15083/4

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

PROJECT COMPLETION REPORT
FOR
(SHORT TERM) RESEARCH GRANT

INVESTIGATION OF SURFACE TRACKING AND EROSION RESISTANCE PERFORMANCE MONITORING AND OPTIMIZATION OF SOLID INSULATION MATERIALS UNDER ELECTRICAL STRESS & ENVIRONMENTAL CONTAMINATION

Principal Researcher : KHAIRUL ANWAR BIN IBRAHIM

Co-Researchers : 1. FARHAN HANAFFI (FKE)

Project Code No. : PJP/2010/FKE (23A) S724

Report Submission Date : 14 March 2014

FACULTY OF ELECTRICAL ENGINEERING

CHAPTER 1

INTRODUCTION

1.1 Introduction

In high voltage engineering or its applications, insulation is the most important part to prevent the flow of current to undesired paths. The dielectric strength and electrical field strength are key properties of insulating material and they become the major factors that determine insulation failure [1-2]. Insulation technology is still undergoing continuous development and improvement, from conventional ceramic type since the early 1900s, until the recent development of a new insulation breed using non-ceramic or polymeric composite materials [3].

Common applications for polymeric type of composite for high voltage outdoor insulation include cable termination, surge arresters, insulators, bus bar insulation and bushing. Currently, the most common polymeric material for high voltage outdoor insulation application are made from silicone rubber (SIR), ethylene propylene monomer (EPM), ethylene propylene diene monomer (EPDM), ethylene vinyl acetate (EVA) and composite of SIR and EPDM or EPM [4-5].

The main factor for the increasing number of polymeric insulation accepted by the user and electrical power utilities is because of its advantages compared to traditional ceramic insulation. Among them are low surface energy and good hydrophobicity surface properties [5-6].

Since polymeric composite insulations were accepted, a large number of significant studies and research activities for improvement on its performance had been made. These studies and research activities can be summarized into several parts such as; the development and performance of newly polymeric materials, the understanding of deterioration due to chemical, electrical and mechanical stresses, the proper dimensioning, design and manufacturing process of the polymeric composite materials; and the development of practical testing, monitoring, reliability methods of measuring and service performance [3].

One of the key indicators widely employed to determine the performance of polymeric insulation either in service or accelerated ageing laboratory test is by investigating their leakage current (LC) signal. Leakage current (LC) signal provides information of the polymeric insulation surface condition and the pollution severity [16]. It is also the most efficient technique because it can be monitored online or offline and this technique has been studied and confirmed by a special task force of the IEEE Working Group on Contamination of Non-ceramic Insulators [17]. The information of magnitude, harmonics content and discharge duration of LC signal has a strong correlation on the surface condition and degradation of polymeric material. For this purpose, Fernando and Gubanski [18] have discussed several methods to evaluate and predict materials performance based on LC measurements and one of them is the tracking and erosion test (TERT) using incline plane test set-up.

In this research work, for surface condition evaluation, a practical laboratory surface LC monitoring system associated with BS EN 60587:2007- erosion and tracking test is employed. Then, LC parameters are used as diagnostic tools to study and predict insulation material surface conditions under electrical stress. The new analytical method with a total frequency component of LC using time-frequency distribution (TFD) technique under surface discharge activity is adopted. It was shown that this new analytical method is useful to reveal the polymeric insulating surface condition. Referring to the rules based value, the classification of polymeric insulation material surface condition state and its severity could be determined instantaneously.

1.2 Problem statement

LC is a function of main parameters such as voltage stress level, contaminant conductivity level, ambient temperature, surrounding humidity, pressure and conductivity flow rate as well as a function of hydrophobicity. Some efforts have been done to study on insulation ageing in relation to surface LC components, especially the correlation between LC harmonic components and the deterioration of the polymeric material surface. In most of previous works, LC is normally analyzed both in time or frequency domains, and the Fast Fourier Transform (FFT) technique is used for transformation. However, LC signals usually have a non-stationary pattern especially during dry-band condition and surface discharge. With reference to O. Rioul and M. Vetter [19], FFT is only suitable for stationary signals and does not provide temporal information. Any abrupt signals localized in time require more than FFT. Another reason was reported by C. Muniraj and S. Chandrasekar [20] who found that the analysis of LC in polluted polymer insulator shows that FFT is fast in computation but possess limitations in resolution. 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.

To overcome this limitation, a Spectrogram (joint time-frequency domain) with digital signal processing (DSP) technique is applied, where the signals are processed within frequency bands rather than time intervals. This DSP time-frequency technique has been successfully employed in pattern recognition, and signal processing application such as audio processing, seismic data analysis, automotive emission, sonar application and power quality disturbance [21]. Then the signal will be presented in time-frequency representation (TFR), where the signal information is presented simultaneously.

Recently, linear time-frequency distribution (TFD) analysis technique is adopted in high voltage engineering for analysis of LC [20]. However, it is still lacking in LC signal information where most of them only considered the harmonic content of the signal. The aim of signal analysis is to extract all relevant information from the signal in order to get an accurate result. In real signal, it not only has fundamental frequency but often contains harmonics and inter-harmonics component that are not multiple integers of fundamental frequency. For example, a 50 Hz signal may distort with a 150 Hz as 3rd harmonic and 175 Hz inter-harmonic [22]. It was proposed by M.H.J Bollen, and I.Y.H. Gu [22] that the total wave form distortion (TWD) that consist of total harmonic distortion (THD) and total inter-harmonic distortion (TnHD) must be taken into consideration when analyzing the quality of the signal. It is due to the fact that the content of total frequency could have a strong influence into the signal.

1.3 Objectives of the research

The following are the objectives of this research:

1. To design & develop an experimental testing platform based on international standard to ASTM D2303, IEC 587 & BS-EN 60587
2. To carry out investigation and assessment on tracking and erosion resistance performance of high voltage solid insulation material under different environmental contamination

1.4 Scope of work

This research work will be focused on the following scope:

1. Polypropylene (PP) polymeric thermoplastic material and artificial wollastonite (AW) product of waste material is used for the testing of the developed system

2. Laboratory investigation will be carried out on dielectric strength, and tracking and erosion performance of the developed polymeric composite material complying with standard BS EN 60243-1:1998 and BS EN 60587: 2007, to provide the information on the suitability of the composite for high voltage application as well as the correlation between LC and surface condition of the composite.

3. Time-frequency distribution (TFD) technique with Spectrogram method is applied for analysis and classification of the surface state event.

1.5 Significance of the research

Insulation plays a critical role in order to determine the reliability and availability of an electrical power apparatus and delivery system. A good insulation system will give better design, performance and life span of the electrical apparatus. For the reliability of this insulation, a continuous improvement is necessary. This research work is an extension of previous studies on the development of practical monitoring and reliable methods of measuring using LC method. The significance of this research work can be summarized as follow: An advance technique for instantaneous and real time surface condition monitoring with time-frequency distribution technique is developed. By this technique, the characteristic of LC parameters and it's correlation to their surface condition was discovered, and then a classification of the insulation surface condition referring to their total waveform distortion is established. This is a more efficient method that considers the total frequency component of the LC signal, instead of only the harmonic frequency component.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Insulation plays a critical role in determining the reliability and availability of an electrical power apparatus and delivery system. Due to the advantages of polymeric insulation composite over the ceramic or glass type of insulation, polymeric insulation is widely used. Since polymeric composite material is accepted as insulation, a large number of significant studies and research activities for improvement on their performance had been made. It can be summarized into several parts such as; the development and performance of newly polymeric materials, the understanding of deterioration due to chemical, electrical and mechanical stresses, the proper dimensioning, design and manufacturing process of the polymeric composite materials; and the development of practical testing, monitoring, reliability methods of measuring and service performance.

2.2 Factors influencing polymeric composite long term performance

Ageing is referred to any significant change in the chemical composition, electrical and mechanical properties of the material[4] and the processes that cause the failure of polymeric insulation to perform their intended purpose or reduce their service life [7]. IEEE Application Guide For Evaluating Non-ceramic Materials for High Voltage Outdoor Applications IEEE Std 1133-1988 explains details about the factors that influenced the long term performance of polymeric material [62]. It also explains the details of the ageing process on the surface that may affect in different ways to the surface. Ageing factors are several factors that affect the long term performance of insulating material. According to IEEE Std 1133-1988, the ageing factors that influence long term performance of polymeric insulation are electrical stress, environmental stress, thermal stress, mechanical stress, biological attack, outdoor weathering contamination and chemical attack either a direct or indirect effectof the performances of polymeric insulation. Meanwhile, the effects referring to the natural processes that cause a failure of surface polymeric insulation to perform their intended purpose after a specific period of service is named as ageing effects [63]. Ageing effects or surface ageing processes are any significant changes in polymeric material such as change in chemical, electrical and mechanical properties on the surface of the polymeric insulation including tracking and erosion, weathering, moisture and heat, corona discharge, and fungi [61-62].

2.3 Accelerated ageing test

Ageing condition of polymeric insulation materials depends on the chemical and physical properties of the material and also the duration of the stresses. These ageing factors either direct or indirect can be determined or explored by proper examination. Although several international and national organization standards are available for accelerated life test such as IEEE, IEC, CIGRE, ANSI, BS and NEMA [5], there is no specific standard applicable for all applications and conditions. This means lack of standardization of meaningful test for all materials. Due to the materials technology continuation, the manufacturing frequently modifies the existing tests to suit a different product form [61].

Due to the fact that ageing effect is a long term process; accelerated ageing tests are typically performed either on the sample materials only or on complete product of polymeric insulation. The test will be conducted on the polymeric insulation either under electrical or environmental stresses. Normally the tests are done for insulation materials such as UV exposure test, tracking and erosion test, corona cutting test and oxidation stability test. Meanwhile, typical tests for complete insulation products like an insulator, surge arrester and others are tracking and erosion tests, salt fog test and multi-environment stress test [4]. These tests are designed to reveal the performance of the materials against stresses and are divided into four components; Electrical properties tests, Mechanical properties test, Physical properties test and Chemical and environment test. Frequently, surface condition of the polymeric material under test is used as diagnostic tools to represent the severity as well as their ageing performance. Figure 2.3 shows the summary of diagnostic tests to measure ageing. Different methods of analysis have been adopted and it is explained inthe next sub-section.

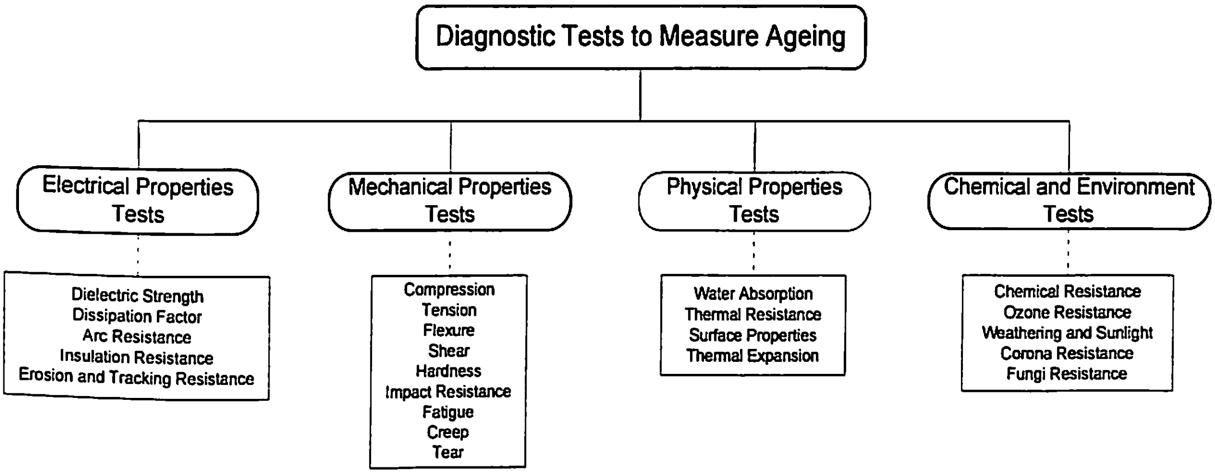

Figure 2.3: Summary of diagnostic tests to measure ageing.

This research work concentrates on the electrical properties of a new polymeric composite. Dielectric strength, tracking and erosion of the proposed material are focussed as properties under study. Since the newly developed polymeric composite is for outdoor application, it should fulfill certain requirements. For this purpose, a Selection Guide for Polymeric Materials for Outdoor Use Under HV Stress BS EN 62039:2007 [8] is employed and it is explained in Chapter 3.

2.4 Methods to analyze ageing effect

Different methods and analytical techniques were used to analyze ageing effect on polymeric insulating materials such as measurement of chemical stability, hydrophobicity and measurement of tracking and erosion resistance. Hydrophobicity measurement techniques are mostly studies on the material surface characterization and chemical investigation. Some of the methods to determine the chemical stability and loss of hydrophobicity are surface morphology by scanning electron microscope (SEM), X-Ray Photoelectron Spectroscopy (XPS), Fourier Transforms Infrared (FTIR), Swedish Transmission Research Institute (STRI) classification, measuring the bead angle using a Goniometer, the equivalent salt deposit density (ESDD), total salt deposit density (TSDD) and non salt deposit density (NSDD) measurement [60, 64-66].

One of the key methods to measure the expected physical, chemical change, hydrophobicity condition as well as surface condition is leakage LC characteristic. Parameters based on LC measurements provide information that can be used for evaluation of insulation performance under field and laboratory conditions, materials assessment and determining the pollution severity [14, 67]. LC is broadly accepted as monitoring tracking and erosion performance based on their waveform signal. LC with their waveform signal provides valuable information on the polymeric material surface condition. LC parameters that have been measured with time variation are maximum, average and standard deviation, and root mean square (RMS) of the signal, harmonic content and accumulated charge, surge counting, peak magnitude and discharge magnitude [14, 17, 68-69].

All insulations that are exposed to the stresses can experience surface activities, but it does not necessarily lead and initiate a flashover [61]. It depends on the performance of polymeric insulation and the interaction between material formulation, proper design and manufacturing process. To ensure a good performance of polymeric insulation and minimize ageing mechanism, a retention and recovery of hydrophobic properties is highly required. If the hydrophobicity is decreased, the LC through the surface of polymeric insulation must not exceed the critical limit to lead dry band formation. If a dry band is formed, the formulation must have a good performance in both tracking and erosion resistance. For LC, the performance factor should be controlled is flashover mechanism due to dry band formed on the surface. The polymeric insulation with good tracking and erosion resistant material is better than the material that can recover their hydrophobicity but have a poor erosion resistance [41]. Since this research work has focused on electrical parameter properties, the LC is used as a diagnostic tool for the surface tracking as well as surface condition monitoring method.

2.5 Previous studies on leakage current and surface tracking properties

Electrical and environment stresses will influence the hydrophobicity performance of polymeric insulation materials. When the surface of polymeric insulation loses its hydrophobicity, a film of water then developed on the surface leading to the flow of LC in the existence of voltage stresses [70-71]. For this reason, a good monitoring and measurement of the ageing process is vital. Degradation processes could develop significant effect on their surface because of the appearance of LCs and discharge affects a surface tracking and erosion [72-73]. LC gives a valuable clue in determining the event occurring on the polymeric insulation surface [74-77]. LC is often used in order to determine the performance as well as the degree of ageing of polymeric in field and laboratory studies such as salt fog, tracking wheels and incline plane test (IPT) [67, 78-81]. G. Karady *et al* [82-83] performed experimental work for flashover mechanism of polymeric insulations. The results of this reveal in detail the flashover mechanism. This flashover mechanism includes the contamination build up, diffusion of low molecular weight (LMW), wetting of the surface, ohmic heating, and the effect of the electric field of water droplets, spot discharges, loss of hydrophobicity and flashover on the surface. In the literature, most of these studies were conducted on hydrocarbon elastomers EPDM or/versus silicone elastomers SIR and their results could be used as references in the development of these works newly polymeric insulation.

2.6 Development of leakage current and flashover mechanism

Contamination flashover or breakdown of polymeric insulation material is related to several stresses that include; electrical stress, environmental stress and mechanical stress. The flashover occurred either through direct or indirect interaction between all the stresses. In general, the activity of contamination flashover for hydrophobic polymer insulation housing is a multi step process and the basic steps of this process are explained in the following statements [41, 82-84]:

1. Contaminations buildup- The present or accumulation of dust, dirt and/or other conductive particle contaminants on the surface of polymeric insulation by wind and etc.
2. Surface wetting- The light rain, dew, fog or high humidity then deposit moisture on the surface and because of hydrophobic properties of insulation, droplets will form. The form of droplets then rolls down to slopy areas due to gravity effect and discrete

droplets remain. The salt/conductive pollution then dissolves with the water droplets, thus increasing the liquid conductivity.

3. Capacitive to resistive changes - The migration of contaminated droplets slowly wets the residual dry polluted surface to form a high resistance conductive layer. Its changes LC from capacitive to resistive LC.
4. Ohmic heating- The flow of LC through the conductive surface causes a decrease in resistance as well as increase in the LC flow. The increase of current accumulates energy dissipation heating (I^2R_t), thereby the water will evaporate and there will be an increase in drying rate.
5. Electric field effect on a hydrophobic surface- The applied voltage field then causes the closely spaced droplets to join together to form a single big droplet to become as a filament. Flashover will take longer on the hydrophobic surface due to the time required to form the filament. The local electrical field has to be highly sufficient enough to form a filament.
6. Spot discharge on a hydrophobic surface- the formation of filament then reduces the polymeric terminal distance (between the high and low potential of applied voltage) and increases the electrical field stresses between the filaments. Surface discharge will occur if the stress is large enough.
7. Reduction in hydrophobicity- Discharge eroding the thin layer of polymer around the droplets, then breaking the polymer chain causes loss or reduces of hydrophobic properties. Loss or reduces of surface hydrophobicity properties results the droplet dispersion and the formation of unbroken conductive films in high stress areas, allowing LC to flow.
8. Dry band formation – The power dissipation per unit area is the results of current density and electrical stress. The areas with higher power dissipation dry first. The current density tends to be concentrated in the smallest sectional area, which is where the drying is accelerated. Drying increase power dissipation because of increasing resistivity, leading to unstable condition where dry band form. As dry band are insulating, the surface activity continues within the band region until the band grows to a sufficient to withstand the applied voltage with only intermittent activity. This activity causes surface erosion and the rate of erosion is depend on material properties and ageing stresses.

9. Partial or full hydrophobicity recovery properties can be achieved if the material is discharge free for a sufficient period of time. Recovery ability depends on the design, material formulation and environment stresses.
10. Partial arcing and flashover- Flashover at the polymeric surface occurs if the surface becomes hydrophilic, wets out, a dry band formed and the discharges extend across to bridge the polymeric terminal (high potential and low potential terminal) with sufficient LC. With insufficient power dissipation, flash over will not occur even visible surface activity appears.

Performance of polymeric insulation is the result of the interaction between material formulation, product design and manufacturing process. For flashover and ageing effects, all the processes must occur in sequence, and if any of the process is disturbed, flashover will not happen.

2.6 Leakage current measurement

Since the LC is very much related to the ageing performance of insulating material, the measurement is typically performed on the complete design / product or polymeric insulation component and polymeric insulation material. The polymeric insulation material test is usually designed with short time test while insulation components design test takes longer time. For that purpose, there are different kind of chambers used for ageing and flashover testing that include; salt fog and clean fog test (IEC 507,IEC1109), dust and dry salt layer deposit chamber (ASTM 2132), rotating deep test and incline plane test IPT (IEC 587) or its equivalence standard.

W.T Starr [85] and R.Barsch *et al* [86] in their review discuss the advantages and constraints of each method. From available literatures, for tracking and erosion tests on polymeric materials, IPT is often used. Tracking and erosion test can be used as a tool for the evaluation and comparison of different material or new material under a controlled electrical stress [23, 80]. IPT is widely accepted because of their reliability on all materials, the relative simplicity of test procedure and low equipment cost. Table 2.4 presents the advantages and disadvantages of the material test methods.

Table 2.4: Testing methods for polymeric insulation material [85].

Method	Properties Measured	Advantages	Disadvantages
Incline plane	Time to track Tracking Voltage Erosion	Fast, a good educational tool, require close attention, cheap	Initial tracking voltage is difficult to be determined, erosion end point is too deep
Dust and fog	Time to track Erosion	Reliable to all material	Takes long time, relatively laborious, erosion method unclear
Tracking wheel	Time to track Erosion	Reproducible, easy to run	Interaction between different materials
Salt fog	Time to track Erosion	Imitate natural condition of seacoast area.	Takes very long time

2.7 Leakage current patterns

The behaviour of LC patterns and the degradation process of polymeric surface insulation due to stresses was explained in the previous research works, especially on hydrocarbon elastomers and/or silicone elastomers. T. Suda [14] and M.A.R.M Fernando [18, 87] have reported the transition steps of LC waveform from the beginning to the flashover occurrence. In these studies, the behavior of the LC, possible causes and their relations to surface hydrophobicity as well as electrical stress are described. A nonlinear behaviour of LC and material ageing has been observed. It can be classified into several stages from capacitive sine wave until the unsymmetrical wave shape. During the dry condition with fully hydrophobic properties, the LC is capacitive with very low in the range of μA. On the other hand, when the surface of the insulation is completely wetted due to the flow of conductive electrolyte, a resistive higher magnitude of LC with pure sinusoidal wave shape appears. The losses of hydrophobicity properties of polymeric insulation increase LC magnitude and raise the temperature as well as evaporate the electrolyte to form a dry band, and then the symmetrical LC wave shape is developed.

A.H. El-Hag*et al* [70] and M.A.R.M Fernando [17] have classified three different ageing periods during the development of LC. This is named as an early ageing period (EAP), transition period (TP) and late ageing period (LAP). It consists of capacitive current, resistive current, non-linear current and non-linear with discharge current [18] which is the basic concept of this research work. Only low capacitive LC flows during EAP and samples are hydrophobic. During the TP condition, the surface becomes hydrophilic. Then, LC changed significantly to be more resistive. Finally, during the LAP, the LC level becomes higher and completely resistive. Then, surface erosion took place as well as producing an unsymmetrical LC wave shape. In the same manner, it was reported by S. Kumagai [88], the LC was separated into capacitive, resistive, non-linear and non-linear with discharge.

Figures 2.4 to 2.7 show the variation of the waveform in the full range from EAP to LAP of waveform. These figures represent the particular surface condition state with duration of 0.1 seconds where a noticeable difference in the behavior of LCs parameter is clearly shown. Generally, this LC waveform is a mixed form of the sinusoidal and the distorted waveform. It can be divided into two parts; one is current by electrolyte conductivity (Figure 2.4 and 2.5) and the other is by dry band activity (Figure 2.6 and 2.7). Only LC by unsymmetrical dry band activity causes an erosion on the surface of polymeric insulation [69], so that the distorted waveform can be used as a good indicator of degradation. The extinguished signal existed after the unsymmetrical LC period prior to the further discharge activity and according to H.G Cho [69], this extinguished period gradually decreases with the degradation of the polymeric composite.

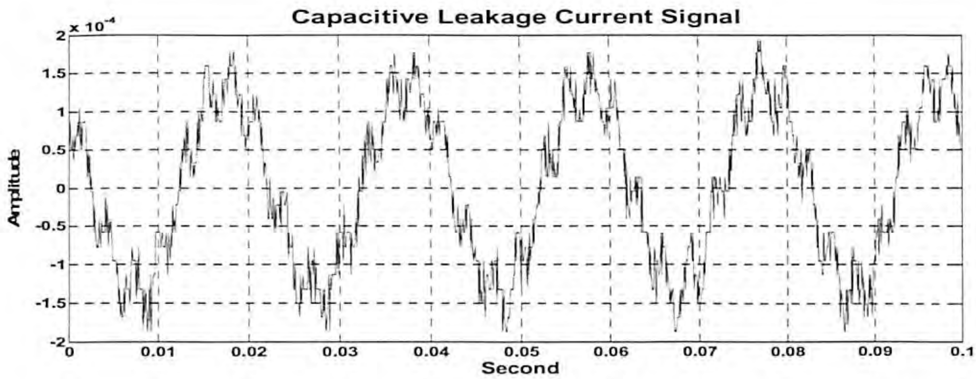

Figure 2.4: Capacitive LC signal

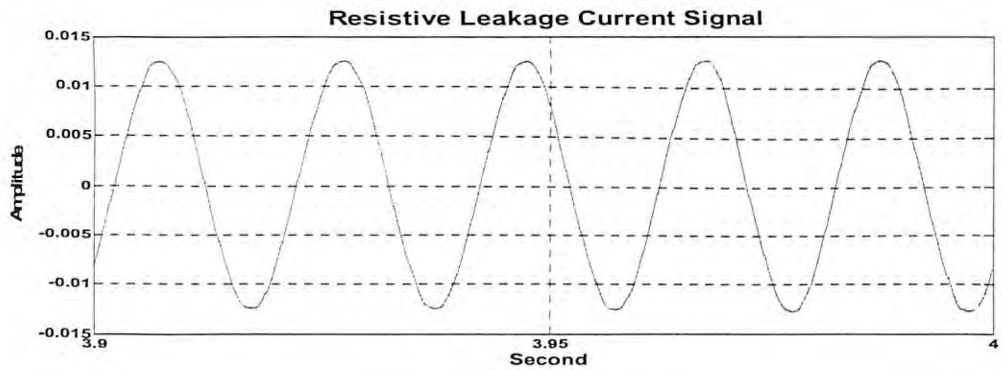

Figure 2.5: Resistive LC signal

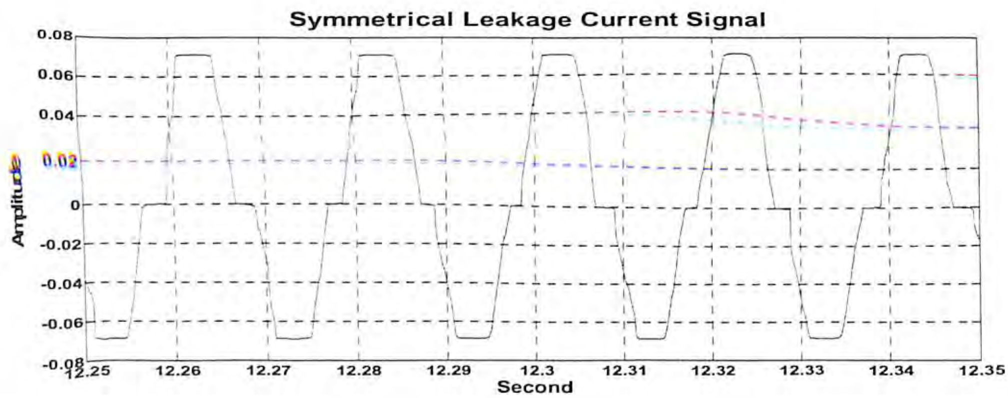

Figure 2.6: Symmetrical LC signal

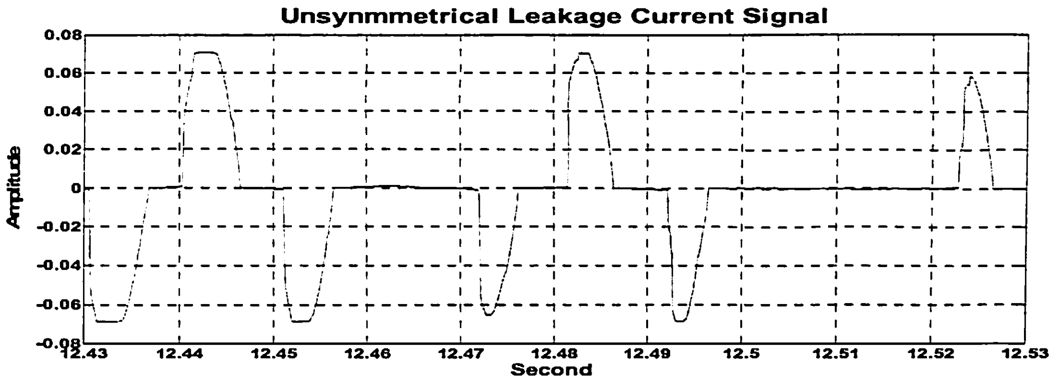

Figure 2.7: Unsymmetrical LC signal

2.8 Leakage current frequency component study

Besides LC patterns as mentioned in the subsection 2.4.3, frequency or harmonic component of LC signal is widely accepted for the surface and ageing studies [23, 89]. Most of these studies conducted on time domain or frequency domain and Fast Fourier Transform (FFT) is frequently adopted for the frequency component as well as harmonic analysis [89]. Frequency component of LC generates a better result than LC peak magnitude and the number of pulses in relationship to ageing studies [90-91]. There are several studies done by the researchers that were based on LC investigation especially on frequency characteristics as well as its harmonic component.

T. Suda [14] studied the frequency characteristic of LC on artificially contaminated pin type suspension insulator in order to establish a method of monitoring and correlation with flashover occurrence. In the presence of the strong local arcs on the surface of an insulator, LC waveforms become similar to symmetrical wave with high intensity of the odd order of harmonic components. Also, the LC harmonic components only exist at frequency <1 kHz and the transition of LC waveform until flashover went through six stages. T. Suda also applied the LC threshold value as a prediction for the possibility of flashover occurrence.

Apart from that, with reference to A.H El-Hag *et al* [89], no arching was seen when the fundamental component was relatively high and low harmonic component are low. The dry band activity as well as arching was seen only when the value of the low 3rd and 5th harmonic component increased. Further works by A.H El-Hag*et al* [70, 92], reports the fundamental and low frequency harmonic component of LC as a diagnostic tool to study ageing of SIR polymeric insulation material where the onset of dry-band arching on the SIR could be determined by measuring the low frequency harmonic component especially for 3rd and 5th harmonic component.

A correlation between different forms of ageing from EAP to LAP with fundamental and low harmonic component of LC has been found. There are three important things that were reported,they are the early ageing period (EAP), transition period (TP) and late ageing period (LAP) [17]. With mild degradation, a slight change in fundamental component of LC and the possible change of low harmonic component is observed. With moderate degradation, the dry band activity is associated with the increasing level of fundamental and low harmonic component of LC. But when the samples approached failure with severe degradation, the fundamental component of LC is relatively high and the low frequency component of the LC tends to decrease. The decreasing trend of the 3th and 5th harmonics indicate the beginning of the tracking as well as erosion [70]. The results show low frequency harmonics of LC is a better indicator than fundamental value of LC and could be used to determine the earliest ageing and the end life of polymeric insulation.

Another effort was done by A.H El-Hag [93] using a time series modeling with low frequency component to predict a dry band arching. Autocorrelation function (ACF) is used to analyze the early EAP of LC. It is observed that distinct differences exist in the behaviour of both fundamental and third harmonic components of the LC during EAP. There was a strong relationship between the ACF of the third harmonic of LC indicating the starting of dry band arcing.

W. Tjokrodiponto *et al* [94] in his study on LC magnitude and wave shape along polymer insulator reported the correlation between LC waveforms and discharge activities on the surface of non-ceramic insulator during the salt fog test. It was found that a 3rd harmonic distorted LC is an indicator of the existence of visual discharges. His report also mentioned that more information can be derived from the harmonics of LC than its peak value alone.

Suwarno and S.K Ardianto [95] in their work on epoxy resin for outdoor insulation under clean and salt fog test also reported that there is a strong correlation between total harmonic distortion (THD) of LC and discharge activity. They also mentioned that on salt-kaolin polluted samples under clean fog at higher humidity, large LC and THD magnitude was observed compared to clean samples under clean fog. The same conclusion was made by H. Ahmad *et al* [96] who concluded that the THD of aged insulators will be higher as compared to new insulators.

Since the frequency as well as harmonic component is well accepted as a valuable diagnostic tool for ageing and degradation mechanism especially on their 3^{rd}, 5^{th} and 7^{th} harmonic component [96], recently there are a few works conducted on the ratio of the harmonic component in order to determine the surface condition of insulation. Although not tested under polymeric insulator, N. Bashir *et al* [97] show the results of LC on 45 units of glass insulator samples. There is a strong correlation between the degree or progress of ageing and the LC's third to fifth ratios. But, H.H Kordkheli *et al* [98] had performed on various profiles of artificially polluted SIR insulators under clean fog condition. Instead of 3^{rd} to 5^{th}, he proposed that an important index is the ratio of the 5th harmonic component to the 3^{rd}. By this index, the operation and critical limits of flashover could be determined.

A different proposed methodology by using LC frequency component to classify the surface condition is by artificial neural network (ANN) approaching [18, 77]. The patterns exhibited by the frequency or harmonic distribution of the insulation were used to construct and train an ANN to determine and recognize the condition of high voltage insulation. ANN was adopted to predict the flash over, the level of pollution, analyze the surface tracking, estimate the critical flash over voltage, predict the LC in SIR and estimate time to flashover characteristic [97, 99-101].

2.9 Factors that affect the leakage current behaviour

In general, the polymeric insulation materials that were exposed to electrical and environment stresses will lose their hydrophobicity to some degree. The loss of the hydrophobicity behaviour is directly responsible for development of LC and the occurrence of tracking and erosion. There are several factors or physical parameters that have affected the LC development on the surface of non-ceramic or polymeric insulating materials, such as electrical stresses and types of supply voltages (AC or DC) [5, 102-103], different contaminations as well as conductivity on the surface[104], environment pressure [105], ambient temperature [106], surrounding humidity [68, 76] and electrolyte flow rate [55].

M.A.M Piah and A. Darus [102, 107] have developed an LC model associated with these physical parameters involved under tracking test. They developed LC model using a mathematical approach based on the dimensional analysis method where all of these physical parameters are presented in a mathematical equation. By this method, the correlation of electrical and environmental stress and LC development could be determined. Tracking and erosion laboratory test is used for the verification of the test results. They also proposed a combination effect of LC magnitude and carbon track (CT) propagation as a new method in evaluating the resistance to surface tracking and erosion. However they found that, CT is not a good tool for the determination of surface condition [54].

2.10 Time-Frequency Distribution analysis technique

Measurement of the LC amplitude, pulse, accumulated charge and discharge duration has been used to provide information on surface condition and its degradation. But onwards literatures show that LC harmonic component analysis will give better information [17, 87-88, 108]. A lot of studies have been done based on LC investigation especially into their harmonic characteristics as well as LC lower harmonic content and their ratios. G.P Bruce and S.M Rowland [103], Suwarno and S.K Ardianto [95], A.H El Hag *et al* [70, 89, 93] and H. Ahmad [96] examined low harmonic components of LC as a diagnostic tool to study ageing and surface condition. Furthermore, N. Bashir *et al* [97] and H.H Kordkheili [98] have verified the ratios of lower harmonics components as the major factor in determining the surface condition.

In most previous works, LC is normally analyzed both in time or frequency domains, and the Fast Fourier Transform (FFT) is used for transformation technique [70, 89, 97]. However according to [19, 109] FFT just presented the signal in spectral information and it is only suitable for stationary signals. Any abrupt signals localized in time require more than FFT. For example, actual LC signals are usually in non-stationary pattern especially during dry-band condition and surface discharge. So it requires an appropriate technique to overcome the constraint. To overcome this limitation, a joint time-frequency domain with digital signal processing (DSP) technique is applied where the signals are processed within frequency bands rather than time intervals [19, 110]. For this purpose, the time-frequency distribution (TFD) technique is used. This TFD technique has been successfully employed in pattern recognition and signal processing application such as audio processing, seismic data analysis, automotive emission, sonar application and power quality disturbance [21, 111]. Then the signal is presented in time-frequency representation (TFR) where the signal information is presented simultaneously in time and frequency representation. Figure 2.8 shows an example of transient power quality signal and in time-frequency representation (TFR).

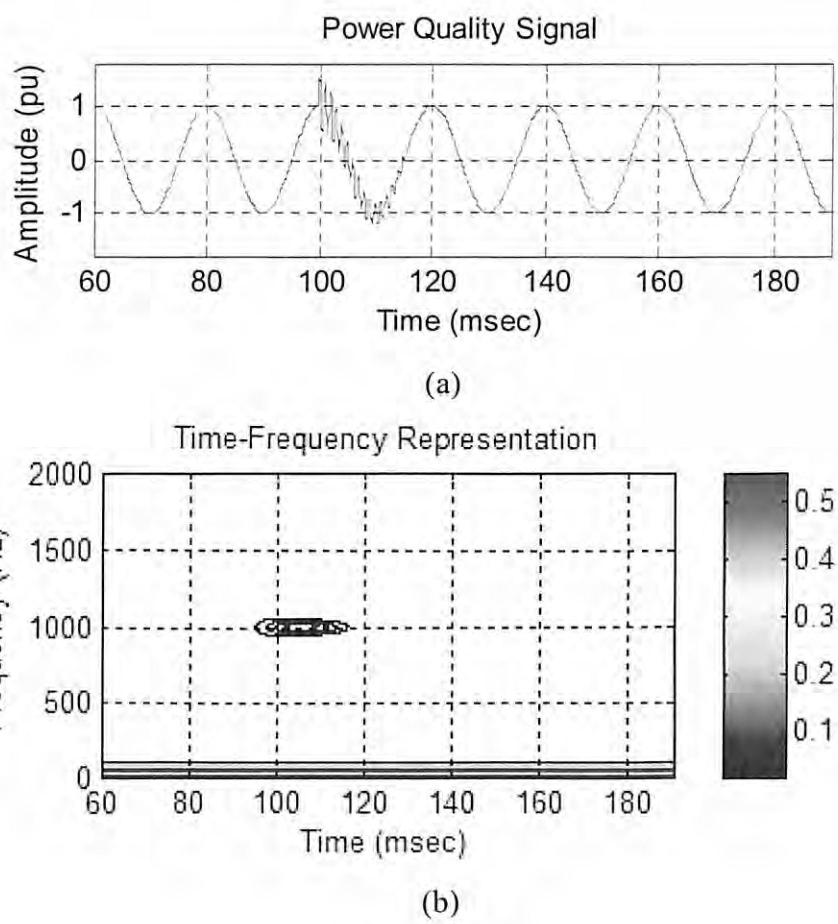

Figure 2.8: a) Transient signal and b) its time-frequency representation [110]

Recently, linear time-frequency distribution (TFD) analysis technique is employed in high voltage engineering for LC analysis especially by using a wavelet method [74, 88, 108]. But, it is still lacking in LC signal information where most of them only consider the harmonic content or harmonic frequency of the signal. According to Math H.J Bollen and I.Y.H. Yu [22], in actual signal, it not only has a fundamental frequency but often contains harmonics and inter-harmonics component (that are not multiple integers of the fundamental frequency). They were claiming the total wave form distortion (TWD) that consists of total harmonic distortion (THD) and total inter-harmonic distortion (TnHD) must be taken into consideration when analyzing the quality of the signal. It is due to the content of total frequency components could have a strong influence into the signal.

A.R Abdullah in [110] had employed the time-frequency distribution (TFD) technique to analyze power quality signal parameters such as their roots mean square (RMS), fundamental current RMS (1RMS), total harmonic distortion (THD),total inter-harmonic distortion (TnHD) and total wave form distortion (TWD), and it is shown impressive results in in-term of time and frequency resolution and its accuracy. He also used RMS per unit (RMS p.u) for monitoring and classification of electrical power quality events such as voltage swell, sag, interruption, harmonic, inter-harmonic, transient and nothing. The use of RMS p.u for power quality signal classification is also proposed in Recommended Practice for Monitoring Electrical Power Quality- IEEE Std 115-1995 [112] standard.

2.11 Leakage current signal parameters

The time-frequency distribution (TFD) technique called Spectrogram is employed inthe LC parameters estimation. These parameters will be used in polymeric insulation surface condition classification. The parameters are instantaneous LC RMS (I_{rms}), LC fundamental RMS (I_{1rms}), total LC harmonic distortion (I_{THD}), total LC inter-harmonics distortion (I_{TnHD}) and total LC waveform distortion (I_{TWD}). Signal parameters are estimated from the TFR.

2.10.1 Instantaneous leakage current RMS, $I_{rms}(t)$

The magnitude of LC RMS (I_{rms})can be obtained from the sample waveform, $x(t)$ as a RMS of the LC waveform. It is expressed as [110]:

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T x(t)^2 dt} \tag{2.4}$$

where T is the duration of the signal. The LC RMS (I_{rms}) can also be derived from TFR in time and referred as instantaneous LC RMS, I_{rms} (t). The instantaneous LC RMS, I_{rms} (t) is defined as [110]:

$$I_{rms}(t) = \sqrt{\int_0^{f_s} P_x(t,f)df} \tag{2.5}$$

where $P_x(t,f)$ is the TFR and f_s is the sampling frequency of the system.

2.10.2 Instantaneous fundamental leakage current RMS, $I_{1rms}(t)$

Instantaneous LC fundamental RMS (I_{1rms}) is defined as source frequency. From the TFR, instantaneous LC fundamental RMS , I_{1rms} (t) can be calculated as [110]:

$$I_{1rms}(t) = \sqrt{2\int_{f_{lo}}^{f_{hi}} P_x(t,f)df} \tag{2.6}$$

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

where $P_x(t,f)$ is the TFR of the signal and f_1 is the fundamental frequency that corresponds to the source frequency. In this work Δf it is set to 50Hz since it covers the fundamental frequency component to calculate the magnitude of the frequency component.

2.10.3 Instantaneous leakage current total harmonic distortion, $I_{THD}(t)$

Total harmonic distortion, THD is used to measure how much harmonic content in a signal waveform. Odd harmonics are normally expressed as 3rd, 5th, 7th, ...nth multiple of the fundamental frequency. Total harmonic distortion of LC waveform is defined as [110]:

$$I_{THD} = \frac{\sqrt{\sum_{h=2}^{H} I_{h,rms}{}^2}}{I_{1rms}} \tag{2.7}$$

where $I_{h,rms}$ is LC RMS voltage at h^{th} harmonic. The THD is a commonly used power quality index to quantify the distortion of a waveform and typically expressed as a percentage value. The THD is defined as the relative signal energy present in non-fundamental frequencies. The instantaneous LC total harmonic distortion, I_{THD}(t) can be defined as [110]:

$$I_{THD}(t) = \frac{\sqrt{\sum_{h=2}^{H} I_{h,rms}(t)^2}}{I_{1rms}(t)} \tag{2.8}$$

where $I_{h,rms}(t)$ is LC RMS harmonic and H is the higher of harmonic components.

2.10.4 Instantaneous leakage current total non-harmonic distortion, $I_{TnHD}(t)$

Besides the harmonic, a signal also contains inter-harmonics components that are not multiple integer of the source frequency, for example 155Hz component in 50 Hz system. The total LC non-harmonics distortion I_{TnHD} can be defined as [110]: