Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 14 (14): 1506-1513, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.1506.1513

Experimental Investigation on Insulation Integrity of Cross Linked Poly Ethylene (XLPE) Cables Due to High Voltage High Frequency (HVHF) Transients Using Double Tuned Circuit Technique

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Abstract: In the context of recent advances in modern power systems that utilize power electronic components for power delivery, cables are prone to High Voltage High Frequency (HFHV) oscillations which may be as a consequence of resonance, over-voltages due to fast switching operations etc., leading to undesirable degradation of insulation. Further, a few current studies by researchers have revealed that there is need for alternate strategies other than the classical insulation integrity tests that need to be formulated to study the degradation of insulation systems due to the influence of high frequency high voltages. In this research, studies are carried out to analysis the breakdown characteristics of cross linked polyethylene (XPLE) insulated power cable by subjecting HVHF oscillations generated using double tuned circuit. HVHF oscillations are generated in the form of damped oscillations and applied to XLPE cable insulation. Breakdown performance due to different ranges of high frequencies are generated and applied as repetitive HVHF oscillation on XLPE cable samples. The same sample is also subjected to high voltage with 50 Hz power frequency, switching and lightning over-voltages for carrying out detailed comparison on the breakdown characteristics. Further, analysis is also carried out to compare breakdown voltage characteristics of the XLPE insulation for varying HFHV oscillations that are most prevalent in systems pertaining to distribution voltage levels.

Key words: XLPE cable, HVHF transients, double tuned circuit

INTRODUCTION

With the advent of growing need for power electronics based power system that has become a part of large installations, problems related to power quality, issues pertaining to insulation degradation that lead to loss of reliability etc have become inevitable. In Flexible Alternating Current Transmission (FACT) systems and High Voltage Direct Current (HVDC) systems modern power electronic devices are used for rapid switching and can generate High Voltage High Frequency (HVHF) oscillations which may superimpose over the applied power frequency voltage leading to possible dangerous consequences such as resonance (with the internal winding of transformer), under damped over-voltages due to switching operation of converters etc which may cumulatively affect the performance of power equipments such as distribution transformers, cables, circuit breakers etc., (Van Cranenbroeck *et al*., 1999, 2000). Such high voltage high frequency studies on power apparatus has not enthused the power system researchers so far. Only few studies have been carried out on transformer oil samples and the breakdown mechanism have been analyzed with HVHF oscillations (Van Cranenbroeck *et al*., 1999; 2000; Sarvanan *et al*., 2006; Hardt and Koenig, 1998; Sels *et al*., 2002).

Recently, studies by a few researchers have observed abnormal failures in cables which have not been divulged during studies conducted utilizing standard classical tests in laboratory environment (Settaouti and Settaouti, 2006). Detailed studies by a group of researchers (Van Cranenbroeck *et al*., 1999, 2000; Sekii, 1995; Grzybowski and McMellon, 1995; Elanseralathan *et al*., 2000) clearly indicated variations in the characteristics voltage response for high frequencies high voltage as well as unconventional wave shapes. Further, renewed attempts have been made by the standardization bodies and the scientific community to analyze this phenomenon with a focus on evolving a comprehensive dielectric test procedure that would in turn provide more reliable quality assurance with regard to insulation response pertaining to withstand capability to transient voltages, switching

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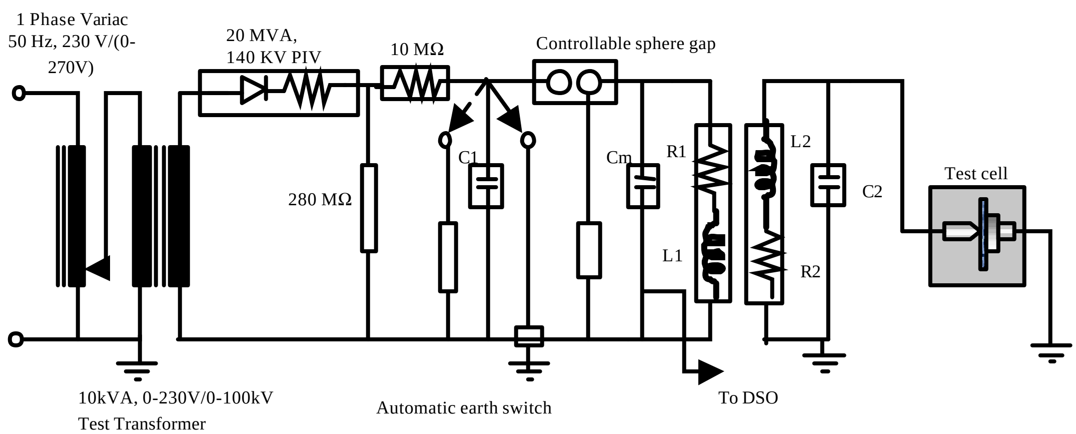

Fig. 1: Typical layout of double tuned resonant test setup

transients, etc. It may hence be emphasized that thorough experimental investigations are necessary to be carried out on XLPE insulation (widely used dielectric) in standard test cell arrangement before any generalized inferences and solutions are hypothesized.

Incidentally, since it is evident that potential distribution and hence electric stresses play a vital role in the cable insulation systems detailed study on the role of inhomogeneous fields in particular becomes inevitable. One major technique of improving the electrical characteristics of the underground cables is by using XLPE insulation. Substantial research has been carried out till date to study the dielectric strength of XLPE insulation (Sekii, 1995; Grzybowski and McMellon, 1995; Elanseralathan *et al*., 2000). However, these studies have been limited to the analysis of the performance of insulation during standard classical high voltage tests.

This study envisages investigations on the breakdown strength of XLPE cable dielectric when subjected to repetitive HFHV transients in inhomogeneous field. An air core inductor coil i.e., Tesla coil (Tesla, 1894; Denicolai, 2001) has been devised for carrying out experimental investigations. Experimentation has been carried out to find out the breakdown voltage of XLPE dielectric at an appropriate range of frequencies (40 to 115 kHz) by utilizing a double tuned circuit which enables a better quality factor under resonant condition. A detailed comparison between HFHV, 50 Hz power frequency, switching impulse and lightning impulse voltage has also been carried out to ascertain the role of high frequency oscillations in relationship to the breakdown voltage characteristics of the sample XLPE cable insulation.

EXPERIMENTAL SET UP FOR HFHV TESTING USING DOUBLE TUNED CIRCUIT

METHODOLOGY

Double tuned resonant circuit: The commonly used resonant transformer (Tesla coil), is designed for obtaining a doubly tuned resonant circuit in order to obtain better coil factor (voltage magnification) at resonant condition. The laboratory experimental test setup comprises a 10 kVA, 230/100 kV high voltage test transformer which is utilized to convert to produce a direct current output at condenser C1 utilizing the rectifier arrangement. A spark gap arrangement (G) is utilized with the aid for controlled trigatron (triggering) mechanism which forms a part of the control circuit of the sphere gaps for obtaining the desired voltage V1 which induces a high self-excitation in the secondary. The primary and secondary windings (L1 and L2) are wound on an air-cored arrangement which comprises the coil with facility to tap-off variable values of inductance. Tapping at various points of the coil provides an appropriate choice of inductance which in turn offers various choices of resonant frequencies. The two coil combinations are tuned to appropriate frequencies in the range of 40-150 kHz in conjunction with condensers C1 and C2. The output voltage is directly a function of the L-C combination (L1, L2, C1 and C2) and the mutual inductance of the coils. Since invariably the winding resistance is small it contributes only to the damping of the oscillations. Figure 1 illustrates a typical layout of the double tuned test setup utilized for studies of XLPE insulation.

It is worth noting that while a discharge takes place in the XPLE cable sample the voltage across the capacitor

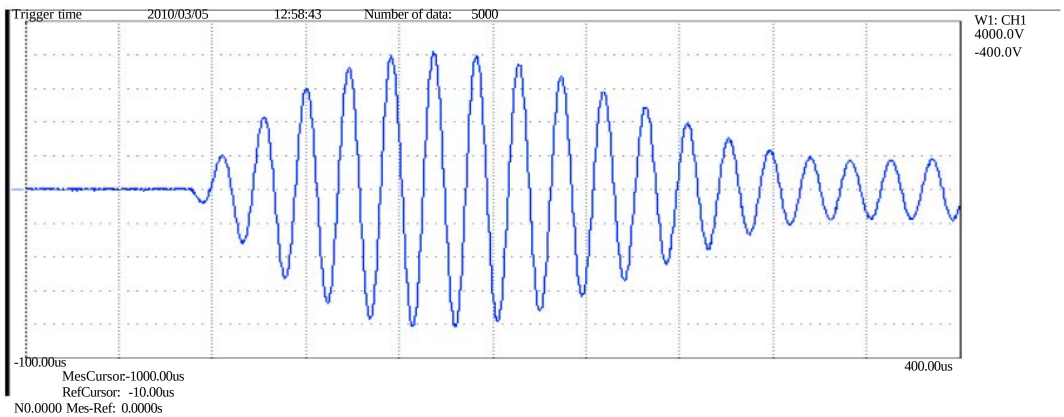

Fig. 2: Double tuned HVHF withstand voltage waveform of XLPE insulation-67 kV at 43 kHz

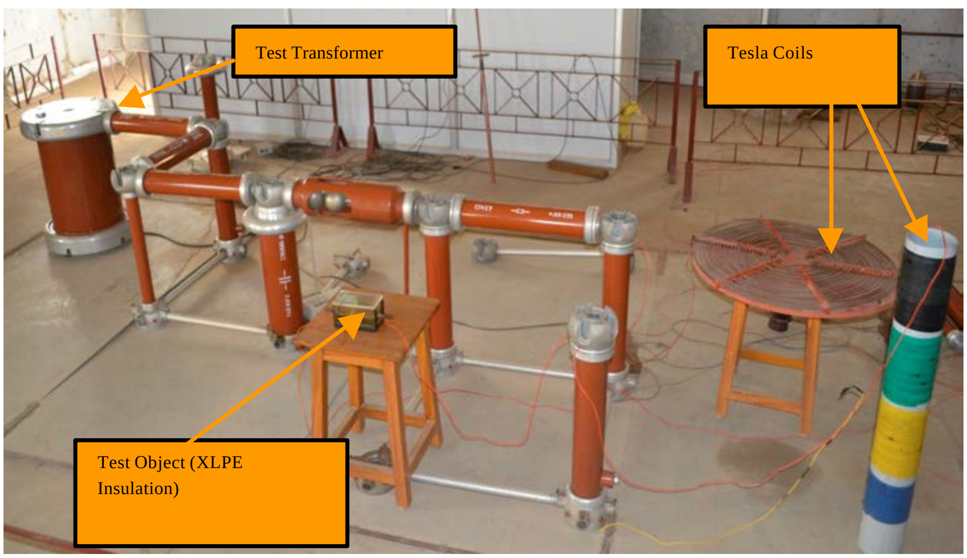

Fig. 3: Photograph of HVHF double tunred experimental test setup

falls and the sparking of the sphere gap is stopped which is attributed to the recombination of the ions in the gap thus isolating the cascaded C1 and C2 which are under resonance. The discharge across the test specimen also ceases due to the reduction in the voltage across the capacitor. HVHF oscillations of two different frequencies can be observed in the waveforms before and after the discharge in the test specimen. Figure 2 shows a typical withstand voltage output plot of a XPLE cable sample.

The experimental test set up comprises a double tuned high voltage high frequency resonant oscillator, resistive divider arrangement and a measuring impedance connected to a 200 MHz, 200 MS sec^{-1} DSO (DL 1620®). The selected range of high frequencies for the experiment varies from 40-115 kHz. This range has been selected since researchers who have carried out HFHV studies on similar such studies have chosen a comparable range of frequencies since a few reported incidents of failures has been observed to occurred at such frequencies. Figure 3 illustrates a photograph of the laboratory test setup of the HFHV double tuned test setup utilized for studies.

XLPE insulation sample preparation: The specimens used for the investigation of breakdown characteristics in

Table 1: HFHV breakdown studies for varying range of frequencies

<table>
<tr><th></th><th colspan="2">Double tuned circuit parameters</th><th></th></tr>
<tr><th>Frequency of HFHV transients (kHz)</th><th>Parameters of primary circuit</th><th>Parameters of secondary circuit</th><th>Breakdown voltage (kV)</th></tr>
<tr><td>43</td><td>C1 = 51200 pF
(25000 pF|| 25000 pF||1200 pF)
L1 = 0.265 mH</td><td>C2 =1300 pF
(1200 pF || 100 pF)
L2 = 10.10 mH</td><td>68</td></tr>
<tr><td>60</td><td>C1 = 25000 pF
L1 = 0.265 mH
L2 = 2.9 mH</td><td>C2 = 2500 pF
(1200 pF ||1200 pF|| 100 pF)</td><td>52</td></tr>
<tr><td>86</td><td>C1 = 26200 pF
(25000 pF|| 1200 pF)
L1 = 0.13 4mH</td><td>C2 = 1200 pF
L2 = 2.83 mH</td><td></td></tr>
<tr><td></td><td></td><td>48 kV</td><td>44</td></tr>
<tr><td>111</td><td>C1 = 13700 pF
(12500 pF|| 1200 pF)
L1 = 0.14 mH</td><td>C2 = 1200 pF
L2 = 1.7 mH</td><td></td></tr>
</table>

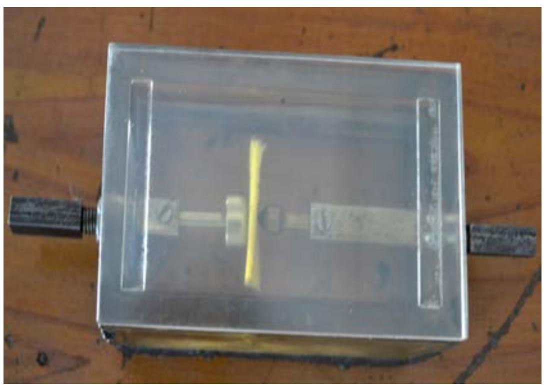

Fig. 4: Sample test speciment from 11 kV XPLE cable for HFHV test

laboratory are obtained from 3-core, 1.1 kV grade, 400 mm^2. XLPE cable. The core of the cable is removed and the outer semi-conducting layer of the XLPE cable is also peeled off. XLPE insulation is cut open and similar samples of 60 mm length are cut and fabricated with a thickness of 2 mm. The type of electrodes used in the present study was typical of point-plane electrode to produce an inhomogeneous field. A special test-cell was fabricated to hold securely the XLPE sample between the point-plane electrodes immersed in filtered degassed transformer oil to prevent flashover. Figure 4 shows typical photograph of an XPLE insulation sample placed in the test-cell which has been taken up for dielectric integrity studies.

TEST SETUP FOR CLASSICAL DIELECTRIC INTEGRITY TESTING

Power frequency and impulse voltage test setup: For the purpose of comparison, studies are carried out to determine the breakdown characteristics during classica test procedures namely the power frequency and impulse (lightning and switching) voltage setup. The power frequency voltage test setup utilizes a high voltage test transformer tunable to 100 kV with appropriate voltage divider for further measurement and acquisition of waveforms. Figure 5 depicts a typical test setup of the power frequency voltage test setup utilized during studies.

A single stage Marx Impulse Voltage generator arrangement is made to carry out impulse voltage testing due to the classical lightning (1.2/50 μ sec) and switching (250/2500 μ sec)transients. The test setup comprises a set of sphere gaps, a charging capacitor and appropriately chosen wave-shaping components for obtaining the standard lightning and switching wave shapes. Figure 6 indicates the Marx impulse generator circuit arrangement utilized for carrying out studies on XLPE cable insulation samples.

Breakdown voltage corresponding to Switching Impulse (SI) and Lightning Impulse (LI) over voltage is also noted. A comparison study is made between the breakdown due to power frequency, HFHV transients, LI/SI voltages in terms of the breakdown voltage and the number of cycles required to cause a breakdown in the XLPE sample.

RESULT AND ANLYSIS

Initially power frequency high voltage is applied and it is observed that the specimen did not break up to 70 kV and at 70.5 kV localized flash over through the oil is observed. Repetitive HFHV transients are applied and the specimens are constantly checked for breakdown. If breakdown occurs, corresponding breakdown voltage for a particular frequency is noted else voltage is increased by 0.5 kV. The corresponding breakdown waveform for a particular high frequency is recorded in DSO. Table 1 depicts the studies conducted for XLPE insulation samples for wide range of HVHF transients.

It is evident from Table 1 that as frequency increases in range of kHz, the breakdown voltage decreases (Sarvanan *et al*., 2006). This may be due to dipole spinning at different frequencies (Sanden, 1997). Figure 7

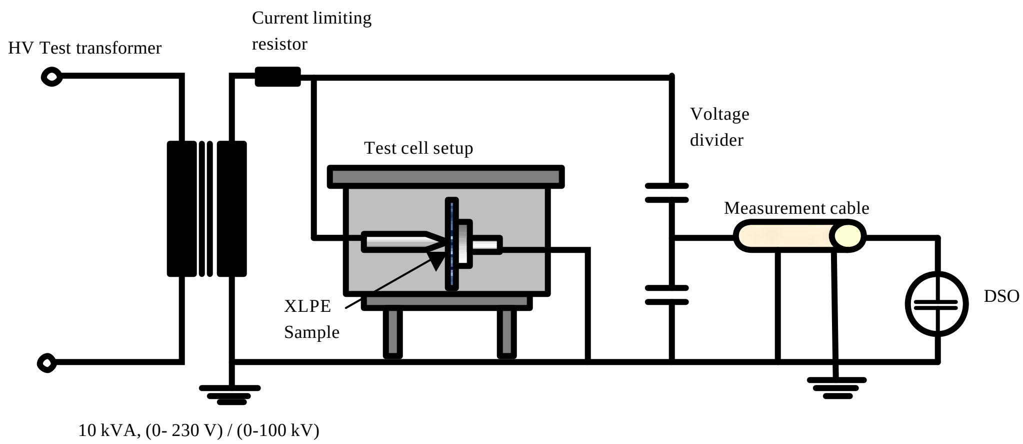

Fig. 5: Power frequency test setup for XLPE insulation testing

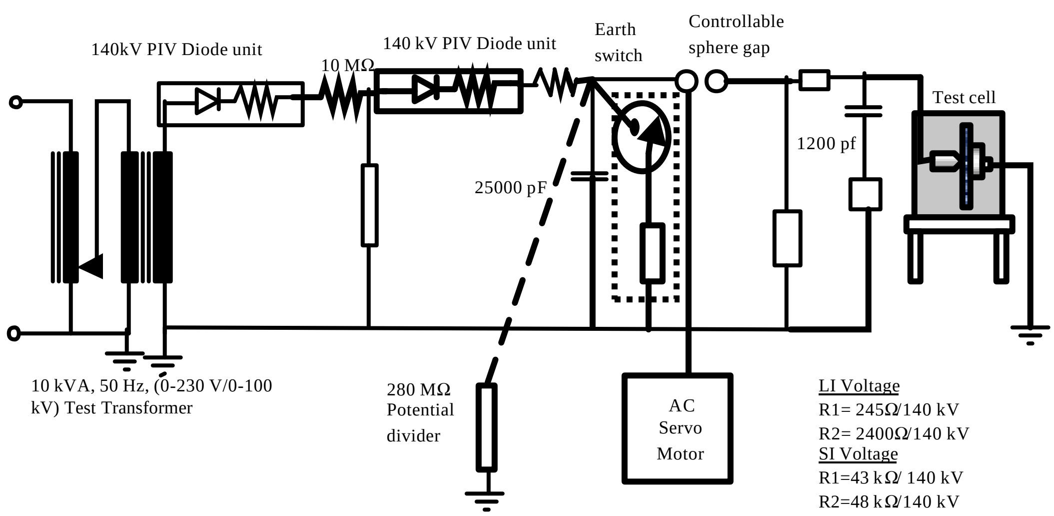

Fig. 6: Experimental test setup for impulse voltage breakdown studies

shows a plot of the analysis carried out for breakdown voltage at various ranges of frequencies.

On the contrary it is also significant to note that when frequency increases in range of kHz, the number of cycles required for breakdown to be initiated for a particular high voltage decreases. However, this is not always mandatory since breakdown process is influenced by cumulative stress rather than only peak magnitude of stress. This aspect is made apparent during studies as shown in Fig. 8 and 9.

In the case of studies pertaining to impulse voltages it is observed that LI causes lower breakdown voltage samples. compared to SI voltages. This is attributed to the fact that energy in switching impulse is much highe than the energy in lightning impulse

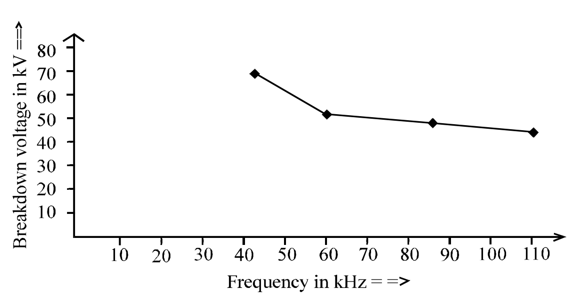

Fig. 7: Breakdown voltage of test specimen versus applied frequency

Figure 10, 11 and 12 indicate a plot of the LI and SI studies conducted on cable samples.

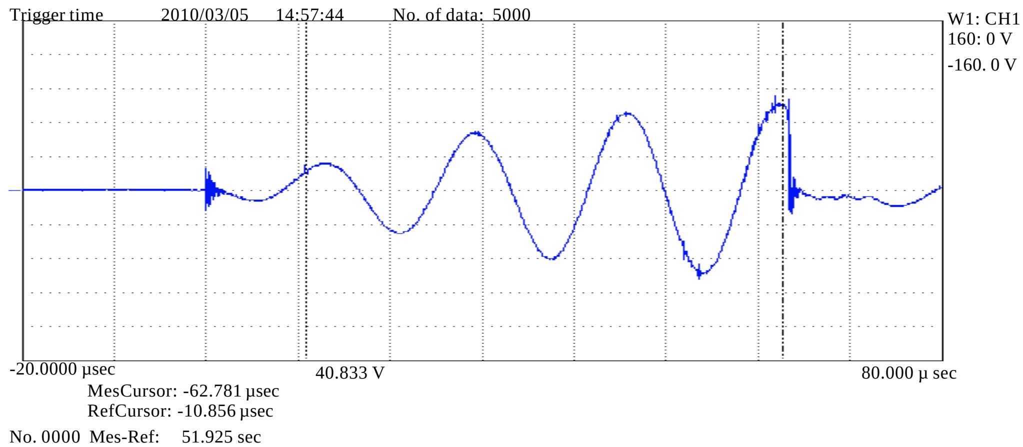

Fig. 8: Breakdown voltage waveform appearing across the specimen when the supply frequency is 60 kHz

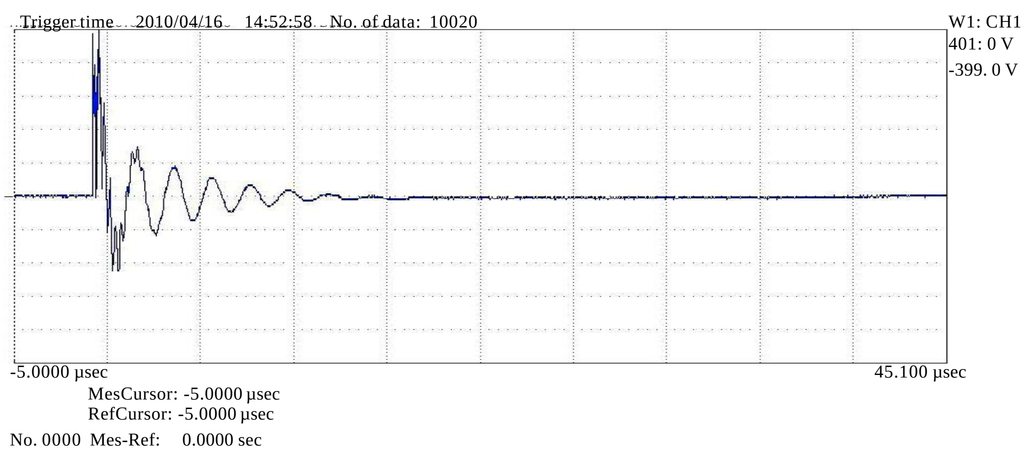

Fig. 9: Breakdown voltage waveform appearing across the specimen when the supply frequency is 86 kHz

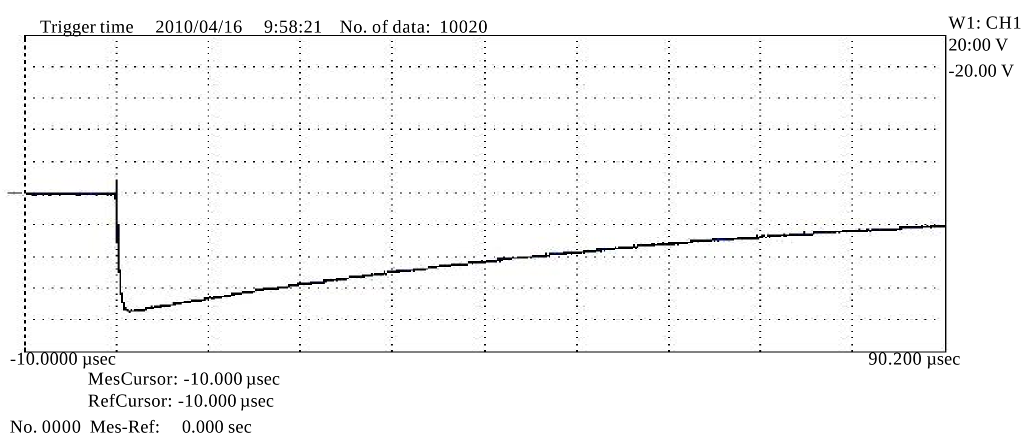

Fig. 10: Lightning impulse voltage waveform appearing across cable insulation sample at a supply voltage of 125 kV

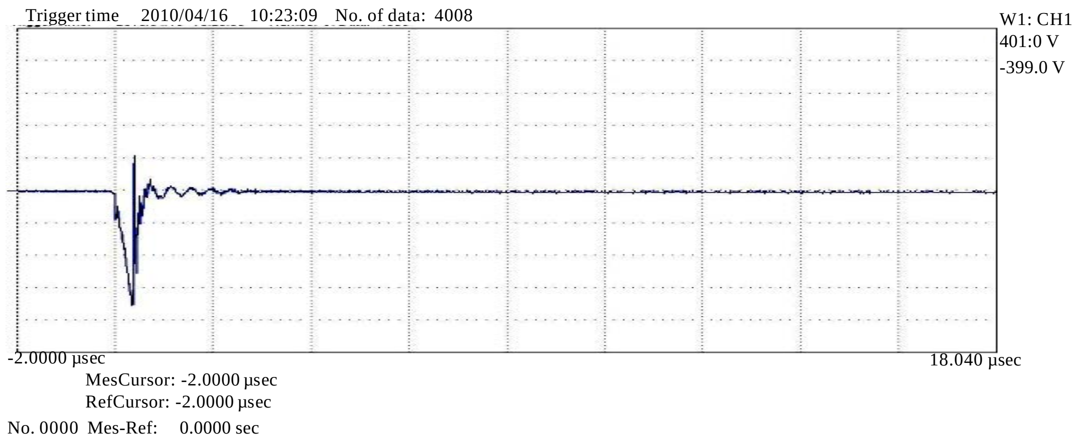

Fig. 11: Lightening impulse breakdown voltage waveform appearing across the insulation sample of cable at a supply voltage of 128kV

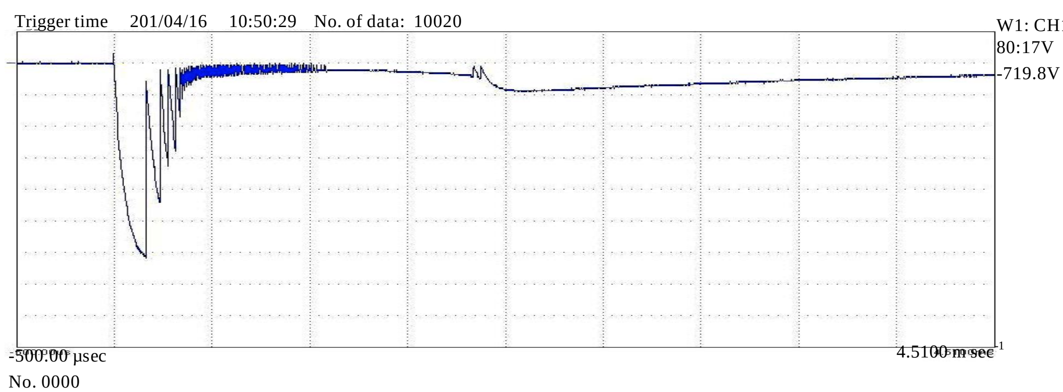

Fig. 12: Switching impulse breakdown voltage waveform appearing across the insulation sample of Cable at supply voltage of 139 kV

CONCLUSION

It is evident from studies that when XLPE insulation samples are subjected to HVHF transients, as the frequency increases, breakdown voltage decreases. Substantial reduction in the breakdown voltage is observed at higher ranges of frequencies (in orders of hundreds of kHz). It is also observed that in the case of studies pertaining to impulse voltages, LI causes lower breakdown voltage compared to SI voltages.

FUTURE SCOPE

This work can be extended with higher orders of frequencies which would in turn facilitate a more comprehensive understanding of the role of space charge effect (Hegerberg and Sanden, 1994) , thermal breakdown mechanism (Mohaupt *et al*., 1997) etc., in breakdown of XLPE insulation systems.

This research can also be extended to assess the breakdown characteristics of composite dielectric systems (including oil) including ageing degradation process (Samee *et al*., 2009) to provide clues into the role played by HVHF transients in complex insulation and improve the dielectric strength.

In addition, the effect of high frequencies when superimposed on power frequencies can also be assessed to determine the combined response of the dielectric system due to varying applied energy (due to power frequency and higher frequencies) applied across the XLPE dielectric sample.

ACKNOWLEDGMENTS

The authors of this work are extremely grateful to Prof. R. Sethuraman, Vice-Chancellor, SASTRA University, Dr. S. Vaidhyasubramaniam, Dean- Planning and Development, SASTRA University and Dr. S. Swaminathan, Dean-Sponsored Research and Director- CeNTAB, SASTRA University for the unwavering motivation and support extended to them during the course of the research. The authors are also grateful to Dr. B. Viswanathan, Dean/SEEE, SASTRA University for many useful suggestions, discussions and motivation.

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