EFFECTS OF LIGHTNING IMPULSES ON THE DIELECTRIC PROPERTIES OF HDPE

N. L. Dao, P. L. Lewin, S. G. Swingler

University of Southampton, UK

ABSTRACT

Impulse over-voltages are very common phenomena in electric power systems. Switching impulses are created by switching surges or local faults while lightning impulses are due to lightning strikes to overhead lines. Both impulses can travel as waves in the system, damaging insulation components and equipment. This paper shows that there may well be a reduction in electric field strength of the insulation of a power cable that experiences a lot of lightning impulse over-voltages. The paper also provides insight into the dominant ageing processes through the analysis of dielectric spectroscopy measurement data.

INTRODUCTION

Ageing and degradation of polymeric insulation materials is a very important topic for research as ageing directly affects the performance of a power system network. Although a lot of work has been done, the understand of ageing mechanisms is still not well established [1]. Several mechanisms have been proposed but none of them has a strong experimental evidence to support their hypothesis. Impulse voltages are quite common and can have significant effects on power systems especially power cable systems [2]. Because the on-time of an impulse is very short especially for a lightning impulse, it is very difficult to observe any change in the dielectric properties of a material if the number of repetitive impulses is not high enough or the level of peak voltage is too low [3]. In fact, the ageing effects of a switching impulse, with repetitive surges on a cable insulation material are easier to obtain compared to lightning impulse information due to their more frequent occurrence within an electric power system[4-7]. However, researchers are also interested in the effect of lightning impulses on the ageing processes of insulation cable materials due to their high level of over-voltage and extremely short front times. Lightning impulses can enter the electric power cable system as an external element. Overhead lines can be struck by lightning that produces a high voltage impulse wave that travels to substations, equipment and underground cable systems.

Sets of moulded samples from HDPE were used to conduct the ageing tests. Samples were aged using the lightning impulse generator in the Tony Davies High Voltage Laboratory. Simulated lightning waveforms were processed using a computer program to automatically obtain correct wave-shape parameters. The aged samples were then electrically stressed to failure using a ramped AC applied voltage. Obtained results were analyzed using Weibull statistics and compared to those for normal samples that did not experience any lightning impulse. Dielectric loss measurements were also taken to give more understanding into mechanisms of this ageing process.

SAMPLE PREPARATION AND AGEING PROCESS

A set of identical samples were produced by a hot press method. HDPE pellets were put into a manufactured mould and heated to 180^0C to make sure all the material had melted. The mould was the pressed by two hot plates up to pressure of about 1 ton. Care was taken during this pressing process to limit the variation of sample thickness. The basis of this process is that the more pressure applied, the more residual material is pushed out of the mould and the thinner sample will become. This method has an advantage compared to the vacuum methods as it ensures the elimination of all bubbles on the sample surface. The mould was cooled using cold water and the residual material that had been pushed out blocks water penetration into the sample within the mould. However, to make sure all water is diffused and that there is no grease on the sample surface, all samples were reheated to 80^0C in a vacuum oven for 20 minutes and then cleaned using acetone.

The produced samples have a shape similar to plastic bottle caps, with the thick rim, flat bottom surface and an inner surface which follows a Rogowski profile (Figure 1). This profile was used to reduce the edge effects inherent with finite dimension samples. The dimensions of the sample are shown in Figure 1, with the central surface thickness between 180µm to 200µm. The top and bottom surfaces were sputter coated with gold, this not only creates better contact between the sample and the electrodes but also produces a virtual electrode that follows the profile of sample surface. With breakdown tests, the samples were physically unaltered after the ageing process, but with dielectric loss tests, after the samples were aged, they then were cut to remove the rim and produce discs with diameter of 18-19mm.

Figure 2 shows the flow chart of the impulse ageing process. The Marx impulse generator was used to generate lightning impulses that were applied to samples. Both samples and generator were put into the closed screen cage to maintain safety. The multi-sample electrode contains 7 mushroom electrodes (Figure 3) to age 7 samples at the same time. With low field ageing where the probability of sample breakdown is low, many samples can be aged at the same time to reduce the overall ageing time. However, with fields high enough to make the samples breakdown, multi sample ageing at the same time is not recommended. If one breakdown happens, the rest of the samples will suffer from the very high breakdown current that results.

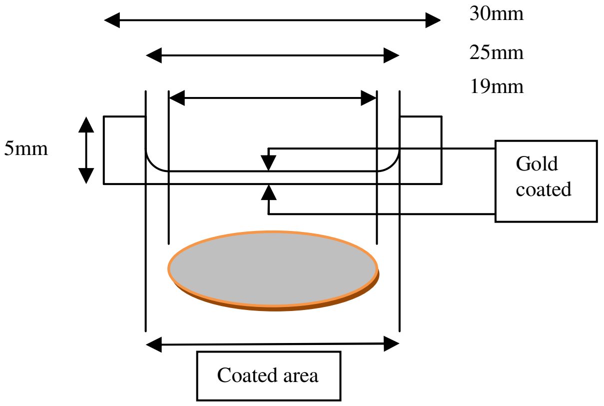

Figure 1: Sample dimensions

Applied voltage signals were obtained using an oscilloscope and sent to the computer for processing. The signal is checked to see whether the samples have broken down or the number of impulses have exceeded the requirement. In this case the oscilloscope has the role of a signal counter. If one of these two aspects is true, a relay box is activated to shut the generator down.

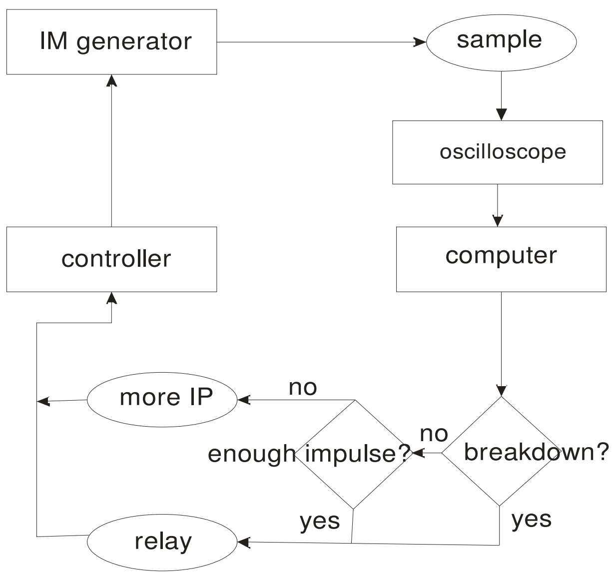

Figure 2: Ageing process flow chart

Mushroom electrodes were used instead of ball bearing electrodes in the ageing process to ensure local field uniformity. The mushroom electrodes also reduce the effect of mechanical deformation. Furthermore, samples were gold coated in order to eliminate the risk of triple junction effects.

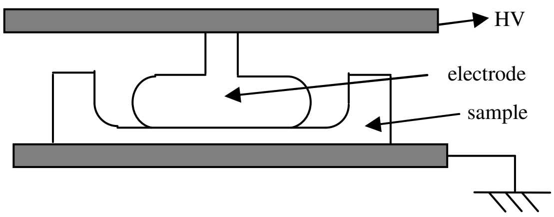

Figure 3: Impulse ageing electrode arrangement

During the ageing process, sets of several thousand lightning impulses (Figure 4) of positive or negative polarity were produced. These simulated lightning impulses were created by a normal RC circuit that has quite high potential value and a very short occurrence time. Due to the laboratory conditions where electromagnetic noise is high, the obtained waveforms of these impulses are always superimposed with overshoots and oscillations, making the accurate determination of impulse parameters more difficult, especially evaluation of front time. A program based on the best fit curve and filter that has been developed at the Tony Davies High Voltage Laboratory was used to calculate the parameters [8,9].

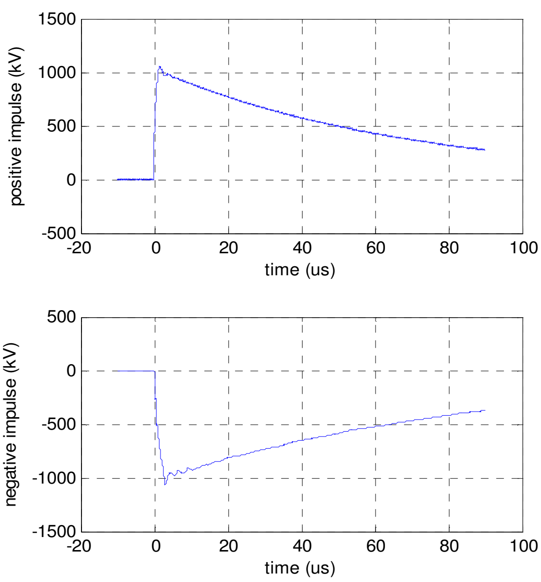

Figure 4: Positive and negative lightning impulse

Samples and electrodes were immersed in silicone oil to prevent flashover during the ageing process. About 3000 impulses of positive or negative polarity were applied over 75 minutes to obtain a peak electric field of 84-85kV/mm across the sample. Due to the charging time for capacitor, it is very hard to modify the repetition rate of the lightning impulse.

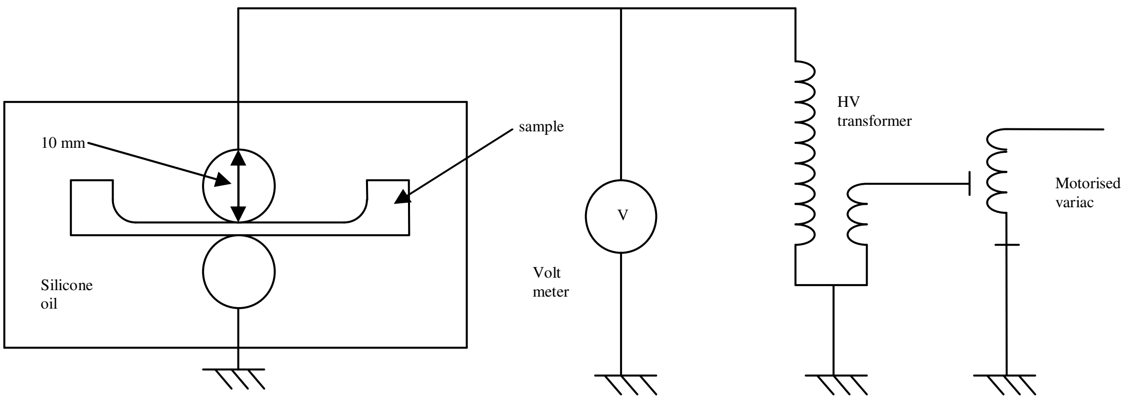

Figure 5: Breakdown test arrangement

BREAKDOWN CHARACTERISTIC CHANGE AS AN EFFECT OF LIGHTNING IMPULSE

After ageing, samples were taken immediately to a Faraday cage for breakdown testing. The electrodes were changed to ball bearings (Figure 5) and a constant ramp AC voltage was applied to samples. Breakdown voltage and time to breakdown were recorded.

The obtained breakdown voltages were then analyzed using Weibull distributions (Figure 6). The results show that positive and negative impulses actually reduce the breakdown strength of the material. The 90% confidence limits for aged and unaged samples only overlapped below 16% in case of negative impulse ageing and below 10% for positive impulse ageing. The breakdown strength is reduced quite significantly by more than 20% after the application of 3000 impulses. This result is not in agreement with some previous published results where the number of impulses may not be enough or the level of peak electric field of impulse not high enough to significantly age the samples[3]. The results presented here show that there is no significant difference between positive and negative impulses on material ageing and subsequent electrical breakdown performance.

Furthermore, from Figure 6, each set of breakdown data can be separated into two different groups, where each group has a different trend slope. This suggests that there are two different breakdown mechanisms for this material. The lightning impulses may produce hot electrons with high energy that enter the material bulk. These electrons when colliding with molecules of the sample can damage molecular bonds and create chemical charge trapping centres. These traps make space charge build up more effectively and therefore affect the breakdown strength of the sample. However, the effect of a lightning impulse may only be creating space charge near the surface of sample or simply supplying thermal energy raising sample temperature. These suggestions are supported by observation of frequent flashovers before breakdown of aged samples.

In order to investigate the ageing mechanisms in more detail, microscopic property tests such as space charge measurement and dielectric loss need to be undertaken.

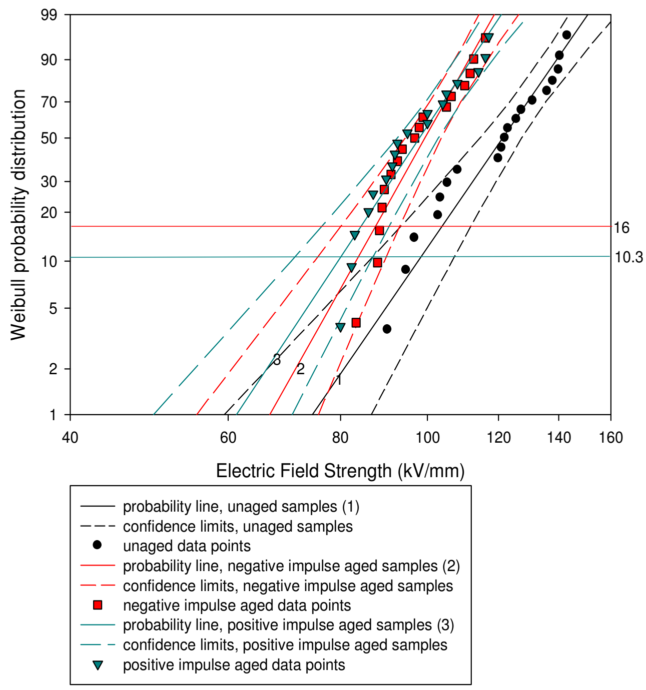

Figure 6: Breakdown probability of HDPE

DIELECTRIC LOSS SPECTRUM

Samples after ageing were cut into circular discs (Figure 1). These samples were cleaned using water and then acetone. The equipment used in this test is a solartron system (1296 dielectric interface and SI1260 Impedance/gain-phase analyzer) that is connected to a computer and a test chamber. The chamber can be heated using an external heater and the temperature of the chamber was measured using a digital thermometer.

Three types of sample were tested including normal unaged uncoated samples, normal coated samples and coated aged samples. The investigated frequency spectrum was from 10^{-2} to 10^{2} Hz. The obtained results are shown in Figures 7-9.

The uncoated sample has a high tan delta compared to other samples and an increase in the real part of its relative permittivity as the frequency decreases. The reason for this may be the poor contact between the electrodes and the sample. This leads to interfacial polarisation and the measurement is affected by stray capacitance and resistance. For the unaged coated sample, the dielectric loss was much less than the other two sample types. However, with such a small tan delta it is very easy for the external noise to affect the measurement. The real part of the relative permittivity of the unaged coated sample is fairly constant but the slope of imaginary part was less than -1 over the frequency range indicating loss due to both conduction and Debye relaxation processes. In the cases of aged samples, the tan delta is higher and closer to the value obtained for the uncoated sample. However, the real part of relative permittivity of aged sample remains constant. Again, the slope of the imaginary part of the relative permittivity of the aged samples approaches -1 suggesting the increase in dielectric loss is due to conduction processes.

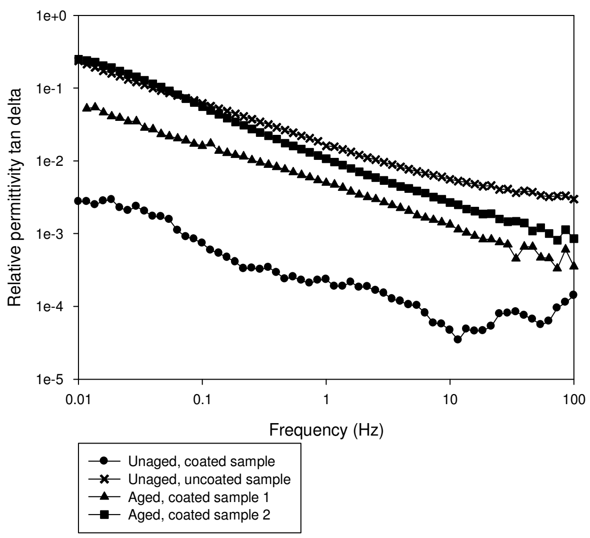

Figure 7: Relative permittivity tan delta

24 hours after the samples were aged, the measurement for dielectric loss was repeated and the results are shown in Figures 10 and 11. Dielectric tan delta has reduced but is still quite high compared with the unaged coated sample. However, there was a significant change in the real part of the relative permittivity, as it had increased. This can be related to a change in the overall charge of the sample and supports the idea that lightning impulses create a certain amount of space charge near the surface of sample which may dissipate over time. In order to observe the space charge more accurately, pulsed electro-acoustic (PEA) measurement will be undertaken as part of this study.

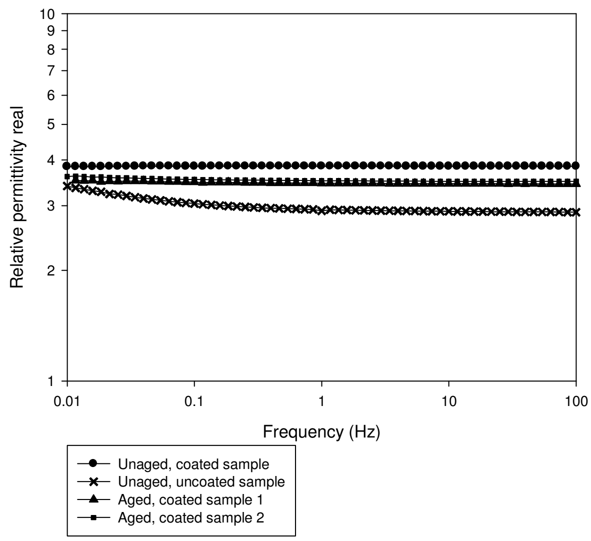

Figure 8:Real part of relative permittivity

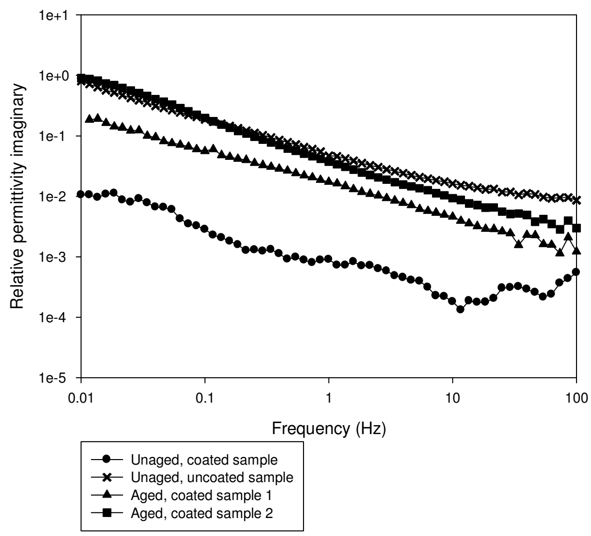

Figure 9: Imaginary part of relative permittivity

CONCLUSION

Lightning impulses can age polymeric insulation materials. The breakdown strength of the material will be reduced after a significant number of lightning impulses events. It is hard to determine the dominant mechanism for material ageing due to lightning impulses. It could be the creation of additional trapping centers or the enhancement of mechanisms that increase the conductivity of the material. The dielectric loss test shows that aged samples are lossier than unaged ones, increased conduction losses ultimately mean that the aged insulating material sample experiences increased temperatures when under the same applied field as an unaged one. PEA tests will be taken to observe the behavior of space charge in samples that have experienced lightning impulses. More experiments will be conducted using different front times, different impulse types and different cable insulation materials.

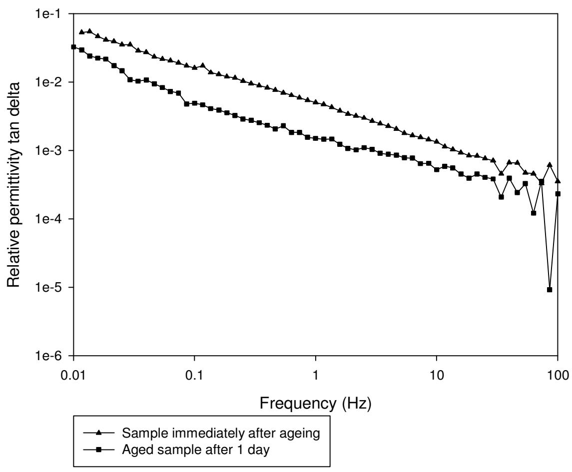

Figure 10:time dependence of relative permittivity

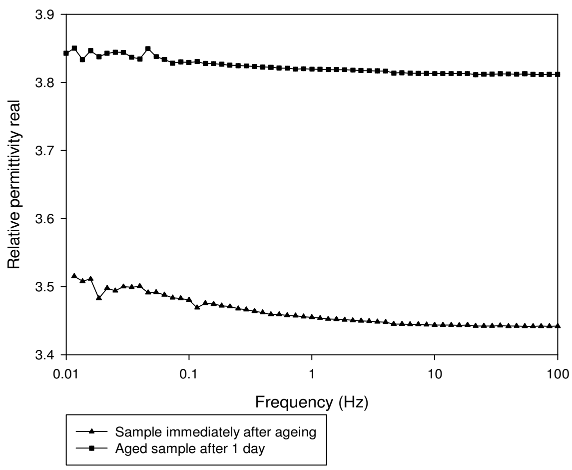

Figure 11: time dependence of real relative permittivity

ACKNOWLEDGEMENT

This work is funded through the EPSRC Supergen V, UK Energy Infrastructure (AMPerES) grant in collaboration with UK electricity network operators working under Ofgem's Innovation Funding Incentive scheme; - full details on http://www.supergen-amperes.org

References

1 *J. C. Fothergill, "Ageing, Space Charge and Nanodielectrics: Ten Things We Don't Know About Dielectrics" 2007 International Conference on Solid Dielectrics, Winchester, UK, July 8-13, 2007, Page(s):1-10*

2 *S. Bahadoorsingh, S. Rowland "The Relationship between Insulation Ageing and Power Network Performance" ICSD 07, IEEE international conference on solid dielectrics, 2007, 8-13 July 2007 Page(s):180 – 183*

3 *Mohamed A. Abdallah "Behavior of XLPE medium voltage cable under switching impulse" Proceedings of the XIVth International Symposium on High Voltage Engineering, Tsinghua University, Beijing, China, August 25-29, 2005, CD-Rom*

4 *S. Grzybowski, Life Fellow, IEEE, P. Trnka, Member, IEEE, J.C. Fulper, Student Member, IEEE "Aging of High Voltage Cables by Switching Impulse" IEEE Electric Ship Technologies Symposium, 2007, p 165-8*

5 *R.A Hartlein, V.S. Harper, Harry Ng "Effects of voltage surges on extruded dielectric cable life project update" IEEE transactions on power delivery, volume 9, issue 2, April 1994 Page(s):611 – 619*

6 *G.C. Stone, R.G. Van Heeswijk, R. Bartnikas "Electrical aging and electroluminescence in epoxy under repetitive voltage surges" IEEE transaction on electrical insulation, volume 27, issue 2, April 1992 Page(s):233 – 244*

7 *S. Boev "Electric aging of polyethylene in pulsed electric field" 12th IEEE International Pulsed Power Conference. (Cat. No.99CH36358) 1999, p 1365-8 vol.2*

8 *D.J.Swaffield, P.L.Lewin, N.L.Dao and J.K.Hallstrom "Lightning impulse wave-shapes: defining the true origin and its impact on parameter evaluation" XVth International Symposium on High Voltage Engineering, University of LjublJana, Elektroinstitut Milan Vidmar, Ljubljana, Slovenia, August 27-31, 2007, T10-203*

9 *P.L.Lewin, member, IEEE, T.N.Tran, D.J.Swaffied and J.K.Hallstrom "Zero phase filtering for lightning impulse evaluation: A K-factor Filter for the revision of IEC60060-1 and -2" IEEE Transactions on Power Delivery, 2008, volume 23 (1). pp. 3-12. ISSN 0885-8977*