Australian Journal of Basic and Applied Sciences, 7(11) Sept 2013, Pages: 7-14

AENSI Journals

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Online Surface Condition Monitoring System using Time Frequency Distribution on High Voltage Insulator

N.Q. Zainal Abidin, A. R. Abdullah, N.Norddin, A.Aman

Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia

ARTICLE INFO

Article history:
Received 5 September 2013
Received in revised form 24 October 2013
Accepted 25October 2013
Available online 20November 2013

Key words:
Leakage current, time-frequency distribution, Spectrogram, real time monitoring

ABSTRACT

Polymeric composite insulation is widely used for high voltage engineering as they are light, easy to fabricate, and have good dielectric properties. Ageing factors are several factors that affect the long term performance of insulating material. One of the key methods to measure the expected physical, chemical change, hydrophobicity condition as well as surface condition is leakage current characteristic. Leakage current is broadly accepted as tools in the determination of surface condition and level of its severity. Hence, an automated monitoring system is needed to reduce diagnostic time, rectify severity and ensure quality of insulators performance. Fast Fourier Transform gives useful information on the analysis of leakage current, but it has some limitation in non-stationary signal that does not provide temporal information. Instead, the new leakage current analytical technique with time frequency distribution approach is employed. This research used spectrogram as time frequency distribution technique that represents the leakage current signals in the joint time frequency domains which they are very appropriate to analyse the leakage current signals that consist of multi-frequency components and magnitude variations. Signal parameters such as instantaneous root mean square and fundamental root mean square current, total harmonic distortion, total non-harmonic distortion, and total waveform distortion are estimated from time-frequency representation. Tracking and erosion test complying with BS EN 60587-2007 are conducted to capture the set of leakage current patterns which are capacitive, resistive, and discharge activities. Based on the analysis, the severity of the insulators could be determined from the percentage of total waveform distortion. Thus, the outcome of this study shows that the system is very appropriate and reliable to be implemented for leakage current online monitoring system.

INTRODUCTION

In high voltage engineering or its applications, insulators are widely used in power industry. It is the most important part to prevent the flow of current to undesired paths and to resist stresses (mechanical stresses, electrical stresses, and environmental stresses)(Ramirez *et al*., 2012a). A good insulation system give better design, performance and life span of the electrical apparatus. Even though they has been used widely, there are still many issues such as ageing performance, expected lifetime and their long-term reliability are not known and therefore are a concern to users. A large number of studies and research activities for improvement on insulator performance have been made. These include the development of new materials, the understanding of deterioration of chemical, electrical and mechanical over the stress, design and manufacturing process of material, and also development of practical testing, monitoring, reliability methods of measuring and service performance.

The dielectric strength and electrical field are a key properties of insulating material and they become the major factors that determine the failure of the insulation(M.S Naidu and Kamaraju, 2009). They are easily exposed to the effects of pollution such the open air that causes tracking and erosion as well as to flashover(El-Hag *et al*., 2010). Measurement of leakage current (LC) can be an effective method for minimizing the pollution flashover of insulators, and better if requires additional information from measurements and analysis of the pollution(Ramirez *et al*., 2012b). For LC performance factor that should be controlled is flashover mechanism because of dry band formation on the surface. Basically, LC signal that leads to surface flashover consists of capacitive current, resistive current, non-linear current and non-linear with discharge current (M. A. R. M. Fernando and Gubanski, 1999). Measurement of the LC such as amplitude, pulse, accumulated charge and discharge duration has been used to provide information on degradation (Fernando and Gubanski, 1999). The degradation process can develop significantly on the insulator surfaces, because of appearing LC and discharges. For this reason, measurements of LC are often performed in order to

Corresponding Author: N.Q. Zainal Abidin, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia

evaluate the performance of the material surface condition.

In many applications in processing, we are interested in the frequency content of a signal locally in time. That is the signal parameters (frequency content, etc.) evolve over time. Such signals are called non-stationary signal. For non- stationary signal, the standard FT is not useful for analyzing the signal [13]. Information which is localized in time such as high frequency bursts cannot be easily detected from FT. Furthermore, in time or frequency domain plot, it just gives half of the information about the signal. A frequency domain plot will tell "what" the signal looks like, but does not notify “when” it occurred. Meanwhile, a time domain plot will present "when" something happened, but it does not notify "what" happened. Another reason was reported by C.Muniraj and S.Chandrasekar (C.Muniraj and S.Chandrasekar, 2009) who found that the analysis of LC in polluted polymer insulator shows that FFT is fast in computation but possess limitations in resolution. Onwards literatures show, LC harmonic component analysis give better information (Fernando and Gubanski, 2010, Fernando and Gubanski, 1999, Chandrasekar *et al*., 2009, Kumagai *et al*., 2006). G.P Bruce and S.M Rowland (G. P. Bruce and Rowland, 2010), Suwarno *et al* (Suwarno and Ardianto, 2008), A.H El Hag *et al* (A. H. El-Hag *et al*., 2001, El-Hag, 2005, Ayman H. El-Hag *et al*., 2003) and Hussein Ahmad (Hussein Ahmad *et al*., 2008) examined low harmonic components of LC as a diagnostic tool to study aging and surface condition. A correlation was found that frequency component correspond to surface discharge event as well as high pollution severity.

Therefore, to overcome these limitations, time frequency distribution (TFD) with spectrogram technique is used. There are other TFD that can be used such as Gabor, S-transform and Wavelet methods. These types of analysis have been successfully employed in signal processing application such as seismic data analysis, audio processing, sonar application and etc. Spectrogram is performed to detect the surface event of the insulator materials. Incline Plane Tracking (IPT) test that complying with BS EN 60578-2007 was conducted on polypropylene polymeric composite to simulate a set of different LC; from capacitive state, resistive state, non-linear state and non-linear with discharge state.

A computer-based online LC monitoring of the insulators surface is found to be more practical due to the long period of time taken in conducting the laboratory test. Online performance monitoring can benefits engineering industries by confirming if the materials is performing as desired by the user. Monitoring system gives instantaneously information on LC parameters such its harmonic components. Normal performance analyses are usually conducted in offline mode which the LC data is saved into other files to be analyzed later.

This paper describes the online LC monitoring system that classifies LC signals in time domain, frequency spectrum, time-frequency representation as analysis method, LC parameters such as root mean square (RMS) value, fundamental value, total harmonic distortion (THD), total non-harmonic distortion (TnHD), and total wave distortion (TWD). These parameters instantaneously is estimated in order to develop and monitoring state condition of the materials insulating condition. The percentage of total waveform distortion TWD% is applied as rule based value for surface classification purpose. The results of LC analysis the online monitoring system is compared with other software that also used to monitor and analyzed the LC performance. This comparison is certainty that the online monitoring system is reliable and can be used in the industry.

Hardware Development:

The Inclined-Plane Tracking (IPT) test is one of the major methods for evaluating tracking and erosion resistance for outdoor insulation. This test evaluates the relative ability of an insulating material to withstand the action of electrical discharges on the surface and further explanation regarding the test installation is described in (Ahmad Darus, 2003). The LC flows along the sample surface when the sample is energized with high voltage stress under wet contaminated. The system for evaluating the surface tracking and erosion test along with the online LC monitoring system is shown in Fig. 1. The whole system is placed inside a separated room to avoid any outside noise or disturbance that could affect the test measurement.

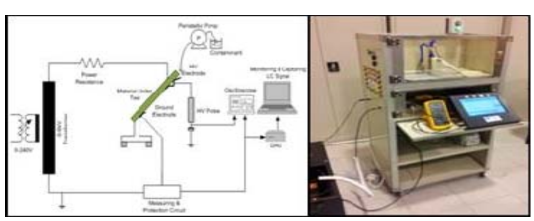

Fig. 1: Schematic diagram of Incline-Plane Tracking (IPT) test

Fig. 1 shows the schematic diagram and hardware development of the IPT test which is conducted following BS EN 60578-2007 standard procedure in (2007). The details of the components and equipments were per standard. A 0-6 kV voltage transformer is used to supply a voltage stress across a contaminated sample via high power 22kΩ-200W ± 10% resistor. The sample is wet contaminated by flowing down continuously the contaminated solution on top of the sample through a PVC tube. The contaminated solution is electrolyte solution that contains 0.1% ammonium chloride and 0.02% by mass nonionic wetting agent Triton X-100. The conductivity of the contaminant solution is 2.5mS/cm, and a peristaltic pump is used for supplying the contaminant solution at a flow rate setting of 0.3ml/min. High voltage probe with ratio of 1000:1V is used to measure the supplied voltage.

Measuring unit which is data acquisition used to capture the LC that flows down on the sample surface. Data acquisition functions as a device that digitizes incoming analog signals so that computer can interpret them. The captured LC is obtained by measuring the voltage drop across a 0-1kΩ variable resistor, which is connected in series with the ground electrode. The output from measuring circuit of resistor is connected to 4-channels of data acquisition device with sampling rate setting of 10kS/s. The graphical user interface (GUI) of visual basic (VB) controls the operation of the DAQ device and used for processing, visualizing, and storing measurement data. Different types of computers are used in different types of applications.

Leakage current monitoring system:

An LC data acquisition system is developed to analyze the LC flowing on the sample surface under laboratory conditions. It consists of three parts; measuring unit (as stated earlier), signal conditioning, and analog-to-digital (ADC) with personal computer. The graphical results of the LC signal are developed using VB software in the personal computer. VB applies events driven programming language and allows users to click on a certain object randomly to make some action. More specifically, the system is designed for interactive user interface. The data is entered and then the result is viewed on the computer screen. The front panel of the graphical user interface (GUI) of the developed program is shown in Fig. 2. The designation illustration as in Fig. 2 has a multi-frame sequence structure, which consists of more sub-diagrams or frames that execute sequentially. Each frame indicates the process of data calculation for the required output, which is LC signal captured from DAQ device, power frequency spectrum, time frequency representation (TFR), instantaneous RMS current and instantaneous fundamental RMS current, instantaneous THD and TnHD, and finally instantaneous TWD. Also it can classify the pattern of the input LC signal at the bottom of the front panel.

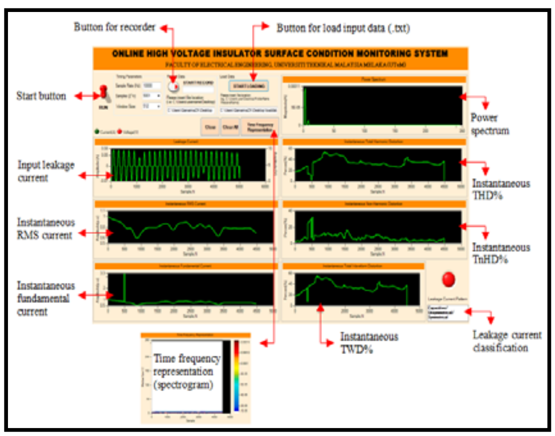

Fig. 2: Front panel of leakage current monitoring system

Signal Analysis:

LC signal samples (discrete time) obtained from DAQ devices constitutes the time domain representation of the signal. This provides a representation of the signal amplitude at that point of time in which it was sampled. Fourier transform (FT) is mathematical techniques which convert signal from time to frequency domain. The sample values of a signal (time domain representation) are converted into frequency domain representation by means of discrete Fourier Transform (DFT), which can be defined as(Soliman and Srinath, 1998, Hayes, 1999);

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi k\left(\frac{n}{N}\right)} \quad (1)$$

For (k = 0, 1, 2, …, N-1), where N is a number of samples and $x(n)$ is a sampled signal. The signal is sampled at a sampling rate of fs Hz. The time interval between the samples is Δt, where;

$$\Delta t = \frac{1}{f_s} \quad (2)$$

Time localization can be achieved by first windowing the signal and then taking its Fourier transform. This gives rise to the short time Fourier transform (STFT) or windowed Fourier transform (Boashash, 2003). The continuous time STFT of a signal, $x(t)$ is defined as;

Australian Journal of Basic and Applied Sciences, 7(11) Sept 2013, Pages: 7-14

$$\rho_x(t,f) = \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-j2\pi ft}\,d\tau \tag{3}$$

where *w(t)* is the observation window. The squared magnitude of the STFT is commonly used in signal analysis wherein it is known as spectrogram. Spectrogram as shown in Fig. 3 provides a distribution of the energy of the signal in a time- frequency plane which given the equation;

$$P_x(t,f) = \left| \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-j2\pi ft}\,d\tau \right|^2 \tag{4}$$

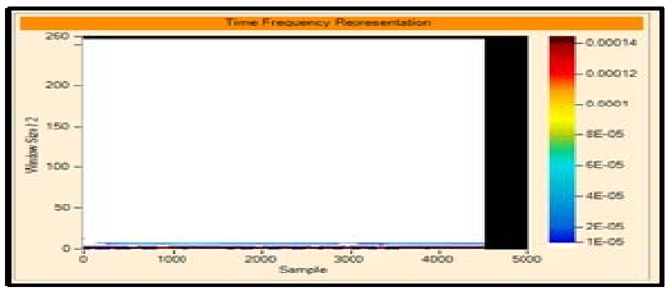

Fig. 3: Time frequency representation (TFR)

Signal parameters are estimated from the TFR in order to present information of the signal in time. These parameters are instantaneous RMS current and instantaneous fundamental RMS current, instantaneous THD and TnHD, and finally instantaneous TWD. The current magnitude, I_{rms} can be derived from TFR in time and referred as instantaneous RMS current, $I_{rms}(t)$, which is;

$$I_{rms}(t) = \sqrt{\int_{0}^{f_s} P_x(t,f)\,df} \tag{5}$$

where $P_x(t,f)$ is the TFR of signal and f_s is sampling frequency of the system. Also from TFR, the instantaneous RMS fundamental current, $I_{1rms}(t)$, can be calculated as;

$$I_{1rms}(t) = \sqrt{2\int_{f_{lo}}^{f_{hi}} P_x(t,f)\,df} \; ; f_{hi} = f_0 + 25Hz, f_{lo} = f_0 - 25Hz \tag{6}$$

where f_0 is fundamental frequency that corresponds to the power system frequency. 25Hz is chosen for f_{hi} and f_{lo} since it can cover the fundamental frequency component to calculate the magnitude of the frequency component. While THD is used to measure of how much harmonic content in a waveform (Bollen and Gu, 2006). The instantaneous THD(t) of a waveform is defined as;

Australian Journal of Basic and Applied Sciences, 7(11) Sept 2013, Pages: 7-14

$$THD(t) = \frac{\sqrt{\sum_{h=2}^{H} I_{h,rms}(t)^2}}{I_{1rms}(t)} \qquad (7)$$

where $I_{h,rms}(t)$ is harmonic current from 2^{nd} to 100^{th} harmonics. While the instantaneous TnHD(t) of a waveform can be written as;

$$TnHD(t) = \frac{\sqrt{I(t)_{rms}^{\;2} - \sum_{h=0}^{H} I_{h,rms}(t)^2}}{I_{1rms}(t)} \qquad (8)$$

Waveform distortion represents all deviations of the voltage waveform from the ideal sinusoidal waveform in terms of magnitude or frequency the signal (Kusko and Thompson, 2007). The TWD is used to quantify the distortion of a waveform and defined as the relative signal energy present at non-fundamental frequency which consists of harmonic distortion and non-harmonic distortion;

$$I_{TWD}(t) = \sqrt{I_{THD}(t)^2 + I_{TnHD}(t)^2} \qquad (9)$$

RESULT AND DISCUSSIONS

The effectiveness and reliability of the online monitoring system is tested by conducting an experiment according to the IPT method. A polypropylene is used for testing the influence of hydrophobicity on the LC behavior. Different stages of the LC behavior are recorded from the experiment as illustrated in Fig. 4 until Fig. 8. Fig. 4 shows the frequency spectrum where the x-axis represents the size of window function which in this study 512 is used.

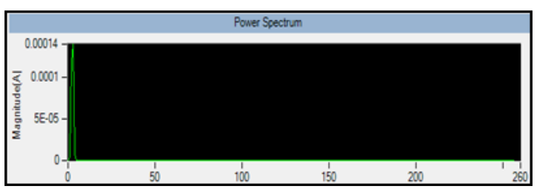

Fig. 4: Frequency spectrum

Hann (Hanning) window is selected because of its lower peak side lope (Jayasundara *et al*., 2008) which is narrow effect on other frequencies around fundamental value (50 Hz in this study) and other frequency components. The highest power in spectrogram represented in red colour, while the lowest is blue colour as seen in Fig. 3.

LC can be classified into capacitive type, resistive type, and non-linear type. During experiment, it is observed that at low voltages level between 0-0.5 kV, there is no erosion and arcing activities occurred on the insulation material. The material used in this study is polymer type. At this level of voltage, the LC is classified to capacitive type as shown in the Fig. 5.

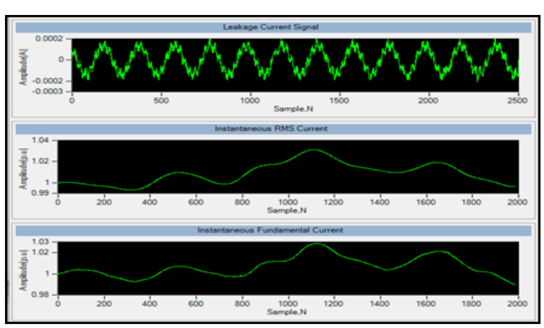

Fig. 5: Capacitive pattern

Australian Journal of Basic and Applied Sciences, 7(11) Sept 2013, Pages: 7-14

On the other hand, at voltage levels between 0.5-2 kV, the LC is classified to resistive type which is a pure sinusoidal as shown in Fig. 6. Since the materials having the contaminant liquid at the surface before sparking occurs, LC flows and represented as pure sinusoidal waveform which there is only fundamental frequency is existed.

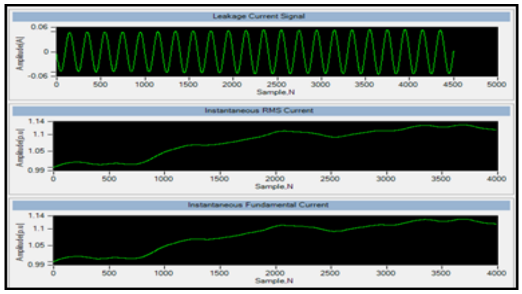

Fig. 6: Resistive pattern

The higher level of voltages until 3.5 kV will increase the energy and generate heat from arcing event and subsequently form dry-band on the surface which then leads to fast tracking and erosion(El-Hag *et al*., 2010). This phenomenon form discharge activities as shown in Fig. 7. Arcing with lower sound is produced because of dry band region resulting from evaporation of conducting film. The effect of distorted non-linear symmetrical is associated with fundamental and non-fundamental frequency component.

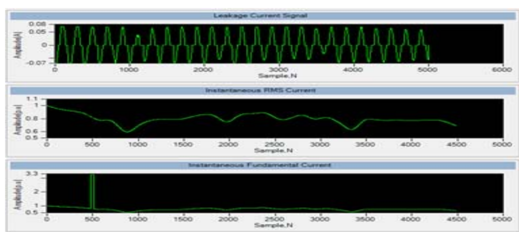

Fig. 7: Non-linear pattern

LC parameters such I_{rms}, I_{1rms}, I_{THD}, I_{TnHD}, and I_{TWD} instantaneously is estimated in order to develop and monitoring state condition of the materials insulating condition. The frequency component is consisting not only harmonics but also non-harmonics (also known as inter-harmonics). They are represented in percentage as in the Fig. 8.

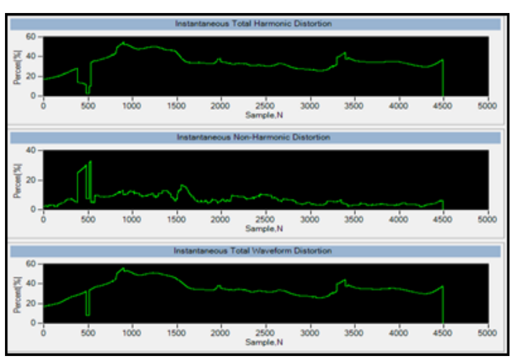

Fig. 8: Harmonic components for non-linear pattern

The percentage of total waveform distortion (TWD%) and RMS per-unit (p.u) system are used as diagnostic tools. TWD% is applied as rule based value for surface classification purpose. The intention application of TWD% and RMS p.u in this analysis is inspired by their reliability and capability in power quality analysis (Abdullah, 2011). Deviation of effective RMS to their fundamental value could be determined by using p.u system and it will represent the severity of signal distortion. From the signal parameters, the rule base is developed for the classification of LC or surface condition state. A ruled base is used to classify the surface condition events instantaneously that are summaries in Table 1.

Table I: Ruled Based Leakage Current Classification

Rule	Leakage CurrentType	TWD%	Classification
1	Capacitive	0-50%	Hydrophobic
2	Sinusoidal/Resistive	0-3%	Hydrophilic
3	Distorted symmetrical	25-60%	Dry band with low arching
4	Distorted un- symmetrical Transition from	0-150%	Dry band with high arching
5	symmetrical to un- symmetrical	>50%	Transition period

Conclusion:

The LC amplitude is directly proportional with voltage stresses, while the frequency component level of the signal can be used as indicator of surface condition event. Also, with higher content will indicate the severity of the LC signal distortion. The different in frequency component behavior is observed significantly with the LC signal shape. The non- fundamental frequency component is appearing associated with the distorted signal for capacitive and non-linear symmetrical LC signal. While, in pure sinusoidal LC signal only fundamental frequency signal is existed.

The correlation of surface event could be determined by frequency component of LC, where the higher content of frequency component represent as LAP and sinusoidal shape represent hydrophilic state of event or TP. The developed system has shown the capability in detecting the performance of insulating materials as well as identifying the characteristics of the surface discharges. Continuous monitoring system of LC is essential for reliable and safe operation since there are high risks in high voltage application besides gain accurate results.

ACKNOWLEDGEMENTS

The authors are gratefully acknowledge Ministry of Higher Education (MOHE) and Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka for giving support in this study and providing research grant of ERGS/1/2013/TK02/UTEM/02/02.

REFERENCES

2007. Electrical insulating materials used under severe ambient conditions - Test method for evaluating resistance to tracking and erosion. BS EN 60857:2007.

EL-HAG, A.H., S. JAYARAM & E.A. CHERNEY, 2001. Low Frequency Harmonic Components of Leakage Current as a Diagnostic Tool to Study Aging of Silicone Rubber Insulators. *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp: 597-600.

ABDULLAH, A.R., 2011. *time frequency analysis for power quality disturbances detection and classification.* PHD, Faculty of Electrical Engineering, Universiti Teknologi Malaysia.

AHMAD DARUS, M.A.M.P., 2003. Computer-based monitoring system for analysing surface leakage current in an IEC 587 test set-up. *JournalTeknologi*.

AYMAN, H., EL-HAG, SHESHA H. JAYARAM & E.A. CHERNEY, 2003. Fundamental and Low Frequency Harmonic Components of Leakage Current as a Diignosiic Tool to Study Aging of RTV and HTV Silicone Rubber in Salt-Fog. *IEEE Transactions on Dielectrics and Electrical Insulation,* 10: 128-136.

BOASHASH, B. (ed.) 2003. *Time-Frequency Signal & Processing: A comprehensive Reference,* Brisbane, Australia.

BOLLEN, H.J. & G.U., Y.H. 2006. *Signal Processing of Power Quality Disturbances*, Wiley-Interscience.

MUNIRAJ, C. & S. CHANDRASEKAR, 2009. Analysis of Leakage Current on Polluted Polymer Insulator by High Resolution Spectrum Estimation Method. *IEEE Third International Conference on Power System.* Kharagpur, India.

CHANDRASEKAR, S., C. KALAIVANAN, A. CAVALLINI, & G. MONTANARI, 2009. Investigations on leakage current and phase angle characteristics of porcelain and polymeric insulator under contaminated conditions. *IEEE Transactions on Dielectrics and Electrical Insulation,* 16: 574-583.

EL-HAG, A., L.H. MEYER, & A. NADERIAN, 2010. Experience with salt-fog and inclined-plane tests for aging polymeric insulators and materials. *Electrical Insulation Magazine, IEEE,* 26: 42-50.

EL-HAG, A.H., 2005. A New Technique to Detect Dry-Band Arcing. *IEEE Transaction on Power Delivery,* 20: 1202-1203.

FERNANDO, M.A.R.M. & S.M. GUBANSKI, 1999. Leakage currents on non-ceramic insulators and materials. *IEEE Transactions on Dielectrics and Electrical Insulation,* 6: 660-667.

FERNANDO, M.A.R.M. & S.M. GUBANSKI, 2010. Ageing of silicone rubber insulators in coastal and inland tropical environment. *IEEE Transactions on Dielectrics and Electrical Insulation,* 17: 326-333.

BRUCE, G.P. & S.M. ROWLAND, 2010. Performance of Silicone Rubber in DC Inclined Plane Tracking Tests. *IEEE Transactions on Dielectrics and Electrical Insulation* 17: 521-532.

HAYES, M.H. 1999. *Digital signal Processing,* USA, McGraw Hill.

HUSSEIN AHMAD, M.A. SALAM, LEE YI YING & N. BASHIR, 2008. Harmonic components of leakage current as a diagnostic tool to study the aging of insulators. *Journal of Electrostatics,* 66: 156-164.

JAYASUNDARA, H.I.S., W.P.S. SUDARSHANI, & M.A.R.M. FERNANDO, 2008. Leakage current patterns on high voltage insulators: Analysis on frequency and time-frequency domains.

KUMAGAI, S., B. MARUNGSRI, H. SHINOKUBO, R. MATSUOKA, & N. YOSHIMURA, 2006. Comparison of leakage current and aging of silicone rubbers and porcelain in both field and salt-fog tests. *IEEE Transactions on Dielectrics and Electrical Insulation,* 13: 1286-1302.

KUSKO, A. & M.T. THOMPSON, 2007. *Power Quality in Electrical Systems*, McGraw Hill.

FERNANDO, M.A.R.M. & S.M. GUBANSKI, 1999. Leakage Current Patterns on Contaminated Polymeric Surfaces. *IEEE Transactions onDielectrics and Electrical Insulation,* 6: 688-694.

NAIDU, M.S. & V. KAMARAJU, 2009. *High Voltage Engineering*, Tata McGraw-Hill Publishing Company Limited.

RAMIREZ, I., R. HERNANDEZ, & G. MONTOYA, 2012a. Measurement of leakage current for monitoring the performance of outdoor insulators in polluted environments. *Electrical Insulation Magazine, IEEE,* 28: 29-34.

RAMIREZ, I., R. HERNÁNDEZ, & G. MONTOYA, 2012b. Measurement of leakage current for monitoring the performance of outdoor insulators in polluted environments. *IEEE Electrical Insulation Magazine,* 28: 29-34.

SOLIMAN, S.S. & M.D. SRINATH, 1998. *Continuous and Discrete Signals and System,* New Jersey, Prentice Hall.

SUWARNO & ARDIANTO, S.K., 2008. Leakage Current Waveforms and Arcing Characteristics of Epoxy Resin for Outdoor Insulators under Clean and Salt Fogs. ITB J. Eng. Sci., 40: 40-60.