Frequency response analysis for accounting the changes in permittivity of natural ester oil with mineral oil

Apurti Jain, Ankita Garg
Department of Electrical and Instrumentation Engineering
Thapar Institute of Engineering and Technology
Patiala, Punjab, India.
apurtijain04@gmail.com
ankita19garg95@gmail.com

Jeyabalan Velandy
Transformer technology in R &D
Formly in CG Power and Industrial Solution Limited
Kanjur Marg (E), Mumbai, Maharastra, India.
jeyabalan27@gmail.com

C.S. Narasimhan
R & D
Savita Oil Technologies Limited
Navi mumbai, Mumbai, India
csnarasimhan@savita.com

***Abstract*—Recently, ester based insulating oils including both natural ester and synthetic ester are being considered as potential alternatives to petroleum based mineral oil due to their better environmental friendly, higher fire safety, non-toxic and continuous overloading benefits. Ester oil has higher permittivity than mineral oil due to chemical compositions. Hence, the higher permittivity of ester oil affects electrical stress distribution in insulation system of transformer and it can also affects frequency response analysis of transformer during sweep frequency response analysis (SFRA). In this paper, to evaluate the differences in permittivity of natural ester and mineral oil, SFRA are performed for a given same winding geometry and insulation arrangement. The mineral oil transformer frequency responses are considered as a reference response and its results are compared with natural ester oil transformer. The frequency domain responses are evaluated using graphical analysis and commonly used numerical indicators of correlation coefficient, standard deviation, absolute sum of logarithmic error, mean square error and Max-min ratio.**

Keywords—Transformer, Condition monitoring, transformer winding, frequency response analysis, numerical indicators, SFRA.

I. INTRODUCTIONS

The petroleum based mineral oil has traditionally been used in transformer as a dielectric medium, coolant and diagnostic tool. The significant experience has been gained in mineral oil filled transformers [1-10]. Unfortunately, mineral oil is harmful to the environment if spilt and it is not biodegradable. Recently, power industry has expressed a growing interest on renewable technologies of ester oils which are rapidly emerging for environmentally friendly, as viable potential alternatives to mineral oil for transformer applications. Because of their advantages, ester oils will play an increasing role in transformer of the future as part of the networks [7-10].

Due to different physical, thermal and chemical compositions of ester oil from mineral oil, it is important to ensure that ester oil filled transformer needs to have different design rules (electrical and thermal), manufacturing, impregnation and execution process with respect to mineral oil filled transformer [5-10]. As ester oils having different molecular structure and chemical composition from mineral oil, hence it is mandatory to investigate their behavior and influence on transformers. Extensive work has been published to understand the physical and chemical properties of ester oils with mineral oils [1-14].

Apart from understanding of differences in physical, chemical and dielectric properties of ester oil, higher permittivity of ester oil as compared to mineral oils is also key difference which affect electrical performance of transformers along with electric stress distribution [9,10,13,14]. The electric stress in a composite system is shared between the oil and cellulose as a function of the dielectric constants of the materials. Since, the higher permittivity of ester oil and cellulose insulation are more evenly matched the electric stress should be more equally shared [15]. Hence, it would be of interest to analyze the effect of permittivity changes of natural ester oil and mineral oil.

This paper utilizes concept of SFRA to account for effect of permittivity changes on natural ester oil transformer. Generally, the frequency response analysis of transformer is quite sensitive to physical configuration and material characteristics of windings [16-23]. In addition, dielectric permittivity modifies the frequency responses for a given geometry of insulation systems, temperature, moisture content in the insulation. Thus, all these factors are carefully controlled in this study during impregnation and drying process of oil and solid insulation in order to solely observe the effect of permittivity on changes in natural ester oil with respect to mineral oil. Interpretations of frequency responses are performed between frequency domain responses of mineral oil and natural ester oil using graphical analyses and numerical indices.

II. EXPERIMENTAL DESCRIPTIONS

A. Liquid dielectrics for transformer applications

For majority of transformer, mineral oil is acceptable, years of experience with using mineral oil in both distribution and power transformer has led to accumulation of a large knowledge database, cost effective, good dielectric properties and better compatibility with cellulose insulations. The mineral oil has a mixture of various hydrocarbon molecules structures of paraffinic, naphthenic and aromatic [5-8,13,14]. Naphthenic oil has very low level of naturally occurring n-paraffins than paraffinic oil and it has more polar features than paraffinic oil due to presence of aromatic molecules [13,14]. To improve the oxidation stability of the mineral oil, mineral oil may contain oxidation inhibitors of 2,6-di-tertiary-butyl-4-methylphenol or 2,6-di-tertiary-butyl-para cresol (DBPC). Mineral oil has some serious disadvantages

of which the worst is its high flammability to low fire point and less biodegradability. Hence, in applications where fire safety and protection of the environment are very important considerations, transformer based on alternative oils of ester oil can be a more viable option.

The use of ester oils as alternative of mineral oil in transformers is not new technology; ester oils have been used for many years in distribution transformers. Lately, there has been a clear trend to use ester oils at ever increasing voltages and power ratings and now there are many examples of ester oils being used in power transformer. The ester oil is derived either from renewable materials (such as rapeseeds and soyabeens for natural ester oil) or synthetically by chemical reactions (for synthetic ester oil). The main molecular component of natural ester oil is triacylglycerols (sometimes called triglycerides) with three different C18 fatty acid chains which will contain one, two or even three double bonds. The fatty acids are saturated, mono unsaturated and poly unsaturated. The chemical composition of fatty acids will give the physical properties of oil mainly, viscosity and oxidation stability [5-8]. In addition, natural ester oil is more polar than mineral oils due to presence of ester linkages. Therefore, the main differences in chemical composition of ester oil are manifested among differences in oil properties interms of physical, chemical, thermal. In this study, Transol grade of mineral oil (naphthenic inhibited base), produced by Savita Oil Technologies Limited and BioTransol grade of natural ester oil produced by Savita polymers limited are considered to compare effect of permittivity differences.

B. Transformer winding under considerations

The two identical transformers are designed and manufactured to study the effect of permittivity changes between natural ester oil and mineral oil. The two identical transformer are designed in such a way to have the same winding resistance, self inductance, mutual inductance, winding capacitance and ground capacitance by having equal number of turns / disc, total no of disc, inter-disc and interturn insulation, conductor dimension and height of the windings etc.,[8]. Since, physical and chemical properties of natural ester oil are different from mineral oil, residual oils effect in the solid insulation can be avoid with two identically manufactured transformer windings.

The transformer has continuous discs type of low voltage (LV) and high voltage (HV) windings. LV winding is placed adjacent to core and then HV winding is set between HV winding and tank. Both LV and HV winding has 62 disc with 10 turns/ disc with the winding conductor dimensions of 12.5 width and 2.2mm thickness. The inter-disc insulation and inter turn insulation of the windings are considered as 6mm of cellulose based pressboard and 1.2mm of thermally upgraded paper. To represent the core inside the LV winding as mild steel plate is used. The top and bottom insulation of both LV and HV windings is 80mm. The insulation between LV and HV winding and core to LV windings are 8mm and 35mm respectively. Hence, design and dimensioning of insulation arrangement has been done judiciously in this transformer, which is based on typical manufacturing practices.

C. Drying and impregnation of transformer insulation

The solid insulation materials used in the transformer are kraft paper, crepe paper, pressboard and permawood, which are formed from the cellulose based insulation. The cellulose insulation has an excellent capacity for being impregnated with oil, thereby improving their insulation strength. Hence, cellulose insulation with oil plays a major role as insulation system for transformers for a very long time [15]. As insulation systems of transformer is made of cellulose based insulating material whose moisture content adversely affects dielectric strength hence, proper drying procedure is mandatory for reliable operation of transformer [15]. Insulation drying procedure generally depends on insulation weight and type of insulation material used in the transformer. In this study, vapor phase drying is used to remove the moisture from the solid insulation. Vapour phase drying is advantageous as compared to conventional drying as solvent used in producing vapour has 'dry-cleaning' action, which removes oil and debris present in the insulation.

As removal of moisture in the winding insulation leads to loosening of winding parts, hence winding is reclamped with force of 60 kN. After reclamping of transformer winding, winding is mounted in mild steel tank which contains 3500 liters of oil. The tank is closed immediately to avoid residual moisture in the solid insulation during tanking. Before oil filling under vacuum into the tank, oil is degassed, filtered with whatmann filter paper of size 0.45 µm and heated at 70°C under vacuum of 720-740mmHg pressure [13,14]. The properties of processed oil for experimental analysis is given in Table I.

TABLE I. PROPERTIES OF PROCESSED OIL FOR EXPERIMENTAL ANALYSIS

Parameters of oil	Mineral oil	Natural ester oil
	Transol grade	BioTransol grade
Breakdown voltage in kV at 2.5mm gap	65-70	65-70
Water content in ppm	5-6	50-55
Loss factor at 90 °C	<0.5%	<0.5%
Relative permittivity of oil	2.2	3.3
Viscosity at 40 °C mm^2/sec	8.83	32

The electronegative property of oxygen atom in natural ester oil makes more polar compound than mineral oil which will aggravate the electrification due to higher oil flow rate. To avoid electrostatic charging problems and higher viscous nature of natural ester oil and reducing risk of creation of air pockets, oil filling rate is limited to 1000 litres per hour. After oil filling into the tank, impregnation time of 48 hrs given under vaccum. Hence, the typical transformer manufacturing and process are followed in this experimental analysis for both mineral oil and natural ester oil.

III. SWEEP FREQUENCY RESPONSE ANALYSIS

SFRA is a non-invasive, low voltage diagnostic test to measure the frequency domain responses of the transformer winding and compare the outputs with references responses in frequency domain [22,23]. Therefore, it provides comprehensive information about mechanical and electrical integrity of active part of transformers.

In this paper, the frequency domain responses of the mineral oil filled transformer is considered as a reference response and natural ester oil filled transformer results are compared with it. Although SFRA is emerging as a powerful diagnostics technique, there is still no general guidelines for interpretations of frequency response. Table II shows the different frequency regions of SFRA and influencing factors in transformer [23,24].

TABLE II.VARIOUS FREQUENYC REGIONS FOR SFRA ANALYSIS

Frequency region	Key factors
< 2 kHz	• Response is purely inductive • Resonance caused by interaction of shunt capacitance of winding with magnetizing inductance.
2kHz-100kHz	Interaction of shunt capacitance and air-cored inductance of windings.
100kHz-1MHz	Interaction between air inductance of winding and series or/and parallel capacitance of winding parts
1MHz	Influence of leads and connection to ground

SFRA techniques are based on graphical analysis using numerical indicator to investigate the frequency domain responses. Graphical analysis comprises of accounting either changes in shape of the curve, creation of new resonant frequency, elimination of existing frequencies, any shifts in resonant frequencies or changes in peak values. However, graphical analyses requires trained expert to interpret test results [21].

To measure the interdependence (symmetric measures) between signals, one can utilize the principle of numerical indicators (either in the time domain or frequency domain). The various numerical indicators have been proposed to analyze SFRA measurements results based on fundamentals of signal processing, mathematical and statistical analysis. In this paper, the commonly used numerical indicators are correlation coefficient, standard deviation, absolute sum of logarithmic error, maximum square error and max-min ratio used to analysis the effect of permittivity changes in ester oil filled transformer with respect to mineral oil filled transformer [21,25].

- Correlation Coefficient

The correlation coefficient is a statistical measure to calculate the strength of relationship between two signals. The correlation coefficient is a bounded measure between one and zero and it is unit less measurement. The highest positive value of one indicates stronger correlation between two signals while zero indicates no linear association.

- Standard deviation

Standard deviation measures the amount of variation or dispersion between the signals. Standard deviation value as 0 indicates a perfect match between two signals, while value greater than zero indicates that the data points are scattered. Standard deviation is an unbounded measure.

- Absolute sum of logarithmic error

Absolute sum of logarithmic error is utilized to realize logarithmic scale comparison between the signals. As absolute sum of logarithmic error compares on logarithmic scale, it will minimize the smaller deviations between two signals. The zero value of absolute sum of logarithmic error indicates that the two signals are perfectly matched well while its value greater than zero indicates dispersion of data points in wider range of values.

- Mean squared error

The mean squared error or mean squared deviation is used to measure the average of squares of the errors. In other words, this average squared difference between the estimated values and the actual value. Hence, mean squared error can be used to suppresses small errors and it will magnify the large errors between the two signals. The mean squared error is always non-negative and values closer to zero are better. If the value of mean squared error value is zero then this indicates two signals are matching perfectly.

- Maximum-Minimum ratio

The maximum-minimum ratio is defined as ratio of calculated maximum value by calculated minimum value to compare peak changes in magnitude plots between two signals since it is very sensitive towards peak changes. If two signals are matches maximum – minimum value will be one.

IV. EXPERIMENTAL RESULTS

Experimental set-up is established to observe changes in relative permittivity in transformer due to variation chemical compositions of mineral oil and natural ester oil. Generally, due to variation in temperature in the insulation and moisture, insulation characteristics changes. Hence, temperature and moisture are well controlled to study the effect of changes in relative permittivity alone between mineral oil and natural ester oil. The relative permittivity of oil and oil impregnated cellulose insulations are given in Table III.

TABLE III. SPECIFICATION OF INSULATION USED IN THIS STUDY

Insulation		**Relative Permittivity**
Liquid Insulation	Mineral oil	2.2
	Ester oil	3.3
Solid insulation impregnated with mineral oil	Kraft paper	3.5
	Pressboard	4.4
Solid insulation impregnated with natural ester	Kraft paper	4.1
	Pressboard	4.8

Though, the several different FRA measurement connections are performed in the transformer winding, the following three connections are presented with voltage application on high voltage winding in order to understand the effect of relative permittivity changes in ester oil.

- Un grounded core and low voltage winding (open circuit).
- Grounded core and open circuited low voltage winding.
- Grounded core and shorted low voltage winding to grounded.

A. Ungrounded Core and Low voltage winding

Figure 1(a) and Table IV shows results of core and LV winding are not grounded and voltage is supplied to HV winding. From Figure 1 (a), following points are observed.

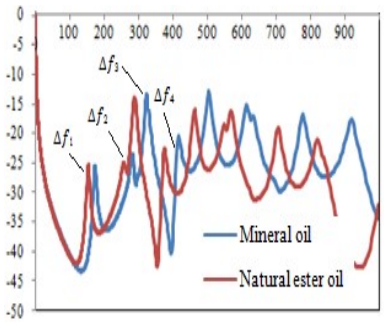

Figure 1(a)

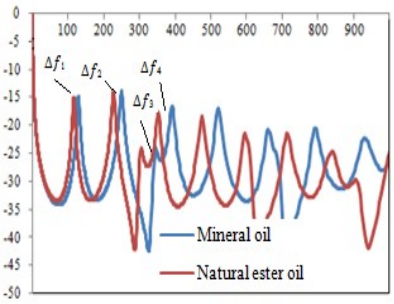

Figure 1(b)

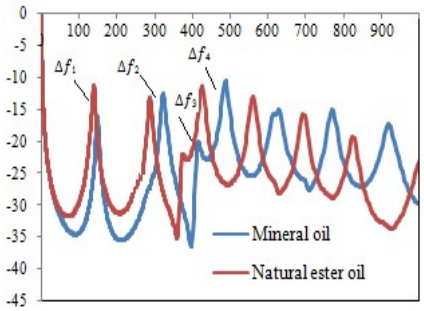

Figure 1(c)

Figure1. Frequency domain responses of transformer winding due to changes in the permittivity of natural ester oil

TABLE IV. RESONANT FREQUENCIES SHIFTS IN PEAK AND RESULTS OF NUMERICAL INDICATORS

Parameter		Core and LV winding not connected to ground	Core grounded and LV winding not grounded	Core and LV winding grounded
Resonant frequency in kHz	First resonance, Δf1	17	10	12
	Second resonance, Δf2	24	15	14
	Third resonance, Δf3	30	20	22
	Fourth resonance, Δf4	40	25	26
Numerical indicator	Correlation Coefficient	0.9752	0.9700	0.9656
	Standard deviation	5.9917	6.3371	6.4216
	Absolute sum of logarithmic error	0.0884	0.1265	0.1059
	Mean square error	35.8648	40.1188	41.1962
	Max-Min ratio	1.1465	1.166	1.2013

- In low frequency region (<100 kHz), frequency domain responses of natural ester oil and mineral oil are similar in nature.
- In high frequency region (>100 kHz), the significant deviation in resonant frequencies shift are observed. The frequency responses of natural ester oil is shifted to lower frequency regions.

The magnitude values are not clearly differentiable at first and second frequencies. However, it can be observed that slight change in magnitude is found in third resonance frequency and for further frequencies. To account for precise computation of frequency shift and magnitude differences, numerical indicator values are obtained.

Following points are observed from numerical indicator results.

- Correlation coefficient deviates to 0.9752 from ideal value of 1 which corresponds to perfectly matching responses. However, the lower value of correlation coefficient describes mismatch in two responses.
- Standard deviations along with mean squared error significantly deviates from their ideal value of zero. However, there is no much significant deviation in values of Absolute sum of logarithmic error and max-min ratio from their ideal value of perfectly matching response

B. Grounded core and open circuited low voltage winding

Figure 1(b) shows results for core is connected to ground and LV winding not grounded. From Figure 1(b) and Table IV, following points are observed.

- In low frequency region (<100 kHz), responses of natural ester and mineral oil do not exhibit deviation. In higher frequency region (>100 kHz), natural ester oil resonant frequencies are observed at lower scale as compared to mineral oil. Table IV displays difference in frequencies of resonant peaks occurring in mineral and natural ester.
- Magnitude difference is not clearly visible at starting resonant frequencies. However, it can be observed at later resonant peaks.

C. Grounded core and shorted low voltage winding to grounded

Figure 1(c) shows the results core and LV windings connected to ground. From Figure 1(c), there is no deviation in low frequency region (<100 kHz) in mineral and natural ester oil. However, frequency shifts are observed and natural ester oil displayed lower resonant frequency same as in earlier two cases.

V. INFERENCES FROM EXPERIMENTS

From, aforementioned experimental analyses following common conclusions can be studied

- In low frequency regions, there is no difference in resonance frequencies between natural ester oil and mineral oil and this indicate that relative permittivity changes in the natural ester oil do not affect inductance property which is solely a magnetic quantity and permittivity reflecting its properties related to electric quantities.
- In high frequency regions (>100 kHz), natural ester oil and mineral oil resonance frequencies differences are clearly visible due to capacitance effect. Since relative permittivity has shown significant impact in higher frequency region, hence it can be concluded to have direct effect on winding capacitance which comprises inter-winding capacitance as well as interturn & inter-disc capacitance of winding itself.
- The correlation coefficient relies on shape of two responses and correlation coefficient is independent of magnitude of signals. Similarly, absolute sum of logarithmic error will neglect the smaller variation between the signals due to logarithmic computation. Hence, absolute sum of logarithmic error will provides less accurate and sensitive. The standard deviation will measure the amount of variation between two frequency responses along with mean squared error signifying the larger deviations. In additions, ratio of max-min calculation is sensitive towards the changes in magnitude between the responses.

V.CONCLUSIONS

In this paper, experimental analyses are performed to investigate the effect of permittivity changes in natural ester oil with respect to mineral oil based on frequency domain analysis. During experiment, moisture content in insulation along with temperature is maintained constant to demonstrate effect of permittivity solely. In low frequency region, results illustrated no effect of permittivity while shift in resonant frequencies is observed in higher frequencies regions. To investigate the frequency domain analysis between mineral oil and natural ester oil, numerical indicators are utilized effectively. The numerical indicators are used to measure how closely the frequency domain responses are formed. Based on the characteristics of the numerical indicator parameters, changes in frequencies or peak are predicted without effect in temperature and moisture.

REFERENCES

[1] J. K. Nelson, "An assessment of the physical basis for the application of design criteria for dielectric structures," IEEE Trans. Electr. Insul., Vol. 24, No. 5, pp. 835 – 847, 1989.

[2] E. O. Forster, "Progress in the field of electrical breakdown in dielectric fluids," IEEE Trans. Dielectr. Electr. Insul., Vol. 20, No. 6, pp. 905–912, 1985.

[3] E. O. Forster, "Critical assessment of the electrical breakdown process in dielectric fluids," IEEE Trans. Dielectr. Electr. Insul., Vol.20, no. 4, pp. 891–896, Oct. 1985.

[4] A. Beroual, and R. Tobazeon, "Prebreakdown phenomena in liquid dielectrics," IEEE Trans. Electr. Insul., vol. 21, no.4, pp. 613–627, Aug. 1986.

[5] Q. Liu, "*Electrical performance of ester liquids under impulse voltage for application in power transformers*," PhD dissertation, School of Electr. and Electronic Eng., The University of Manchester, UK., 2011.

[6] X. Wang, "*Partial discharge behavior and breakdown mechanisms of ester transformer liquids under ac stress*," PhD dissertation, School of Electr. and Electronic Eng.,The University of Manchester, UK., 2011.

[7] Wu Lu, "*Prebreakdown and breakdown phenomena of alternative transformer liquids under lightning impulse voltages*," PhD dissertation, School of Electr. and Electronic Eng.,The University of Manchester, UK., 2011.

[8] Muhammad Daghrah, "*Experimental study of transformer liquid flow and temperature distributions*", Ph.D thesis, The university of Manchester, 2017.

[9] Dhruvesh M. Mehta, P. Kundu, V. K. Lakhiani and A. S. Jhala, "A review of critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part I", IEEE Trans. Dielectr. Electr. Insul., Vol.23, Issue 2, pp. 873 – 880, 2016.

[10] Dhruvesh M. Mehta, P. Kundu, V. K. Lakhiani and A. S. Jhala, "A review of critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part II", IEEE Trans. Dielectr. Electr. Insul., Vol.23, Issue 3, pp. 1705-1712, 2016.

[11] Muhammad Daghrah, "*Experimental study of transformer liquid flow and temperature distributions*", Ph.D thesis, The university of Manchester, 2017.

[12] Xiang Zhang, "Dimensional analysis based CFD modeling for power transformers", Ph.D thesis, The university of Manchester, 2017.

[13] Pavitra Sharma, Ritika Agarwal, Anjali Uppal, C.S. Narasimhan, Girish A Morde and Jeyabalan Velandy, "Lightning impulse polarity effect in ester oils and mineral oil for transformer applications ," IEEE Condition Assessment Techniques in Electrical Systems (CATCON), Acceted for publications, 2019.

[14] Anjali Uppal, Ritika Agarwal, Pavitra Sharma, Jeyabalan Velandy, C.S. Narasimhan and Girish A Morde, "Effect of dielectric strength of mineral oil on mixing with a natural ester oil as a polar contaminant under AC stress," IEEE Condition Assessment Techniques in Electrical Systems (CATCON), Acceted for publications, 2019.

[15] S.V. Kulkarni and S.A. Khaparde, *Transformer engineering: design and practice*. CRC Press, 2004.

[16] J. Christian and K.Feser, "Procedures for detecting windingdisplacements in power transformers by the transfer function method", IEEE Trans. Power Deliv., 2004, 19, (1) pp. 214–220.

[17] S.A. Ryder "Methods of comparing frequency response measurements," Proc.IEEE Int.Symp.Electr Insul.,2002,pp.187-190

[18] V. Behjat, M. Mahvi and E. Rahimpour, "New statistical approach to interpret power transformer frequency response analysis: Non-parametric statistical methods", IET Sci. Meas. Technol. 2016, 10, 364–369.

[19] M. Bagheri, B.T, Phung and T. Blackburn, "Transformer frequency response analysis: mathematical and practical approach to interpret mid-frequency oscillations," IEEE Trans. Dielectr. Electr. Insul. 2013, 20, 1962–1970

[20] E. Rahimpour, J. Christian, K. Feser and H. Mohseni, "Transfer function method to diagnose axial displacement and radial deformation of transformer winding," IEEE Trans. Power Delivery, vol. 18, no. 2, April 2003, pp. 493-505.

[21] P.M. Nirgude, D. Ashokraju, A.D. Rajkumar and B.P. Singh, "Application of numerical evaluation techniques for interpreting frequency responses measurements in power transformers", IEE Proc. Sci. Meas. Technol. 2 (5) (2007) 275–285.

[22] IEEE Std. C57.149-2012 "*IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers*", pp. 1- 72, 2013.

[23] IEC 60076-18, "*Power transformers –Measurement of frequency response*", International Electrotechnical Commission, Ed.1 2012,

[24] E. Rahimpour, J. Christian, K. Feser and H. Mohseni, "Transfer function method to diagnose axial displacement and radial deformation of transformer windings", IEEE Trans. Power Delivery, Vol. 18, pp. 493-505, 2003.

[25] W. Hauschild and W. Mosch, *Statistical Techniques for High Voltage Engineering*, IEEE Power Series, Peregrinus Ltd., London, UK, 1992.