2011.

[17] J. C. Gonzales Arispe and E. E. Mombello, "Detection of Failures Within Transformers by FRA Using Multiresolution Decomposition," Power Delivery, IEEE Transactions on, vol. 29, pp. 1127-1137, 2014.

[18] M. Ş. VIHACENCU, A. CIURIUC, and L. Marius, "Experimental Study of Electrical Properties of Mineral and Vegetable Transformer Oils," in International Conference on Innovation and Engineering Research, 2013, pp. 2-4.

[19] Y. B. a. L. C. Hoang, "VEGETABLE OILS AS SUBSTITUTE FOR MINERAL INSULATING OILS IN MEDIUM-VOLTAGE EQUIPMENTS," CIGRE, FRANCE2007 2004.

[20] T. Judendorfer, A. Pirker, and M. Muhr, "Conductivity measurements of electrical insulating oils," in Dielectric Liquids (ICDL), 2011 IEEE International Conference on, 2011, pp. 1-4.

[21] M. Spohner, "COMPARISON OF MINERAL OIL WITH NATURAL AND SYNTHETIC OILS."

[22] K. Yasuda, S. Arazoe, T. Igarashi, S. Yanabu, G. Ueta, and S. Okabe, "Comparison of the insulation characteristics of environmentally-friendly oils," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 17, pp. 791-798, 2010.

[23] J. Jung-Il, A. Jung-Sik, and H. Chan-Su, "Accelerated aging effects of mineral and vegetable transformer oils on medium voltage power transformers," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 19, pp. 156-161, 2012.

[24] L. V. Badicu, B. Gorgan, L. M. Dumitran, and P. V. Notingher, "Assessment of transformer mineral oil condition based on dc and ac conductivity," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 19, pp. 1544-1551, 2012.

[25] M. Bagheri, B. T. Phung, and T. Blackburn, "Influence of temperature and moisture content on frequency response analysis of transformer winding," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 21, pp. 1393-1404, 2014.

[26] M. R. Barzegaran, M. Mirzaie, and A. S. Akmal, "Investigating short-circuit in power transformer winding with quasi-static finite element analysis and circuit-based model," in Transmission and Distribution Conference and Exposition, 2010 IEEE PES, 2010, pp. 1-8.

[27] "Ansoft Maxwell," REV 6.0 ed. Canonsburg: ANSYS Inc., 2012, p. 1006.

[28] A. Hyun-Mo, L. Ji-Yeon, K. Joong-Kyoung, O. Yeon-Ho, J. Sang-Yong, and H. Sung-Chin, "Finite-Element Analysis of Short-Circuit Electromagnetic Force in Power Transformer," Industry Applications, IEEE Transactions on, vol. 47, pp. 1267-1272, 2011.

[29] Z. Haijun, Y. Bin, X. Weijie, W. Shuhong, W. Guolin, H. Youpeng, et al., "Dynamic Deformation Analysis of Power Transformer Windings in Short-Circuit Fault by FEM," Applied Superconductivity, IEEE Transactions on, vol. 24, pp. 1-4, 2014.

[30] O. Aljohani and A. Abu-Siada, "Application of FRA polar plot technique to diagnose internal faults in power transformers," in PES General Meeting | Conference & Exposition, 2014 IEEE, 2014, pp. 1-5.

[31] R. C. Gonzalez, Digital image processing / Rafael C. Gonzalez, Richard E. Woods. Upper Saddle River, N.J.: Upper Saddle River, N.J. : Pearson/Prentice Hall, 2008.

[32] A. McAndrew, "An introduction to digital image processing with matlab notes for SCM2511 image processing," School of Computer Science and Mathematics, Victoria University of Technology, pp. 1-264, 2004.

[33] A. Abu-Siada, S. Hmood, and S. Islam, "A new fuzzy logic approach for consistent interpretation of dissolved gas-in-oil analysis," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 20, pp. 2343-2349, 2013.