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High Voltage Insulation Surface Condition Analysis using Time Frequency Distribution

Nurbahirah Norddin, Abdul Rahim Abdullah, Nur Qamarina Zainal Abidin and Aminudin Aman

Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Electrical Engineering, Malacca, Malaysia.

Abstract: This paper presents an analysis of high voltage insulation surface condition under high contamination level using experimental test of tracking and erosion according to BS EN 60587 standard. Surface condition on glass and polymeric types of insulation is investigated. The leakage current patterns on these types of insulation are applied for surface condition classification. Due to the limitation fast Fourier transforms (FFT), a new approach of time frequency distributions (TFD) analysis is employed. Spectrogram and s-transform as time frequency distribution (TFD) are then applied to represent and analysis of the leakage current (LC) in time frequency representation (TFR) in temporal and spectral. These techniques extract relevant information from leakage current (LC) signal, and then leakage current (LC) parameters are estimated to identify its characteristics. These include root mean square current (RMS), total harmonic distortion (THD), total non harmonic distortion (TnHD) and total current waveform distortion (TWD). Leakage current's instantaneous root mean square current per unit value and total current waveform distortion percentage are useful to reveal the insulator surface condition. Referring to rules based value, the classification of material surface state could be determined instantaneously. Instead of fast Fourier transform (FFT), it was found that time frequency distribution (TFD) is an appropriate tool for surface condition classification. Then, the unsymmetrical discharge pattern on polymeric insulation material indicated that erosion is occurred on the surface of the insulator.

Key words: Time frequency distribution; Spectrogram; S-transform; Tracking and erosion; Insulation.

INTRODUCTION

In high voltage the important materials used are conductors and insulators. While the conductor carrys current and insulation avoid the flow of current to unwanted path. The reliability of electrical power supply to the utility should be concerned to ensure the power lines and substations operated and protected. Insulation technology is still undergoing continuous development and improvement, from conventional ceramic type since the early 1900s, until the development of polymeric composite insulation materials. Polymeric or polymeric composite insulation is widely accepted (M.H. Ahmad *et al*. 2011) compare to conventional ceramic insulation because of its several advantages as mentioned by Hackam, Jeffry Mackevich and M.Shah in (Reuben Hackam 1999; M. A. R. M. Fernando and S.M. Gubanski 1999). However, polymeric insulation still has certain limitations such as dificulty in detecting defective insulation, lack of knowledge in its long term reliability and loss of hydrophobicity that leads to tracking and erosion as well as to flashover under contaminated condition.

Hydrophobic effect of the insulator provides high surface resistance even with the existence of contamination and moisture (R.S. Gorur *et al*. 2001). Different methods and analytical techniques are used to analyze the aging effect on polymeric insulating materials. One of the methods is by determining the loss of hydrophobicity. The methods to determine the loss of hydrophobicity are surface morphology by scanning electron microscope (SEM), Swedish Transmission Research Institute (STRI) classification, measuring the bead angle using a Goniometer and the equivalent salt deposit density (ESDD). Besides that, one of the key indicators widely accepted to determine performance of polymeric insulation either in service or accelerated aging laboratory test is by investigating the leakage curent (LC) signal. LC signal provides information of polymeric insulation surface condition and the pollution severity (N. Bashir and H. Ahmad 2009). LC measurement is popular technique because it can be monitored the performance of insulation either online or offline (D. Pylarinos *et al*. 2012; T. Zuo *et al*. 2012). Measurement of the peak current, accumulated charge (R.J. Chang and L. Mazeika 2000a) and discharge duration has been used by some researchers to provide information on degradation.

But onwards literatures show, LC harmonic component analysis will give better information on insulation surface (M.A.R.M. Fernando and S.M. Gubanski 2010; S. Chandrasekar *et al*. 2009; M.A.R.M. Fernando and S.M. Gubanski 1999b; S. Kumagai *et al*. 2006). A lot of studies have been done based on LC investigation especially into their harmonics characteristics as well as LC lower harmonic content and their ratios. As an example, G.P Bruce and S.M Rowland (2010), A.H. El Hag *et al*. (2005) and Hussein Ahmad (2008) examined low harmonic components of LC as a diagnostic tool to study aging and surface condition. While N. Bashir *et al*. (2010) and Kordkheili (2010) have verified the ratios of lower harmonics components as the major factor in

Corresponding Author: Nurbahirah Norddin, Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Electrical Engineering, Malacca, Malaysia.

determining the surface condition. Most of them use fast Fourier transform (FFT) to analyze the leakage current signal (N. Bashir and H. Ahmad 2010; M.A.R.M. Fernando and S.M. Gubanski 1999a).

However, FFT does not provide temporal information and is not appropriate for non stationary signal (O. Rioul and M. Vetterli 1991). Instead, the analysis using time frequency distribution (TFD) such as spectrogram and s-transform is used. The linear time frequency distribution approaches resolve the limitation of FFT. In this recent work, TFD is employed to analyze LC components to identify surface condition of polymer and non-polymer materials. According to Al-Ammar and Karady (2005), spectrogram is appropriate to analyze signal in high or low frequency depending on its frequency resolution based on window selection but it does not track the signal dynamics properly. Moreover, s-transform offers higher accuracy than spectrogram in term of its time and frequency resolution (Z. Leonowicz, T. Lobos and K. Wozniak 2009).

Surface hydrophobicity performance and its surface condition severity could be determined by a LC behavior. El-Hag *et al*. (2008) and Fernando and Gubanski (1999b) in their work had been separated the surface events into a several stages. The stages are early aging period (EAP), transition period (TP) and late aging period (LAP). These stages determine the level of surface condition as well as its contamination levels. At early aging period (EAP) only capacitive leakage current signify the insulator in hydrophobic condition. Then, during transition period (TP) the surface of insulator becomes hydrophilic and leakage current significantly changes to resistive condition. Finally, during late aging period (LAP) the leakage current level become higher and become completely resistive. At this moment, the surface erosion took place as well as produce unsymmetrical leakage current wave shape.

In this recent work, glass is selected as non-polymeric and Polypropylene (PP) as the polymeric insulation material. Tracking and erosion test complying with BS EN 60587-2007 are conducted on these materials and data acquisition Lab View program is employed for LC storage. Then LC parameters such as current root mean square (Irms), instantaneous total harmonic distortion (ITHD), instantaneous total non-harmonic distortion (ITnHD), and instantaneous total waveform distortion (ITWD) are determined instantaneously by using (TFD) spectrogram and s-transform respectively. By these parameters the classification of surface events is made. In real time leakage current signal consist of non-stationary signal, it can be concluded that TFD is appropriate tools for surface condition monitoring. It also observed that no unsymmetrical discharge pattern (LAP) on glass and its indicated that no erosion is occurred on the surface of the insulator compared with polypropylene.

MATERIAL AND METHODS

1) Experimental Setup:

Inclined-Plane Test (IPT) is normally used to evaluate the tracking and erosion resistance of insulating materials and recommended by BS EN 60587 (B.standard 2007). It is a valuable tool for the comparison and evaluation of new and different materials under electrical stress, and to compare the suitability of materials for the dielectric surface of an insulator. Two materials are being evaluated which are non-polymeric (glass) and polymeric (polypropylene) having the dimensions of 50 mm wide by 120 mm long and 6 mm thick and inclined at 45° angle as shown in the schematic Fig. 1 which is the experimental setup for IPT test that are subjected to high voltage of 3.5 kV.

In the test procedure, since it is done in the same place every day, there are three parameters that are assumed constant; humidity, pressure, and temperature. As stated in the standard, the contaminant conductivity level is set to 2.533 S/m measured by Hanna Dist 4 conductivity meter and its flow rate at 0.6 ml/min. A non-ionic wetting agent (Triton X100) is added as prescribed in the standard test to provide uniform liquid for contamination (R.J. Chang and L. Mazeika 2000b). LABVIEW program is developed for LC data monitoring and storage for analysis purpose.

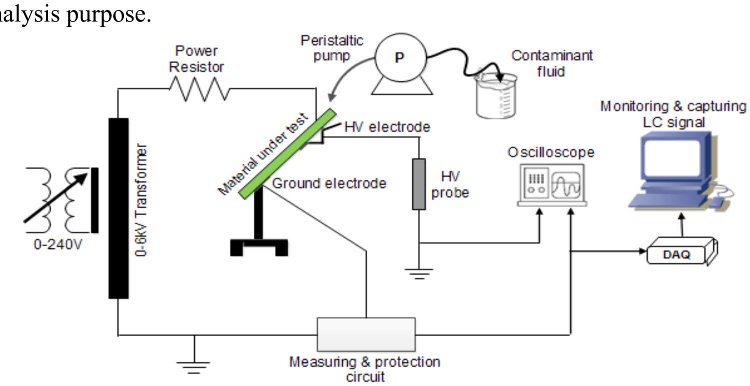


Fig. 1: Schematic diagram of Incline Plane Test.

2) Time Frequency Distribution:

Linear time frequency distributions (TFD) provide the information about time variation as well as frequency spectrum of leakage current simultaneously which using spectrogram and s-transform. From the TFR, characteristics of the signals can be calculated and used as input for signals classification. The signal characteristics are total harmonic distortion, total non harmonic distortion, total waveform distortion and current root mean square (IRMS).

A. Spectrogram:

Spectrogram is one of the time-frequency representations (TFR) that represents a three-dimensional of the signal energy with respect to time and frequency. Spectrogram is the squared magnitude of the STFT. This technique roughly reflects how frequency content changes over time. However it has the limitation of a fixed window width that results is a compromise between time and frequency resolution The window effect caused smaller window size produces better time resolution but it also reduces frequency resolution and vice versa. The spectrogram defined as

$$S_x(t,f) = \left| \int_{-\infty}^{\infty} h(\tau) w(\tau - t) e^{-j2\pi f \tau} d\tau \right|^2 \quad (1)$$

Where $h(\tau)$ is the input signal and $w(t)$ is the window observation window. In this study, Hanning window is selected because of its lower peak side lope (H.I.S. Jayasundara, W.P.S. Sudarshani and M.A.R.M. Fernando 2008) which is narrow effect on other frequencies around fundamental value (50 Hz in this study) and other frequency components.

B. S-transform:

S-transform is proposed by Stockwell *et al*. (1996) which time frequency spectral localization method that combine element of Wavelet transform and short time Fourier transform (STFT). S-transform employs a moving and scalable localizing Gaussian window and the equation of Gaussian window shown in (3). It combines a frequency dependent resolution with simultaneous localizing the real and imaginary spectra. The basis functions for the s-transform are Gaussian modulated cosinusoids whose width varies inversely with the frequency. S-transform, introduced by Stockwell *et al*. (1996) is defined by the general equation (2)

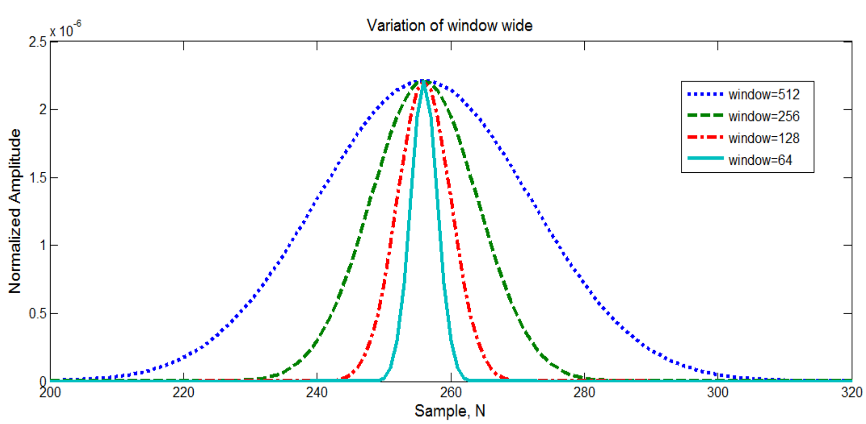
$$ST(\tau,f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} e^{\frac{-(\tau-t)^2 f^2}{2}} e^{-j2\pi f t} dt \quad (2)$$

$$g(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-t^2}{2\sigma^2}} \quad (3)$$

$$\sigma(f) = \frac{1}{|f|} \quad (4)$$

Where $h(t)$ is the signal, t represent the time, f the frequency, $g(t)$ the scalable Gaussian window and σ is a parameter which control the position of the Gaussian window on the x-axis. When the window is wider in time domain, s-transform provides better frequency resolution for lower frequency. While the window in narrower, it provide better time resolution for higher frequency.

Figure 2 shows Gaussian window with variable length used in s-transform.



3) Parameter Estimation:

Parameters of the signal are estimated from the time frequency distribution to recognize the signal information in time. These parameters are important to use as an effective indicator for insulator surface condition.

A. Instantaneous RMS Current:

The instantaneous RMS current is

$$I_{rms}(t) = \sqrt{\int_0^{f_{\max}} S_x(t,f)\,df} \tag{5}$$

B. Instantaneous RMS Fundamental Current (I1rms):

Instantaneous RMS fundamental current $I_{1rms}(t)$ is defined as the RMS current at power system frequency (A. Kusko and M.T. Thompson 2007) and can be calculated as

$$I_{1rms}(t) = \sqrt{2\int_{f_{lo}}^{f_{hi}} S_x(t,f)\,df}$$

$$f_{hi} = f_1 + \frac{\Delta f}{2}, f_{lo} = f_1 - \frac{\Delta f}{2} \tag{6}$$

Where f_1 is the fundamental frequency that corresponds to the power system frequency and Δf is the bandwidth which is set to 50Hz.

C. Total Harmonic Distortion (THD):

THD is the relative signal energy present at non-fundamental frequencies and written as:

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

Where $I_{h,RMS}$(t) is RMS harmonic current and H is the highest measured harmonic component.

D. Total non Harmonic Distortion (TnHD):

Nonharmonics are not multiple integer signal components frequency of the power system frequency. Therefore, TnHD is referred as distinguishing between nonharmonic and noise, and is calculated as:

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

E. Total Waveform Distortion (TWD):

TWD consists of harmonic distortion and nonharmonic distortion. It can define as:

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

RESULT AND DISCUSSION

Polypropylene and glass are used as insulating material was tested under IPT condition at 2.5mS/cm conductivity level and 0.3 ml/min, while increasing the voltage stresses from 0 to 3.5kV. There are three patterns can be seen for glass and four pattern for polypropylene. These conditions were monitored and collected using LABVIEW software package.

A. Material Analysis:

1. Glass:

During dry surface condition, there are no activities take places when the voltage level is increased from 0-3.5 kV. Meanwhile, during wet condition, it is observed that at low voltage levels between 0-1 kV, no erosion and arcing activities occurred but vapor develop on the glass surface. Capacitive state occurs and the amplitude value in the range of µA. The capacitive state from both materials shows the same capacitive sinusoidal shape depicts in fig. 3a. All patterns amplitudes of RMS current have been normalized by dividing by the RMS value of the normal signal (resistive signal). This is because at resistive signal only fundamental frequency exists. Fig

3b shows the spectrogram for capacitive glass with 400Hz of harmonic exists. Fig. 3c shows the small values of RMS current per unit (pu) for capacitive signal. Total waveform distortion (TWD) during this state around 30 to 20%.

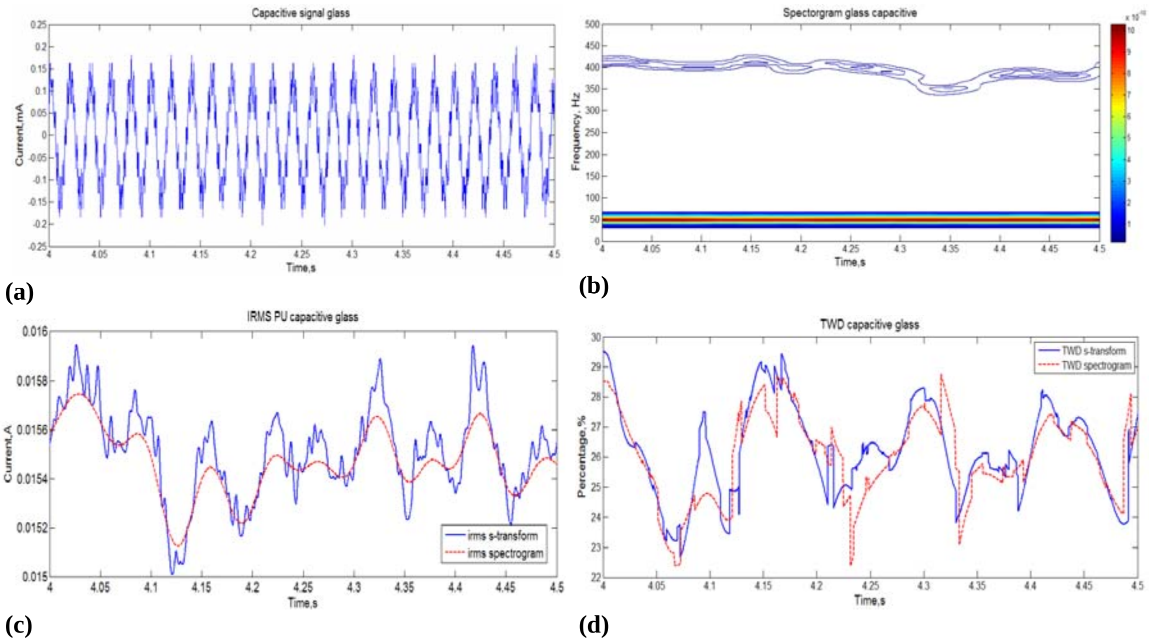


Fig. 3: (a) Glass capacitive signal (b) Spectrogram (c) IRMS (d) TWD.

At this resistive state for glass, only fundamental frequency 50Hz exist and the amplitude is about 10mA. This condition appeared at voltage stresses 1kV until 1.5kV. The average instantaneous RMS current is approximately 1.0pu and it has a smallest TWD value that is below 3% because of low distortion on the signal. The symmetrical discharge for glass take place on 2kV which arcing sound produced but there is no spark on the glass surface and the signal has low distortion state. At 2.5 kV, sparks occurred on the glass surface form discharge activities. The amplitude for symmetrical signal for glass is about 70mA. The RMS current for this state is a lot higher than 1.0 pu and the TWD is below 100%. During this state, smokes appear and contamination fluid spread wildly with discharges scattered on the insulator surface. The pattern for symmetrical discharge for glass is same with polypropylene symmetrical pattern shown in fig.5a.

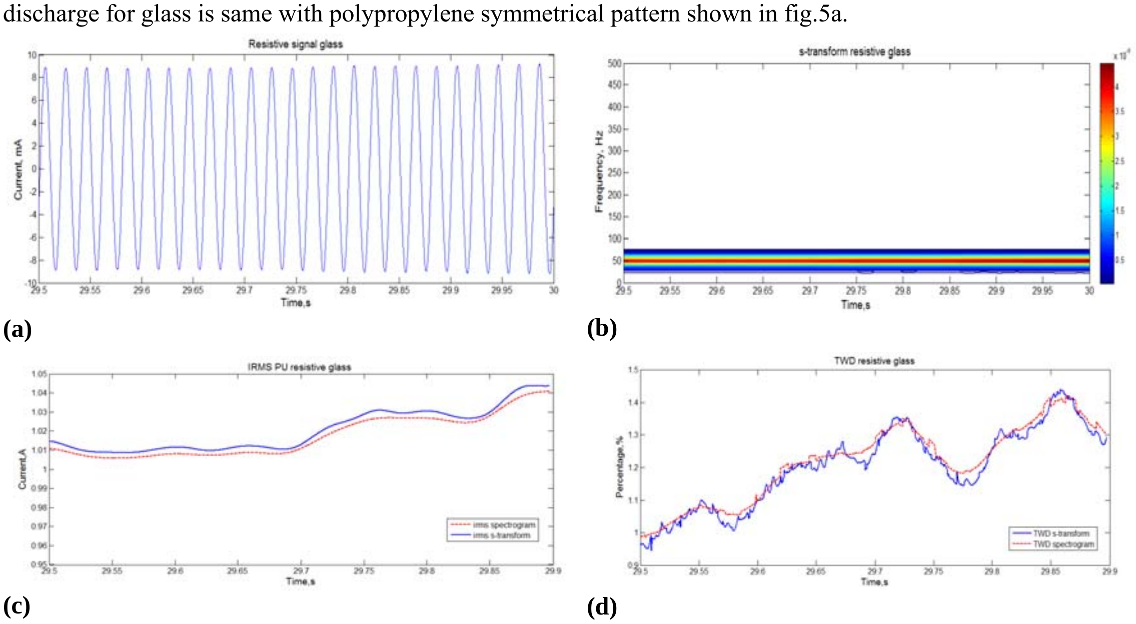
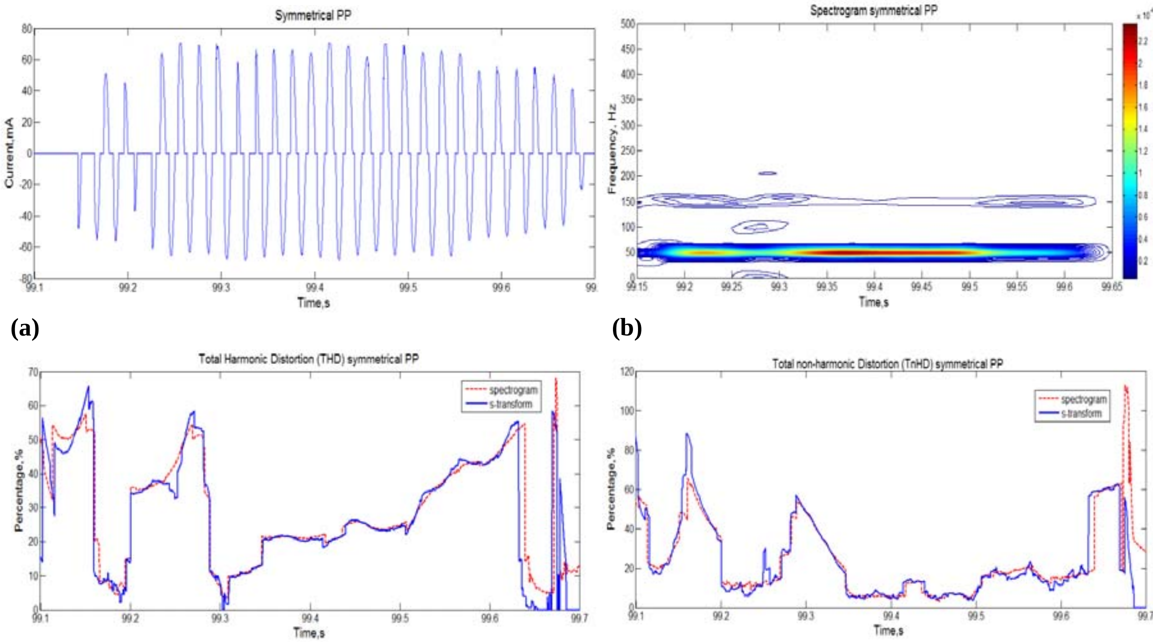


Fig. 4: (a) Glass resistive signal (b) S-transform (c) IRMS (d) TWD.

2. Polypropylene:

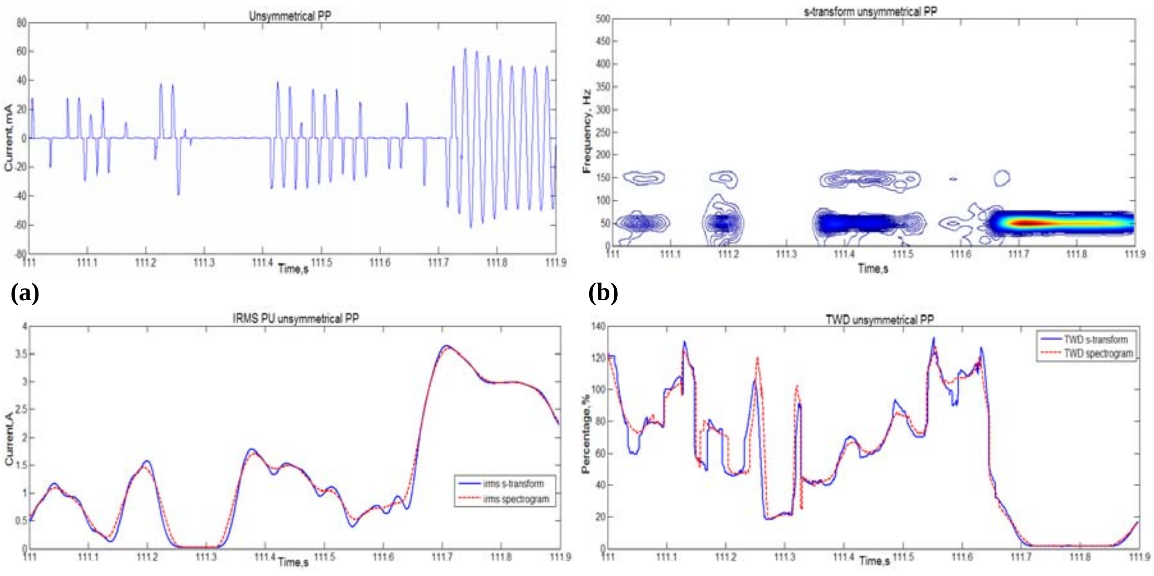
Polypropylene (PP) has good balance between electrical and mechanical properties (A. Aman *et al*. 2013). It also has high dielectric strength (S. Naidu and N.M. S 1999). It is observed that at low voltages levels between 0-1 kV, no erosion and arcing activities occurred. At this level of voltage, the LC is classified to capacitive type at wet condition. The amplitude for capacitive types for polypropylene is around 0.15mA. The RMS current pu for this state is around 6.6mA and the percentage of TWD around 30% to 20%. At 1kV until 1.5kV resistive state with fundamental frequency of 50Hz exist. The amplitude of LC during resistive is about 15mA. At 1.5kV, smokes appear during the test. The RMS current for this pattern is 1.0 pu and has low TWD value that is below 3%. At 1.8kV, waveform of the symmetrical signal with distortion exists depict in fig.5a and the sounds of arcing without spark are produced. The RMS current pu for this state is higher than 1.0 pu. THD and TnHD value lower than 100% shown in fig 6c and fig 6d respectively.



(a) **(b)** **(c)** **(d)**

Fig. 5: (a) Polypropylene symmetrical signal (b) Spectrogram (c) THD (d) TnHD.

Fig 6.a show the unsymmetrical discharge for polymeric insulator which there are the ‘rest’ time requisite for a full hydrophobic condition to take place again. It is the temporary loss of hydrophobicity during discharge. Hydrophobicity transfer or recovery occurs because of absorption of low molecular weight to pollution layer. Arc current dissipated energy large enough to cause rupture in the polymer chains and is transferred to the surface directly. The severities because of degradation on the surface become higher (K. Jeong-Ho *et al*. 2001). The unsymmetrical discharge pattern on polymeric insulation material also indicated that erosion is occurred on the surface of the insulator. The difference between glass and polypropylene is there are no unsymmetrical discharge patterns or the late aging period (LAP) for glass. This is because glass can withstand substantial heat without serious damage due to its high melting temperature of 1252ºC (R. Hackam 1999) while polypropylene have low thermal stability (A. Aman, M.M. Yaacob and J.A. Razak 2011) about 180ºC and easily damaged by intense heat generated on the surface by the dry band arcing. There are methods to improve the resistance to tracking and erosion process on polymeric insulator by adding filler as have been done by Vas *et al*. (2012) and Piah (2003) but this study focused on investigation for tracking and erosion of the insulator surface using time frequency distribution. The amplitude for unsymmetrical discharge is about 40mA and the values of the amplitude is varies because of the rest time. The RMS values also vary in range higher or same to 1.0 pu of lower or same to 1.0 pu shown in fig 6c but TWD is high because of the high distortion happen in the signal depict in fig 6d.



(a) **(b)** **(c)** **(d)**

Fig. 6: (a) Polypropylene unsymmetrical signal (b) S-transform (c) IRMS PU, (d) TWD.

B. Surface Condition Classification:

In order to find out the relation between RMS current pu and total waveform distortion (TWD) to the surface condition of the insulator signal classification have been conducted. Analysis results are made based on leakage current parameter estimation obtained from spectrogram and s-transform. The rules based are used to classify the surface condition event instanteously are summaries in Table 1.

Table 1: Ruled based on surface condition classification.

Pattern	Parameter	Glass	Polypropylene	Condition
Capacitive	IRMS	<1.0 pu	<1.0 pu	No arching
	TWD	50 – 3%	50 – 3%	
Resistive	IRMS	1.0 pu	1.0 pu	Arching sound
	TWD	<3%	<3%	
Symmetrical	IRMS	>1.0 pu	>1.0 pu	Low arching for polypropylene and high arching for glass
	TWD	Percentage varies around 5 - 100%	Percentage varies around 5 - 100%	
Unsymmetrical	IRMS	/	varies 1.0 ≤x≥1.0	Dry band with high arcing which lead to erosion
	TWD	/	Percentage varies around 100 % – 200%	

Conclusion:

This study using new approach to presents the comparison and analysis of non polymeric and polymeric insulation leakage current patterns using parameter estimation to identify the surface condition of the insulator. In conclusion, it was found that late aging period state with unsymmetrical discharge pattern on polymeric insulation material can be use as erosion indicator occurred on the surface of the insulator. Erosion does not occur on glass surface at 3.5kV because of their endurance to high temperature and they have high molecular weight compared to polypropylene. Instead of using LC amplitude, ruled based obtained from spectrogram and s-transform can be use to determine the surface condition of the insulator instantaneously. In term accuracy s-transform offers better performance than spectrogram because shows better time and frequency resolution.

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