LIGHTNING IMPULSE AGEING OF HDPE

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

University of Southampton, Sothampton, Hampshire, SO17 1BJ, UK
*contact: nld06r@ecs.soton.ac.uk

Keywords: Lightning-Impulse, Ageing, Life-time, Breakdown.

Abstract

This work is concerned with the hypothesis that lightning impulses can lead to accelerated ageing of extruded polymeric cables. The behaviour of an insulation material when suffering lightning impulses is different from that for DC or power frequency over-voltages. Shaped HDPE material samples have been manufactured using a mould tool. The samples then may be electrically aged using one of the Tony Davies High Voltage Laboratory's impulse generators. A real-time software based monitoring tool has been designed to control the impulse wave-shape and process the measurement data. Sets of identical lightning impulses were applied to samples and this was then followed by ramped AC breakdown tests. The obtained results were analyzed using the Weibull distribution method to identify the difference in lifetime. These results will inform the further development of models describing the multifactor ageing mechanisms that in-service cables experience.

1 Introduction

Lightning strikes to overhead line power systems or overvoltage surges due to faults or switching actions are quite common. These surges may travel through the system as waves to underground cables and other equipment. Insulation quality of devices and cables will suffer from impulse over-voltages. These impulses can lead to accelerated ageing of extruded cables [1-4]. Lightning impulses are voltages with very high magnitudes and very short on times. Therefore the behaviour of a material when suffering lightning impulses is different from DC or power frequency over-voltage behaviour. In order to investigate the effect of lightning impulses on the ageing process of high voltage power cable insulation, pre-designed and shaped HDPE samples have been manufactured using a mould tool. The samples then can be electrically aged using one of impulse generators in the Tony Davies High Voltage Laboratory. A real-time software based monitoring tool has been designed to control the impulse wave-shape and process the measurement data. Sets of identical lightning impulses were applied to samples and then this was followed by ramped AC breakdown tests. The obtained results were analyzed using the Weibull distribution method to identify the difference, if any, in lifetime. These results will be used to improve our understanding of ageing mechanisms and facilitate lifetime prediction.

2 Lightning impulse definitions and parameters

A lightning impulse is a high voltage impulse that occurs over extremely short times (µs for lightning and ms for switching) with high magnitude. According to the IEC 60060-1[6] the smooth lightning impulse (Figure 1) is defined by a set of parameters:

Test voltage V_p: the peak value of the waveform.

Front time T_1: is measured as 1.67 times the interval T between the instants when the impulse is 30% and 90% of the peak value.

Tail time T_2: is measured as the time interval between the virtual origin O_1 and the instant when the voltage has decayed to half of peak value.

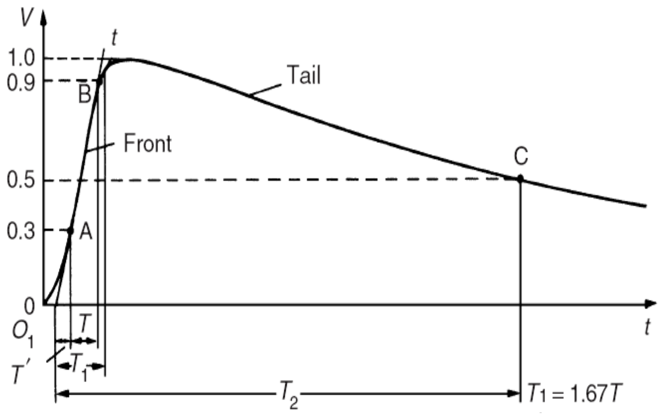

Figure 1: Lightning impulse [5]

The virtual origin is characterised by the value of t_0 where:

$$t_0 = \frac{t_{90}v_{30} - t_{30}v_{90}}{v_{30} - v_{90}} \qquad (1)$$

Typically, the standard lightning impulse has the front time T_1=1.2µs±30% (0.84µs≤T_1≤1.56µs), the tail time T_2=50µs±20% (40µs ≤T_2≤60µs) and also the tolerance for peak value is ±3%. The time parameters for a switching impulse are much greater than the lightning case, they are in the order of milliseconds. A mathematical formula that represents the smooth impulse is:

$$f(t) = A\left(e^{\frac{-(t-t_0)}{\tau_2}} - e^{\frac{-(t-t_0)}{\tau_1}} \right) \qquad (2)$$

In order to measure the parameters of a lightning impulse that is generated in laboratory conditions where electromagnetic waves created by other equipment can superimpose into lightning waveform to create noise and overshoots, a programme was written to collect the data from oscilloscope, process it and produce a smooth curve and its parameters. The new IEC approach was used to process the waveform, raw measurement data was first taken, then the best fit curve found and subtracted from the raw data to create a residual. Applying the K-factor [7] to the residual and summing the result with the best fit curve provides a final curve for parameter calculation. The recommended K-factor filter has been developed at the University of Southampton. A new separated double exponential function (SDE) instead of normal double exponential (DE) [8] was used as the best fit curve.

$$f(t) = A_2 e^{\frac{-(t-t_0)}{\tau_2}} - A_1 e^{\frac{-(t-t_0)}{\tau_1}} \qquad (3)$$

This best fit curve approach has also been developed within the Tony Davies High Voltage Laboratory

3 Sample production process

Disc-shape (Figure 2) samples were produced by heat-press method using a 4 parts mould tool (Figure 3). HDPE pellets with melt flow index 2.2 were put inside the mould and heated to about 180^{o}C until all pellets were melted. After that, a pressure of 1 ton was applied to push all the residual material and air bubbles out. Cold water was used to quench cool the sample. When released from the mould, the sample has a thickness of approximately 180 µm and the inner surface of the sample has the Rogowski profile. The sample has inner/outer diameter: 25/30 mm, and a height of 5 mm. All samples were heat treated in a vacuum oven with temperature of 90^{o}C for half an hour before the top and bottom of the samples were gold sputter coated. Samples have electrodes that follow the profile thus reducing the edge effect and the likelihood of triple junctions. Mushroom electrodes were used instead of ball bearing electrodes to reduce the mechanical deformation.

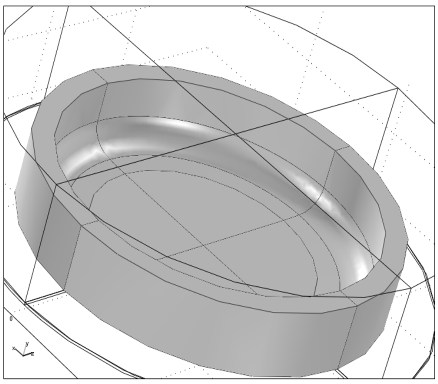

Figure 2: Disc sample

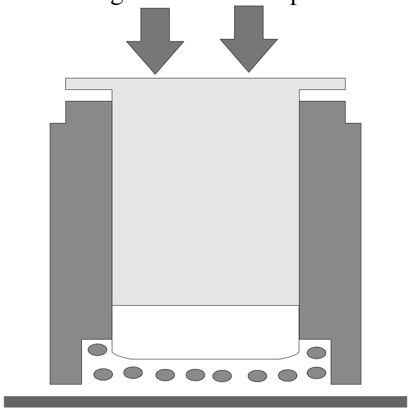

Figure 3: mould tool

4 Impulse ageing experiment

Figure 4 shows the lightning ageing experiment. The two-stage Marx impulse generator produced an impulse voltage that was applied to the samples. A multi-electrode system was made to age many samples at the same time. The impulse generator was controlled by a computer programme using signals from an oscilloscope. The impulse wave-shape from the scope is filtered and impulse parameters are returned using the new IEC 60060-1 standard. Signals were counted by the oscilloscope and Breakdown checking was done using a Labview program. After signal checking, if breakdown or flashover did not occur, the computer would send a command to the generator controller to generate the next impulse voltage, otherwise a signal would be sent to a relay circuit to shut the generator down.

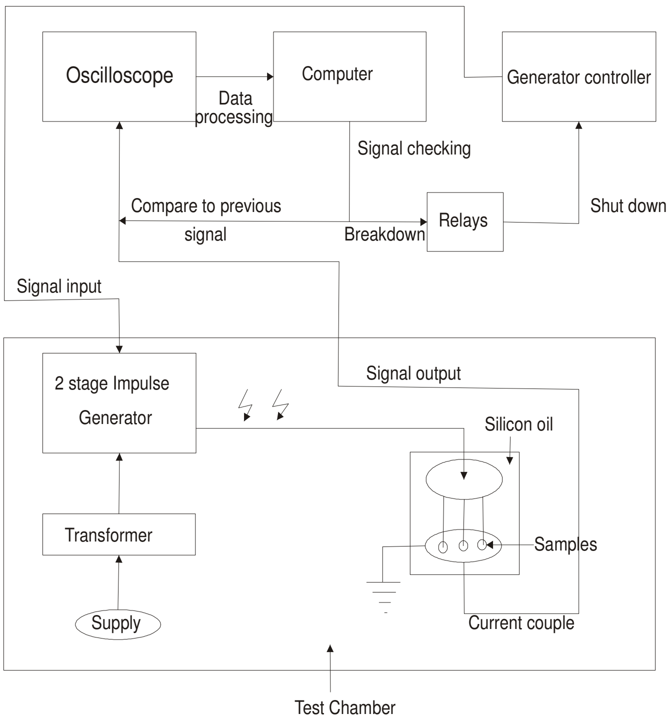

Figure 4: Ageing process

Approximately 3000 Impulses of front time 1.15us and tail time 42.6us were used to age samples for a duration of 75 minutes. These impulses generated a peak electric field of about 84kV/mm on the samples for both negative and positive polarity impulses.

5 AC ramp breakdown results

Aged samples and normal samples were subjected to an AC ramp breakdown test after the ageing process. Breakdown voltages were recorded and processed to obtain a Weibull probability distribution of breakdown strength [9-10], using

$$F_F(V) = 1 - \exp\left[-\left(\frac{V}{\eta}\right)^{\beta}\right] \quad (4)$$

In order to estimate the cumulative probability the Bernard estimator was used [11].

$$F = \frac{i - 0.3}{n + 0.4} \quad (5)$$

Where F is cumulative probability of i^{th} point, n is the number of data. 90% confidence limits were obtained using Weibull ++7 software.

6 Discussions

From figure 5, the breakdown strength of unaged samples is higher than the aged samples as the confidence limits do not overlap for breakdown probabilities higher than 16%. Parameters of the Weibull distribution are reasonable and are shown in table 1. Figure 6 shows that, both positive and negative lightning impulses lead to a reduction in breakdown strength. However, there is no significant statistical difference between them except the breakdown voltages for positive impulse aged samples are little bit lower than the negative case. During AC ramp breakdown tests for aged samples, surface discharges were usually observed but not with the unaged samples. This may suggest that there are surface charges or space charge near the surface that has increased as a result of the impulse ageing process. As the on-time for each impulse is very short, space charge injected from the electrode may not be the dominant reason for ageing but the generation of hot electrons by the impulse voltage may cause damage to the molecular structure.

	β	η
Unaged samples	8.68	126.5
Negative impulse aged samples	10.6	102.8
Positive impulse aged samples	9	102.1

Table 1: Weibull parameters

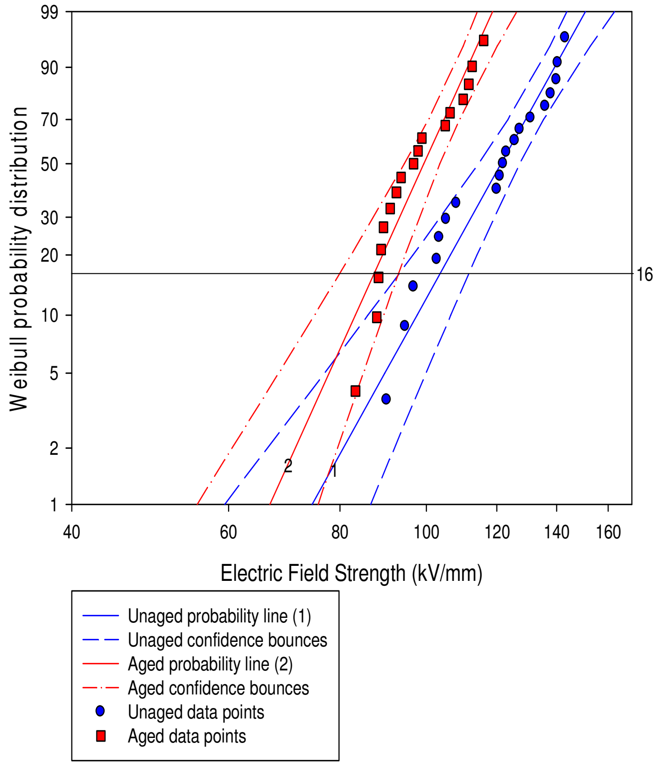

Figure 5: Aged and unaged HDPE

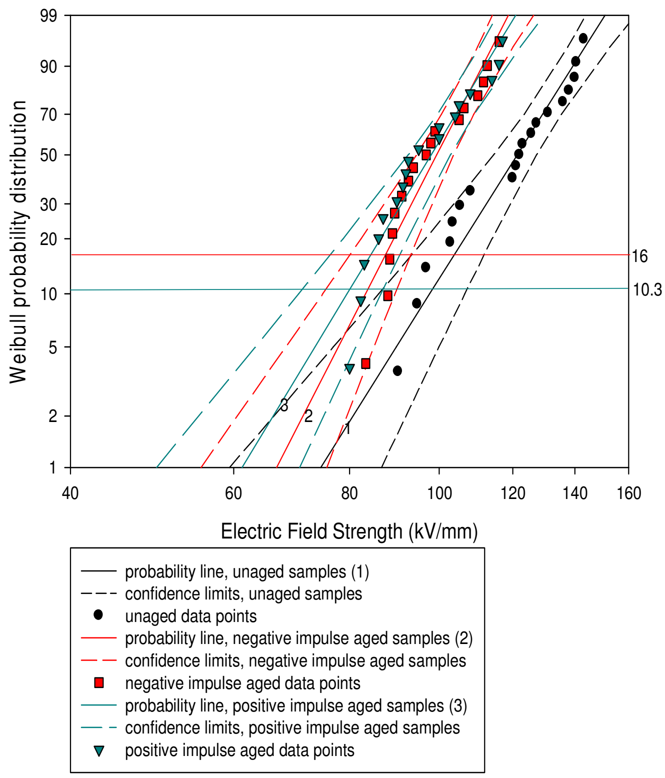

Figure 6: Positive and negative impulse ageing

7 Conclusions and Further Work

The results showed that a significant number of lightning impulse events accelerate the ageing process of HDPE. More comparison between the effects of lightning and switching impulses will be undertaken to identify the role of space charge on this ageing process. Front time variation of the impulse will also be altered as it will vary the gradient of the applied voltage. The relationship between level of electric field stress, number of impulses and the lifetime of materials will be considered.

References

[1] 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

[2] 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

[3] 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

[4] 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

[5] E. Kuffel, W.S. Zaengl, J. Kuffel, "High voltage engineering fundamental", *Newnes, second edition, July 17, 2000*

[6] IEC 60060-1: 1998, BRITISH STANDARD, "High voltage test techniques" – Part 1 "General definition and test require ment" *Published by the International Electrotechnical Commission*

[7] 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

[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" *XV^{th} International Symposium on High Voltage Engineering, University of LjublJana, Elektroinstitut Milan Vidmar, Ljubljana, Slovenia, August 27-31, 2007*

[9] G.C. Stone "The statistics of aging models and practical reality" *IEEE transaction on electrical insulation*, volume 28, issue 5, Oct 1993, page (s): 716-728

[10] L.A. Dissado, J.C. Fothrgill "Electrical degradation and breakdown in polymer" *IEE materials and devices series 9, Peter Peregrinus Ltd. On behalf of the Institution of Electrical engineers, 1992*

[11] J. C. Fothergill "Estimating the Cumulative Probability of Failure Data Points to be Plotted on Weibull and other Probability Paper" *IEEE Transactions on Electrical Insulation* Vol. 25 No. 3, June 1990 pp. 489-492