J Electr Eng Technol Vol. 8, No. 6: 1503-1511, 2013
http://dx.doi.org/10.5370/JEET.2013.8.6.1503

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Investigation on Flashover Development Mechanism of Polymeric Insulators by Time Frequency Analysis

C. Muniraj†, K.Krishnamoorthi* and S.Chandrasekar**

Abstract - This paper deals with the analysis of leakage current characteristics of silicone rubber insulator in order to develop a new condition monitoring tool to identify the flashover of outdoor insulators. In this work, laboratory based pollution performance tests are carried out on silicone rubber insulator under ac voltage at different pollution levels and relative humidity conditions with sodium chloride (NaCl) as a contaminant. Min-Norm spectral analysis is adopted to calculate the higher order harmonics and Signal Noise Ratio (SNR). Choi-Williams Distribution (CWD) function is employed to understand the time frequency characteristics of the leakage current signal. Reported results on silicone rubber insulators show that the flashover development process of outdoor polymer insulators could be identified from the higher order harmonics and signal noise ratio values of leakage current signals.

Keywords: Polymer insulator, Flashover, Leakage current, Min-Norm, Choi-Williams distribution.

1. Introduction

IN a power system, outdoor insulators play an important role in maintaining the reliability of the system. Ceramic insulators are widely used in power transmission and distribution lines for a long time. In recent times, polymeric insulators are mostly preferred because of their superior insulation performance, in terms of contamination endurance compared with conventional ceramic insulators [1,2]. When these insulators are installed near industrial, agricultural or coastal areas, airborne particles are deposited on these insulators and the pollution builds up gradually, which results in the flow of leakage current (LC) during wet weather conditions such as dew, fog or drizzle. The LC density is non-uniform over the insulator surface and in some areas sufficient heat is developed leading to the formation of dry bands. Voltage redistribution along the insulator causes high electric field intensity across dry bands leading to the formation of partial arcs. In the case of polymeric insulators, these partial arcs will lead to erosion and chemical degradation of the insulating material. When the surface resistance is sufficiently low, these partial discharges will elongate along the insulator profile and may eventually cause insulator flashover.

It is important to point out that the failure at any single point of the transmission network can bring down the entire system. Recent reports [3, 4] on grid disturbance in India indicate the loss of five thousand million rupees and 97% of interconnected generation on 2nd January 2001. Similar disturbances of lesser magnitudes were also observed during the period of December 2002 & 2005, Feb & Dec 2006, Jan/Feb 2007 & March 2008. One of the major causes identified was the pollution/contamination induced flashovers. These events have amply portrayed that the performance of overhead transmission line string insulators and those used in outdoor Transmission is a critical factor which governs the reliability of power delivery systems.

G. George et al., [5] have proved by experiments that contamination performance of composite insulators is better than porcelain insulators. They studied the flashover mechanism of silicone rubber insulators with hydrophobicity. T. Suda [6], studied the LC waveforms and frequency characteristics of an artificially polluted cap and pin type insulator and classified the transition of LC waveforms into six stages in order to predict the flashover. B. Subba Reddy et al., [7] studied the leakage current behavior on artificially polluted ceramic insulator surface and derived the relation between the surface resistance and leakage current. A.H. El-Hag et al.,[8] studied the fundamental and low frequency harmonic components of leakage current to analyses the aging of silicone rubber in salt-fog. They suggested that both the fundamental and low frequency harmonics of leakage current can be used a tools to determine both the beginning of aging and end of life of silicone rubber in salt-fog. R. Sarathi et al., [9] have shown that application of moving average technique for the trend analysis of leakage current signal could be useful to predict the surface condition of outdoor polymeric insulators. Farhad Shahnia et al., [10] have studied the characteristics of polluted composite insulator and concluded that the densities of pollution and electrical field caused flashover

† Corresponding Author: Dept. of Electrical and Electronic Engineering, K. S. Rangasamy College of Technology, India. (c.muniraj@gmail.com)
* Dept. of Electrical and Electronic Engineering, Sona College of Technology, India. (krishrevathi25@gmail.com)
** Dept. of Electrical and Electronic Engineering, Gnanamani College of Technology, India. (chandrukvt@gmail.com)
Received: November 29, 2012; Accepted: July 4, 2013

for polluted insulators. M. T. Gencoglu,and M. Cebeci[11] have developed a dynamic model to compute the AC flashover voltage of polluted high voltage porcelain insulators with various profiles. In the previous work [12] studied the impact of eclectic field on polluted polymer insulator and concluded that electrical filed enhancement under polluted condition will cause the flashover.

S. Chandrasekar et al., [13, 14] Investigated the harmonic content present in the leakage current under the polluted porcelain insulator based on the FFT spectrum. FFT is limited in their resolving power, requiring long observation intervals in order to achieve acceptable accuracy and reduce leakage. For data sets of short duration, this conventional technique is unsustainable, and an alternative approach is required. This has led to parametric (Minimum-Norm) spectral estimation, which has proven usefulness in extracting high resolution frequency spectra from relatively short data sets. This method is proved in the in the previous work [15].

On this basis, the aim of the present work is to carry out laboratory experiments in order to understand the pollution flashover process of silicone rubber insulator at different pollution levels and relative humidity conditions. A due importance is given to understand higher order harmonics and signal noise ratio values of silicone rubber insulator at different relative humidity and pollution conditions. Min-Norm technique has been adopted to calculate the SNR values of leakage current signal. Choi-Williams distribution technique is used to understand the trend followed by the frequency components of LC signal with respect to time at different pollution conditions.

2. Leakage Current Analysis

2.1 Minimum-norm technique

Min-Norm method is a flexible method for the analysis of transients and non-stationary, multiple component signals [17]. It allows simultaneous time and frequency analysis of signals. This method involves the separating the original signals from noise by autocorrelation matrix. The one dimensional signal model is defined as

$$x[n] = \sum_{i=1}^{M} A_i \exp(j\omega_i n) + z[n]$$

Where A_i is a complex number representing the magnitude and phase of the i[th] frequency component and $z[n]$ represents the noise. The structure of signals composed of several frequency components, usually starts with examining its autocorrelation matrix R_{xx}.

$$R_{xx} = \sum_{i=1}^{M} P_i e_i e_i^{*T} + \sigma_0^2 I \quad (1)$$

$$R_{xx} = R_{Signal} + R_{noise} \quad (2)$$

$e_i = \left[1 e^{j\omega i}\, e^{j\omega i^2} \ldots\ldots e^{j\omega i(M-1)}\right]$ is a eignevector of matrix R_{signal} with eigenvalue $\lambda_i = M\left|A_i\right|^2$ where P_i stands for the powers of each complex sinusoid, e_i stands for the eigenvectors of the autocorrelation matrix, and I denotes the identity matrix (* means complex conjugate and T denotes matrix transposition). R*xx* is the sum of a signal autocorrelation matrix Rsignal and a noise autocorrelation matrix Rnoise. The frequency information is contained within the matrix Rsignal. The matrix R*xx* can be decomposed into its eigenvectors and eigenvalues. The eigenvectors corresponding to the M largest eigenvalues contain information about signal parameters. To extract the information, it is also possible to use the property of the orthogonality of eigenvectors. It is said that the eigenvectors containing information about the signal span the signal subspace, and the remaining eigenvectors span the noise subspace. The min-norm method uses only one optimal vector, i.e., d, for frequency estimation.

$$d = \frac{1}{c^{*T} c} E_{noise} c \quad (3)$$

$$d = \begin{bmatrix} 1 \\ (E_{noise}^{'} c)/(c^{*T} c) \end{bmatrix} \quad (4)$$

Power spectrum is calculate with help of d

$$\widehat{P}(e^{j\omega}) = \frac{1}{w^{*T} d d^{*T} w} \quad (5)$$

$$w = [1 \;\; e^{j\omega_i} \ldots e^{j(N-1)\omega_i}]^T$$

The denominator of (5) is estimated for each time instant. Instantaneous estimates of $\widehat{P}(e^{j\omega})$ can be regarded as estimates of the instantaneous frequency of the signal. Using Min-Norm method, all frequencies of harmonic components can be extracted from the LC waveform. Harmonic components are classified to be low frequency harmonic components where 2[nd] harmonic ≤ frequency ≤ 11[th] harmonic, and high frequency harmonic where frequency > 11[th] harmonic.

The basic idea for classification the harmonic components is described here. Observation of LC waveforms on clean insulator under normal environmental conditions as in [12] and [13] shows that LC waveforms have distorted from sinusoidal wave. Harmonic distortion is caused by nonlinear devices in the power system. This means that insulator has a characteristic as a nonlinear device. Harmonic components of clean insulator as mentioned above, significantly, appear only in harmonics ≤ 11[th] harmonic, and harmonics greater than 11[th] are appeared as a noise. Under clean surface conditions, LC magnitude is very low and it is affected by large high frequency components (noise). For insulator under high environmental stresses such as pollution, arc activity can appear potentially. Under this condition the LC waveforms have less distortion (approximately sinusoidal) than clean condition. It is mean that high frequency harmonics (noise) appear in waveform is reduced. The measure of LC signal can be expressed as:

Total Harmonic Distortion (THD) is used as a measure of harmonic contents of the leakage current signal. THD of leakage current signal is calculated as follows,

$$THD = \frac{\sqrt{\sum_{h=2}^{200} I_{h,rms}^2}}{I_{rms}} \times 100\% \tag{6}$$

$$I_{rms} = \sqrt{\sum_{h=1}^{200} I_{h,rms}^2}$$

$$THD_L = \frac{\sqrt{\sum_{h=2}^{11} I_{h,rms}^2}}{I_{rms}} \times 100\% \tag{7}$$

$$THD_H = \frac{\sqrt{\sum_{h=12}^{200} I_{h,rms}^2}}{I_{rms}} \times 100\% \tag{8}$$

An index of insulator performance can be defined as a logarithmic ratio of low frequency harmonics to high frequency harmonics using SNR as in Eq. (9).

$$SNR = 10 * \log\left(\frac{THD_L}{THD_H}\right) \tag{9}$$

2.2 CWD analysis

One representative of Cohen's family is the CWD. Lowering the cross-term interference is achieved here by the convolution of the integrant of Wigner Distribution (WD) with a Gaussian smoothing kernel in the form exp(($\theta\tau$)2/σ) [18, 19] Choi-Williams function is a flexible method for the time frequency analysis of transients and non-stationary waves [16]. It allows simultaneous time and frequency analysis of signals and how the energy of the signal is distributed over the two-dimensional time-frequency space. Choi-williams function is given by,

$$CWD_x(t,\omega) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{\sqrt{\sigma}}{4\sqrt{\pi}\left|\tau\right|} e^{-\omega^2\sigma/(16\tau^2)} x(t+u+\frac{\tau}{2}) \\ x^*(t+u-\frac{\tau}{2}) e^{-j2\pi\omega\tau} d\omega d\tau \tag{10}$$

where t denotes the time, ω is the angular frequency, τ is the time lag, θ is the angular frequency lag, and u is the additional integral time variable. One crucial property of the kernel function is the smoothing of the cross terms with preservation of the useful properties of the distribution. Introduced by Choi and Williams, the Gaussian kernel belongs to a subclass that is characterized by a very specific structure of the kernel function that can be treated as a 1-D function of the product of $\theta\tau$. From a mathematical point of view, such kernel functions allow suppression of the effect of undesirable cross terms.

3. Experimental Study

3.1 Experimental setup

A 11 kV silicone rubber insulator was used for the contamination experiments. Fig. 1 shows the overall dimension of a 11 kV silicone rubber insulator used in this study [16]. Fig. 2 shows the schematic diagram of the experimental setup, where PU-Protection Unit, DSO-Digital Storage Oscilloscope, DAS-Data Acquisition System, PC-Personal Computer. The test insulator was suspended vertically inside the fog chamber (1.5 m× 1.5 m × 1.5 m). The test voltage was 11 kVrms, 50 Hz. Pollution tests were conducted as per IEC 60507 clean fog test procedure. Before tests, the insulator surfaces were cleaned by washing with isopropylic alcohol and rinsing with distilled water, in order to remove any trace of dirt and grease. To reproduce saline pollution typical of coastal areas, a contamination layer consisting of NaCl and 40g of kaolin mixed with 1 litre of deionized water was applied to the surface of insulator.

The concentration of NaCl salt was varied to give Equivalent Salt Deposit Density (ESDD) in mg/cm^2 to 0.03 (very lightly polluted), 0.06 (lightly polluted) and 0.12

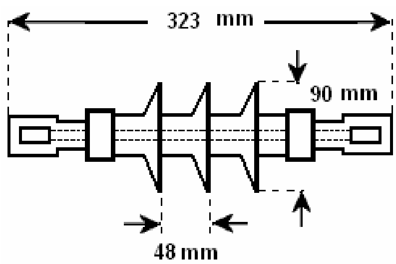


Fig. 1. Dimensions of the 11 kV composite insulator

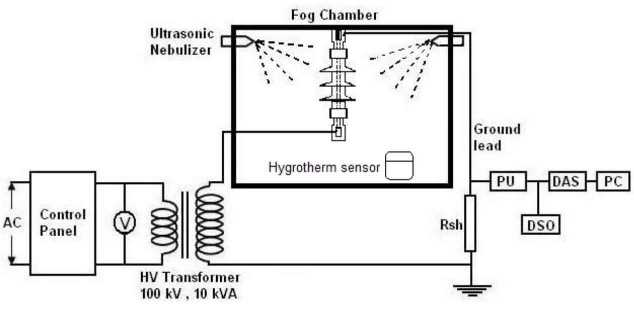


Fig. 2. Schematic diagram of the experimental setup

(highly polluted). FOG-MAX (particles size 8-10 microns, area coverage 600-800 sq.fts) ultrasonic nebulizers were used to maintain the required relative humidity level inside the fog chamber. Relative humidity inside the fog chamber was measured using a wall-mounted Extech 445703 Hygro-Thermometer. It indicates humidity with 1" digits on a super large LCD. It features the MAX/MIN function with the option to reset. The relative humidity range is 10 to 99% while the temperature range is 14 to 140F. The RH level inside the fog chamber is increased gradually from 40 to 99%.

The leakage current was measured through a series resistance in the ground lead. A high sampling rate data acquisition system (USB-6218- National Instruments, 32 channels, 1.25 MSa/sec) was used in the present study. A software system developed for this data acquisition system provides the user with the complete LC waveforms, which are therefore available for further signal processing. Agilent (DSO3014A) Digital Storage Oscilloscope (sampling rate of 1 GSa/s) was used to visualize the leakage current waveforms. In this study, all the signals were captured at a sampling rate of 5 kHz and the data was stored in PC for further processing. The DAQ was protected by back-to-back zener diode as a protection unit (PU).

3.2 Test procedure

Laboratory tests were carried out in the following test conditions. (i) Silicone rubber insulator at clean surface condition, with different relative humidity levels. (ii) Silicone rubber insulator at a constant pollution level of 0.06 ESDD, with different relative humidity conditions. (iii) Silicone rubber insulator at different pollution levels varying from 0.06 ESDD to 0.25 ESDD, at a constant 100 % relative humidity conditions.

The insulator samples were applied with AC voltage of 11kVrms. During each test the peak value of LC is recorded and the all the experimental test results are summarized in the Fig. 3. It show the trends followed by the leakage current peak value of silicone rubber with an increase in relative humidity of the fog chamber at different pollution conditions of NaCl.

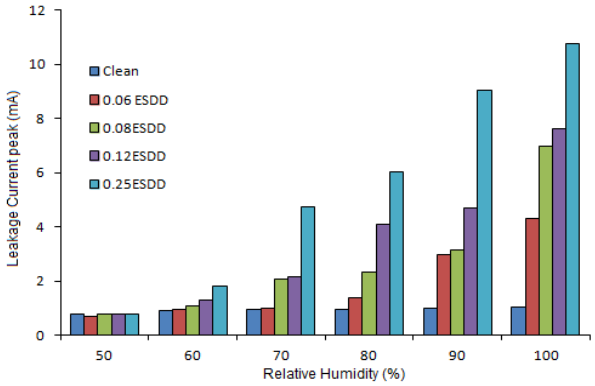


Fig. 3 summarized experimental test results

3.3 Analysis by SNR

Outdoor insulators are exposed to high temperature and humidity, as well as pollution, from coastal areas and industries. Under wet conditions, contamination layer allows the flow of leakage current, which in turn finally leads to the development of flashover. In this section, the development of flashover of outdoor polymeric insulators due to wet pollution is explained based on leakage current and time frequency analysis. Fig. 4(a) shows the LC signal obtained during clean dry surface condition and all other Figs. 4(b)-4(f) and 4g show the leakage current signals obtained at 100 % relative humidity conditions inside the fog chamber at different pollution levels. Fig. 4(a) shows the typical LC signal obtained during clean-dry surface condition of insulator and corresponding harmonic measurement. Under clean surface conditions, LC magnitude is very low and it is affected by large high frequency components (see THD_H value). Fig. 4(b) shows the initial LC flow under wet conditions when the pollution layer builds up over the surface of the insulator. In this condition, no visible discharge is observed. Further increase in pollution level leads to the inception of discharges, leading to distortions of the original waveform.

From the experimental observations, it is possible to classify the discharges as short duration discharges (which last for a maximum of 1 cycle) and long arcs (which last for 5 to 20 cycles). Figs. 4(c) and 4(d) show the typical short duration discharges and the corresponding Harmonic table. These short duration discharges are the precursors for the development of long arcs which will lead to flashover. It is observed that the value of SNR is increased when compared with other high frequency components in Fig. 4(d). This indicates that when the frequency of occurrence of short duration discharges raises the magnitude of third harmonic component increases in the LC signal. When there is a formation of heavy arcing at both top and bottom surface due to the increase in pollution and relative humidity, significant increase in magnitude of the fundamental component of LC and reduction in high frequency components is noticed (Figs. 4(e), and 4(f)). When the insulator approaches flashover, the LC pattern almost looks like sinusoidal pattern with a very high magnitude (Fig. 4(g)) and most of the high frequency components are lost in this phase. Therefore, the identification of the presence of high frequency components can play a major role in order to predict flashover phenomena of insulator. Fig. 5 reports photographs of short duration discharges observed at 0.06 ESDD pollution, 95 % relative humidity and long arcs observed at 0.12 ESDD pollution, 98% relative humidity.

From the above observations, the importance of understanding the time-frequency characteristics LC pattern in order to develop better diagnostic tools for preventive maintenance work is brought out. Gorur et al [20] identified that the frequency contents of the leakage

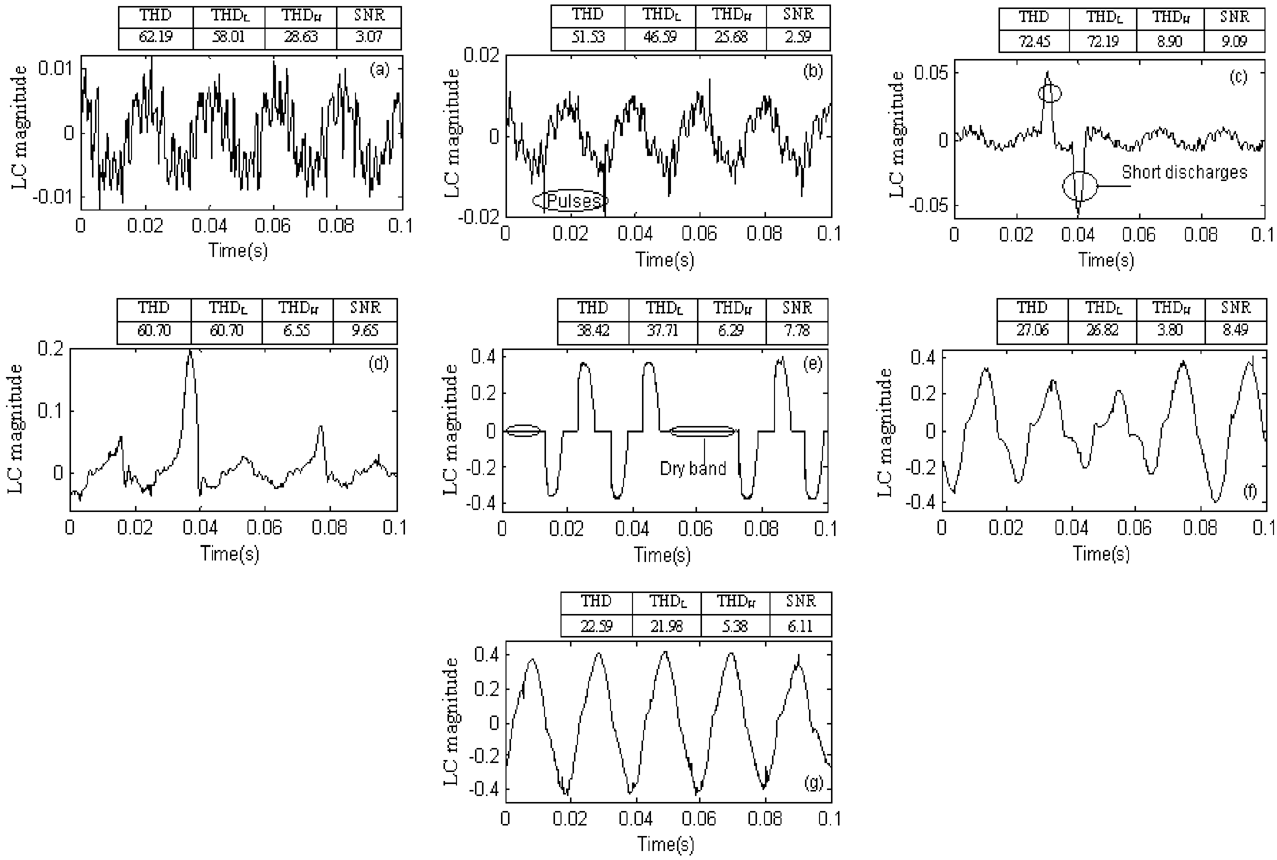


Fig. 4. ypical LC patterns obtained during pollution experiments: (a) LC during clean dry surface; (b) LC during initial wet polluted surface; (c, d) Short duration discharges; (e) dry band formations; (f, g) Long arcs and corresponding harmonics, SNR values

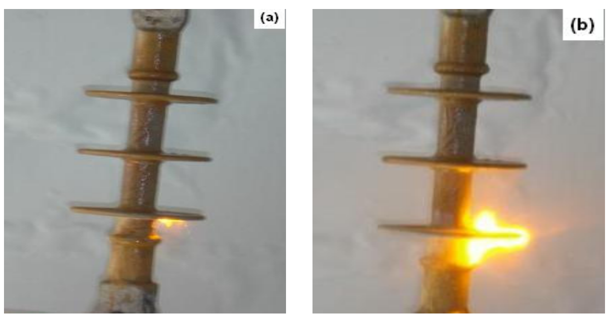


Fig. 5. Photograph of (a) Short duration partial arcs observed at 0.06 ESDD pollution, 95% relative humidity; (b) Long arc nearer to high voltage end observed at 0.12 ESDD pollution, 98 % relative humidity.

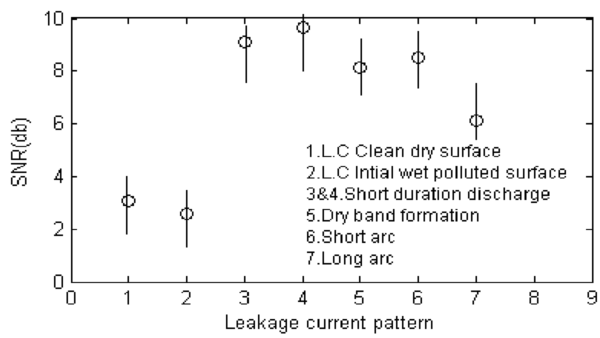


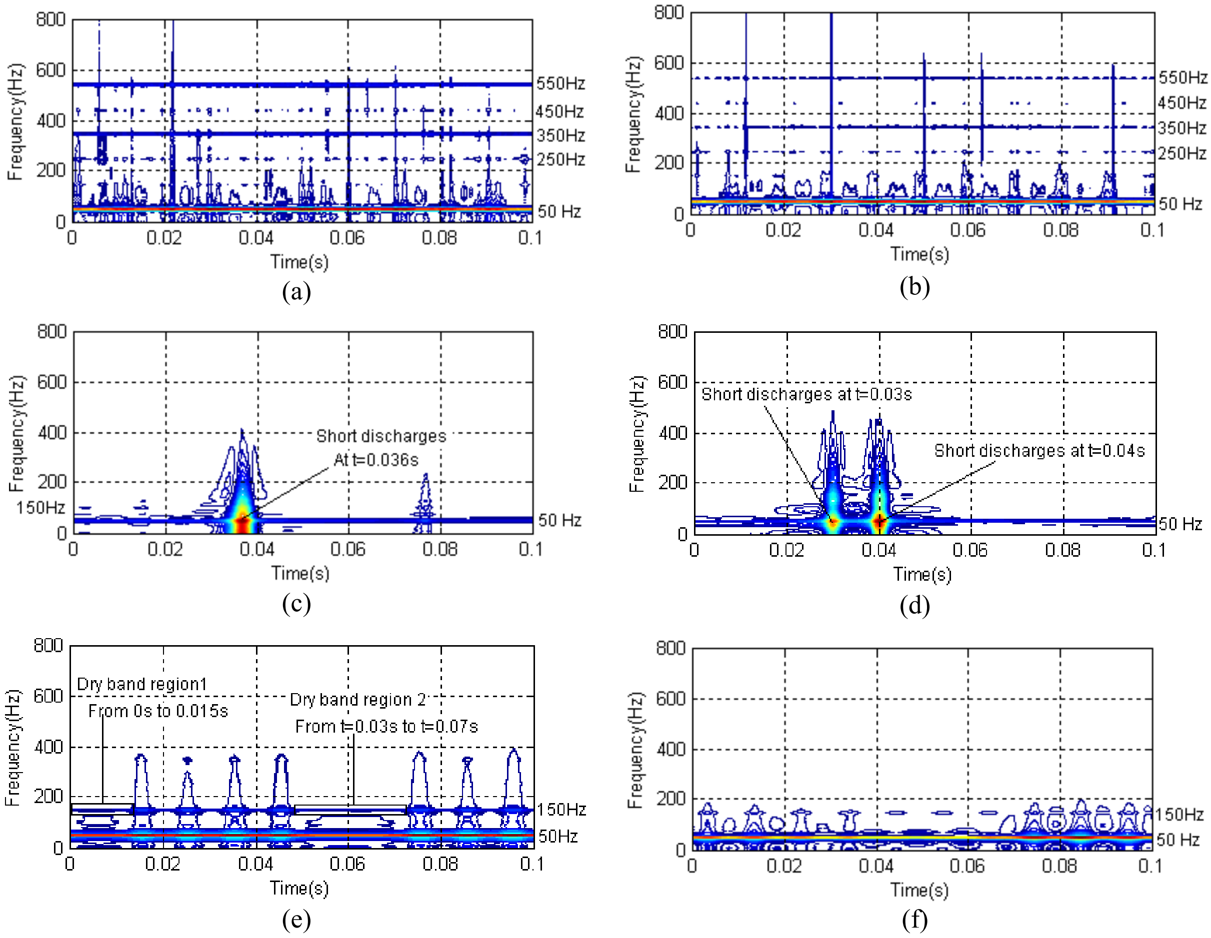
Fig. 6. Variation of SNR (db) at different leakage current pattern

current signal obtained with polymeric insulators varies during surface discharge and tracking condition. From the above figures, it is clearly noticed THD_H and SNR, estimated from the Min-Norm method, increases considerably during the formation of short duration discharges (Fig. 4-(c, d)), while a significant reduction occurs during the formation of long arcs (Figs. 4(f) and 4(g)). In order to understand the range of variation of the SNR, the tests were repeated several times. The variation in distortion ratio for different types of LC patterns is shown in the Fig. 6.

3.4 Analysis by Time-frequency spectrum

The leakage current during the flashover process is generally divided into the initial, short duration discharges, dry band formation, short arc and long arc [12, 13]. At the initial stage, the current waveforms are always non sinusoidal due to the capacitive current driven by the source voltage. When only a few weak discharges occur, the waveforms have a little distortion into the original shape. As the discharges are weak and the resistive performance dominates the insulator surface, the current magnitudes are small. The intermediate stage is transition from the initial stage to the just to flashover stage, during which the peak value of the current increases. Such transition of LC is due to the occurrence of weak local arcs on the insulator surface. Just prior to flashover stage, the current waveforms are similar to sinusoidal wave. The larger magnitude is measured, which is in accordance with intensive local arcs clearly observed on the insulator surface. With development of the weak local arcs, they connect together and generate the arcing channel, which is initial trace of the flashover.

Fig. 7 shows the results of the time frequency analysis for the leakage current waveforms given in Fig. 4. The time frequency analysis is made using MATLAB. Fig. 6(a) shows the clean surface condition stage and 6b shows the initial wet condition. Both are similar time frequency patterns like 1st, 5th, 7th, 9th and 11th, but in initial wet condition the magnitude of the 5th, 7th, 9th, 11th are reduced and 1st is increased, which is indicated by the color density of the harmonic pattern in Fig. 6(b). Figs. 7(c, d) shows the short duration discharge stage. In this stage the time frequency patterns are totally different than Fig. 7(a). All the harmonic components reported in the previous stage are expert 1st harmonic component disappeared. The



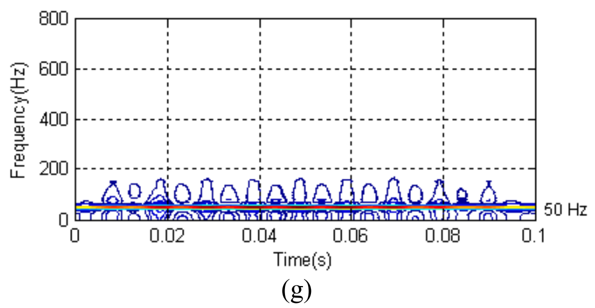


Fig. 7 Time frequency pattern for different leakage current patterns: (a) LC during clean dry surface; (b) LC during initial wet polluted surface; (c, d) Short duration discharges; (e) dry band formations; (f, g) Long arcs

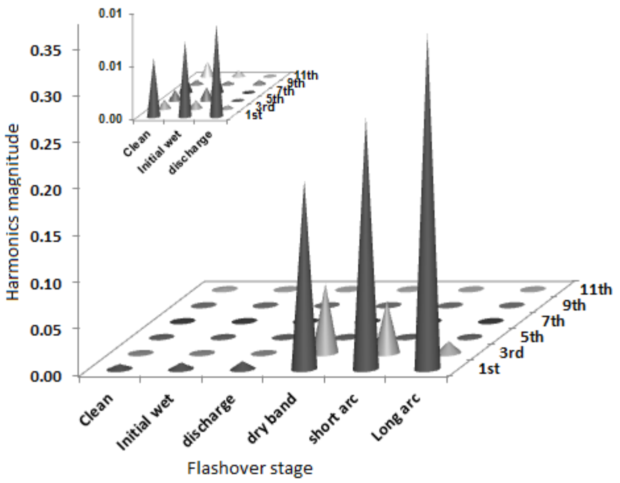


Fig. 8. Relation between the stage of flashovers and changed harmonic components

fundamental harmonic pattern color density is increased more than early stage, which indicates that magnitude of LC is increased. At t=0.036s in Fig. 6(c) At t=0.03s to 0.04s in Fig. 6(d) the fundamental components get collapsed because of discharge recorded at this time. Fig. 7(e) shows the dry band stage. In this stage continuous peaks are recorded in the LC wave form and LC current value is zero during t=0.00s to 0.015s and t=0.03s to 0.07s. This duration is called as dry band zone. In time frequency pattern all the harmonic components reported in the early stage disappear expert fundamental components. Additionally a new 3rd harmonic components pattern appears in the time frequency pattern in Fig. 6. In the dry band zone there are no strip peaks but in the reaming area the strip peaks appear. The color density of the 3rd harmonic pattern is high due to high magnitude of 3rd harmonic components. Fig. 7(g) shows the short arc stage, in this stage only two [1st and 3rd] harmonics patterns are appeared. The color density of the 3rd harmonic is reduced due to low magnitude, but color density of 1st harmonic is increased due to high LC magnitude. During this stage a small arc is recorded. Fig. 6(g) shows the long arc stage, in this stage basic (1st) harmonic component only appears reaming all disappear. The color density of 1st harmonic is very high due to very high LC magnitude. During this stage long arcs are recorded. This is the stage before flashover occurs. The relationship between the flashover stage and harmonic components is shown in Fig. 8.

4. Results and Discussion

Fig. 4 shows LC waveforms and parameter values of polymer insulator under different surface conditions. Form the results, SNR values may give a good interpretation of insulator surface conditions. For clean insulator under normal conditions of the SNR value is low, it indicates that higher order harmonics are present in the leakage current, i.e THD_H value is large. For light wet condition, LC waveform is same as the clean insulator but LC magnitude is bigger than clean insulator. THD_H is almost same as the clean insulator, but SNR is lightly smaller. For surface discharge condition, LC waveform has an intermediate peak. This gives a high THD_H, and SNR increased. In this condition, no arc activity recorded. For dry band surface condition, LC waveform has a continuous peak and during some time interval the current value is zero. This zone called as dry band zone. For the same insulator, the LC magnitude under the dry band formation will be higher than under clean condition and THD_H,SNR values are decreased. For short arching conditions, LC waveform looks like partial sinusoidal. The THD_H value is reduced and a SNR value is increased slightly but not more than discharge conditions. In this conditions short arc activity is recorded. For long arching conditions, LC wave form looks like sinusoidal. The THD_H value is increased but the SNR value is reduced. In this condition long arc activity is recorded. Also it is the stage just before flashover stage. The SNR value correlates to insulators surface conditions, the stage before flashover of the polymer insulator may be identified based on the SNR value.

The above reported SNR value and time frequency characteristics of LC pattern under contaminated conditions shows that the pollution severity and flashover phenomena of outdoor insulators can be assessed by looking at the evolution of LC activity in the course of time. In particular, change in harmonic components of LC is noticeable and can be possibly detected by installing suitable devices on transmission line poles. During clean-dry surface conditions, no discharges were found. This is because the conductive pollution on the surface is absent and the eclectic field intensity of the insulators is normal. The LC wave shape is completely distorted and it contains large higher order frequency components and single noise ratio value is low.

Fig. 9 shows the %THD values of leakage current on insulator surface for varying relative humidity conditions.

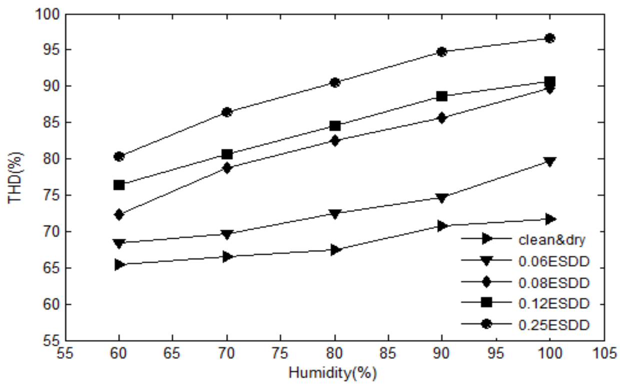


Fig. 9. Variation of THD value with respect to humidity at different ESDD

The THD value is almost constant in clean and dry surface even at high relative humidity conditions. However, under initial wet conditions, a conductive layer is formed on the contaminated insulator surface, which initiates LC. At initial wet conditions the leakage current density is non-uniform and in some areas sufficient heat is developed leading to the formation of dry bands.

Voltage redistribution along the insulator cause high electric field intensity across dry bands leading to the formation of partial arcs. Therefore during wet polluted tests, discharges were observed at bottom surface. Formation of dry bands and partial arcs leads to the distortion and discontinuities in sinusoidal waveform, which is the major cause for increase in third harmonic component during polluted tests. These partial discharges will elongate along the insulator profile in series with the wet low surface resistance area. This may eventually cause the insulator flashover. Therefore, when the insulator approaches flashover, the LC almost follows a sinusoidal pattern, with significant reduction in third harmonic components. In general, developments of partial arcs are the precursor of flashover phenomena. In an operational system, several arcing periods precede actual flashover.

5. Conclusion

Experimental results on silicone rubber insulator to understand the pollution flashover condition by SNR value of leakage current signal have been presented in this paper. Pollution performance studies on silicone rubber insulator have been carried out at different relative humidity and pollution levels. Variations in higher order frequency components of LC waveform with fundamental component are closely related to the surface condition of the insulator. Time frequency analysis of LC by CWD will be useful to predict the surface wetness and to classify different discharge patterns. These preliminary lab results appear promising to predict the pollution flashover conditions of outdoor insulators based on the SNR value analysis.

Acknowledgements

Authors would like to thank All India Council for Technical Education (AICTE), NewDelhi for providing financial support under Research Promotion Scheme to carry out this Experimental work.

References

[1] J.S.T. Looms, Insulators for High Voltages, IEE series, 1990.

[2] R.S. Gorur, E. A.Cherney and J. T. Burnham; Outdoor Insulators (Ravi S. Gorur, Inc., Phoenix, Arizona 85044, USA), 1999.

[3] Rebati Dass, “Grid disturbance in India on 2nd January 2001”, No:196, pp 6-15, Electra, June 2001.

[4] CEA Enquiry Committee report of Grid incident of Northern region, 2007

[5] George G. Karady, Minesh shah, R.L. Brown, “Flashover mechanism of silicone rubber insulators used for outdoor insulation-I”, IEEE Transactions on Power Delivery, Vol. 10, No.4, pp-1965-1971,1995.

[6] T.Suda, “Frequency characteristics of leakage current waveforms of an artificially polluted suspension insulator”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.8, No.4,pp.705-709,Aug 2001

[7] B. Subba Reddy, G. R. Nagabhushana, “Study of Leakage Current Behaviour on Artificially Polluted Surface of Ceramic Insulator”, Plasma Science & Technology, vo1.5, No.4, pp-1921-1926, (2003).

[8] A. H. El-Hag, S. H. Jayaram and E. A. Cherney, “Fundamental and Low Frequency Harmonic Components of Leakage Current as a Diagnostic Tool to Study Aging of RTV and HTV Silicone Rubber in Salt Fog”, IEEE Trans. Dielectr. Electr. Insul., Vol. 10, pp.128-136, 2003.

[9] R. Sarathi and S. Chandrasekar, “Diagnostic study of the surface condition of the insulation structure using wavelet transform and neural networks”, Electric Power Systems Research, Elsevier, Vol.68, pp.137-147, 2004.

[10] Farhad Shahnia and Ghasem Ahrabian. “Different Characteristics of Artificially Polluted High Voltage Composite Insulators”, Proceedings of the XIVth International Symposium on High Voltage Engineering, pp-1-6, August 25-29, 2005.

[11] M. T. Gencoglu, and M. Cebeci, “ Computation of AC flashover voltage of polluted HV insulators using a dynamic arc model”, European Transactions of Electrical power Vol, 2008

[12] C.Muniraj, S.Chandrasekar, “computation of Electric field and potential distribution pullulated composite insulator by finite element method” Proceeding of international conference, Electrical Energy systems & power Electronics in Emerging Economics ICEESPEEE 09, SRM university, India, pp 185-189,April 16th & 17th,2009.

[13] S. Chandrasekar, K. Krishnamoorthi, M. Panneer-selvam and C.Kalaivanan, “Investigations on Flashover Performance of Porcelain Insulators under Con-taminated Conditions”, Proceedings of National Conference on Electrical Engineering and Embedded Systems, NCEEE’08, pp.112-116, 20-21 March 2008.

[14] S.Chandrasekar, and C.Kalaivanan “Investigations on Harmonic Contents of Leakage Current of Porcelain Insulator under Polluted Conditions”, Proceedings of Fifteenth National Power Systems Conference (NPSC), pp.340-344, December 2008.

[15] C.Muniraj, S.Chandrasekar, “Analysis of Leakage Current on Polluted Polymer Insulator by High

Resolution Spectrum Estimation method" Proceeding of Third International Conference on Power Systems, (ICPS) IEEE Kharagpur section, INDIA Dec2009.
[16] IEC 60507, Artificial pollution test on high voltage insualtors to be used on AC systems,1991.
[17] Tadeusz Lobos, Zbigniew Leonowicz, Jacek Rezmer, and Peter Schegner, "High-Resolution Spectrum-Estimation Methods for Signal Analysis in Power Systems", IEEE Transactions on Instrumentation and Measurement, Vol. 55, No. 1, pp. 219-225, February 2006
[18] H. I. Choi and W. J. Williams, "Improved time–frequency representation of multicomponent signals using exponential kernels," IEEE Trans.Acoust., Speech Signal Process., vol. 37, no. 6, pp. 862-9871, Jun. 1989.
[19] Zbigniew Leonowicz, Tadeusz Lobos, and Tomasz Sikorski, "Time - Frequency Analysis of Complex Space Phasor in Power Electronics", IEEE Transactions on Instrumentation and Measurement, Vol. 56, No. 6, pp. 2395-2402, 2007.
[20] R.S. Gorur, J. Montesinos, L. Varadadesikan, S. Simmons, and M. Shah, "A laboratory test for tracking and erosion resistance of HV outdoor insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 4, pp. 767-774, 1997. July 2001.

C.Muniraj He received B.E degree in Electrical and Electronics Engineering from Erode sengunthar Engineering College, Erode in 2003 and M.E. degree in Power Electronics and drives from K.S. Rangasamy College of Technology, Tiruchengode, in 2006, and he received Ph.D. degree from Anna University in 2012. His research interest includes condition monitoring of Power apparatus and Systems, Power Electronics and drives, Signal processing and Intelligence techniques Application in Electrical power Engineering.

K. Krishnamoorthi He received B.E degree Electrical and Electronics Engineering from K.S. Rangasamy College of technology, Tiruchengode in 2001 and the M.Tech degree in power Electronics from Vellore Institute of technology, Vellore in India in 2003 and the Ph.D. degree from the Anna University Chennai, India in 2012. His research interest on condition monitoring of pollution flashover of power transmission line insulators in high voltage Engineering and power electronics drive systems.

S.Chandrasekar He received B.E. degree in Electrical and Electronics Engineering in Thiagarajar college of Engineering, Madurai in 1996 and M.E degree in Power Systems Engineering in Coimbatore Institute of Technology, Coimbatore in India, in 2001 and Ph.D. degree in the Indian Institute of Technology Madras, India in 2005. He was a postdoctoral research fellow at the University of Bologna, Italy from 2005 to 2006). His research interests include Condition Monitoring of Power Apparatus and Systems, Insulation Engineering, Signal Processing and Artificial Intelligence Techniques Applications in Electric Power Engineering.