Modelling of Electroluminescence in Polymeric Material using Dimensional Analysis Method: Effect of Applied Voltage and Frequency

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Abstract
Electroluminescence (EL) method has been used by several researchers to observe the behaviour of an aged polymeric material. EL is a phenomenon that occurs when the atoms of a material are being excited due to the application of and external high electrical stresses. The changes in the energy level of these excitation states can be used as an indicator for the initiation of electrical ageing. There are several factors that affect the behaviour of EL emission such as, among others, applied voltage, applied frequency, ageing of material and types of materials and gases used are discussed in this paper. A mathematical approach relating these factors and the intensity of EL is proposed through the aid of Dimensional Analysis method. A close relationship is obtained between experimental and simulation that suggests this mathematical approach can be utilized as a tool to predict electrical ageing of insulation material.

Keywords. Dimensional analysis; Electrical discharge; Electroluminescence; Modelling

Introduction

Electrical breakdown of polymeric insulation has become a major concern in all aspects related to the generation of electricity. Numerous investigations have been conducted by researchers to observe the behaviour and effect of polymeric electrical breakdown. Polymeric insulating materials are widely used in high voltage cable due to their cost-effectiveness, in addition to their excellent electrical and physical properties. Electrical breakdown is the result of prolong electrical degradation in polymeric material such as electrical treeing and partial discharges. The former and latter degradation phenomena are closely related to the behaviour of mobile and trapped charges in dielectric material [1-2]. To measure the energy dissipation of these charges, a reliable method known as electroluminescence (EL) method has been opted. EL measures the energy dissipation of trapped and mobile charge when subjected to high external field, where light emission of visible photons is released due to the interaction between both charges. Therefore, it can be said that EL is largely associated with the injection and recombination of charge carriers of opposite polarity into the bulk of the insulating material. However, the characteristics of the EL emission can be affected by several factors such as applied voltage, applied frequency, ageing material and types of material used in a particular study. It is to the interest of this study to develop a mathematical model relating the light emission data and the factors contributing to it through the aid of Dimensional Analysis method. Dimensional Analysis (DA) is a great mathematical tool that can be used to deduce information about a phenomenon e.g. EL, from the fact that the phenomenon can be described by a dimensionally correct equation among certain variables [3]. In this study, some strong factors affecting the emission of EL will be considered. The results are modelled using DA mathematical outcome and they are compared with the experimental results.

Methods
2.1 The Electroluminescence Measurement

The experimental setup for EL measurement has been in details elsewhere [4]. The EL measurement was collected from an additive-free virgin low density polyethylene (LDPE) of 100 ± 5μm, 60mm x 60mm squares with 35mm diameter of semi-transparent gold layer on both sides of the sample. The detection system utilizes a Peltier cooled electron multiplying charge coupled device (EMCCD) camera and connected to high voltage amplifier and function generator. Phase-resolved measurements involve 100 sets of 1000, 2.168ms exposures, synchronized with the applied field using the zero crossing point trigger. Two experiments are conducted to observe the voltage dependence and frequency dependence of EL intensity.

2.2 The Electroluminescence Model

The EL phenomenon is largely associated with the rate of charge injection and recombination of positive and negative charge carriers within the polymeric material and it can be affected by several factors such as applied voltage, applied angular frequency, types of material, ageing temperature and recombination rate of charges. In this present paper, the effect of these factors on EL emission is investigated. The relationship between these variables can be written as;

$$EL = \Phi\ (V, T, R, \varepsilon_o\varepsilon_r, \omega, X) \quad (1)$$

where EL is the electroluminescence intensity, V is the applied voltage, T is the aging temperature of material, R is the recombination rate of charges, $\varepsilon_o\varepsilon_r$ is the permittivity of the sample, ω is the applied angular frequency, X is the thickness of the sample. In order to represent these variables on dimensional matrix, the physical units of the parameters are used indicated by Table 1.

Table 3. Parameter and its physical units

Parameters	Physical Units
EL	$T^{-2}A^{-1}$
V	$L^2M^1T^{-3}A^{-1}$
T	$L^2M^1T^{-2}$
R	L^{-3}
$\varepsilon_o\varepsilon_r$	$L^{-3}M^{-1}T^4A^2$
ω	T^{-1}
X	L^1

Using dimensional matrix, homogeneous linear algebraic equations, simultaneous equation technique and by applying Buckingham's π-theorem we obtained;

$$\pi_1 = EL\ R^{\frac{n}{3}}\omega^{-2}X^n, \qquad \pi_2 = V\ R^{-\frac{1}{3}+\frac{n}{3}}\varepsilon\,\omega X^n, \qquad \pi_3 = T\ R^{-\frac{1}{3}+\frac{n}{3}}\varepsilon\,\omega^2 X^n$$

For identifying the effect of varying applied electrical stress and frequency on virgin LDPE sample, by taking into consideration the general relationship between light intensity and applied voltage, we deduced that;

$$EL = D_c\, V^2 R^{-\frac{2}{3}+\frac{n}{3}}\varepsilon^2\omega^4 X^n$$

where D_c is a dimensionless constant depending on the experiment conducted. The product of π_3 is ignored in this equation as virgin samples are not affected by temperature. The recombination rate is calculated using equation (4) in [5].

Results and Discussion

3.1 Voltage Dependency of EL Intensity

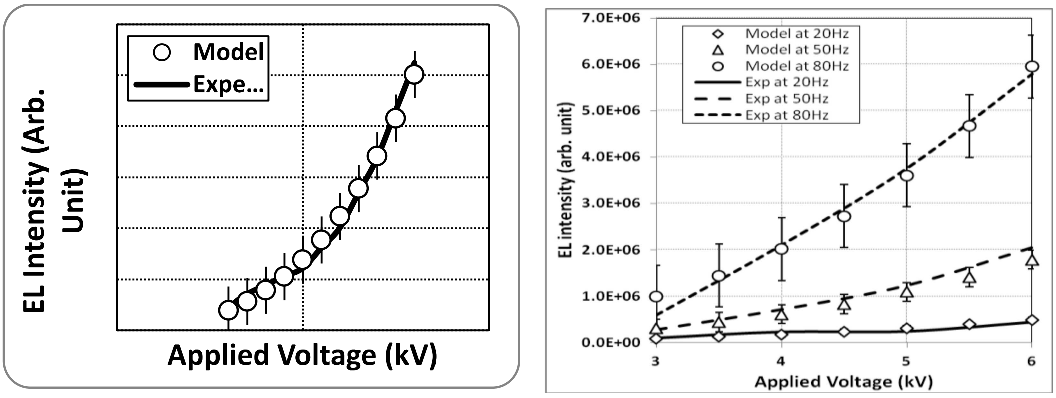
The main goal of the modelling is to reproduce the experimental EL phenomena for better understanding of the behaviour of EL phenomena. This model uses a virgin LDPE material with a thickness of 100 μm under a constant frequency of 50 Hz with varying field from 3kVp to 8kVp. Set of parameters used in this model is defined in Table 2 for voltage dependency experiment. The values for the constant parameters are chosen such that it can produce a good correlation between experimental and modelling data. The data to be compared is the average EL intensity produced by the sample. The model is in good agreement with experimental data as depicted in Figure 1(a). The EL intensity increases as applied voltage increases. This is expected due to the increase of charge injection at the metal-polymer interface as applied voltage increases, thus increase the recombination rate of charge carriers within the material. There is slight variation in the simulation. Slightly bigger differences can be observed at 7.5kVp and 8kVp. The experimental data is trending towards exponential-like behaviour which explains the high EL intensity at higher applied voltage.

Table 2. Set of parameters and its value

Parameters	Physical Units Value for Voltage Dependency	Physical Units Value for Frequency Dependency
D_c	7×10^{24}	3×10^{26}
V	3kVp – 8kVp	3kVp – 6kVp
n	2.5	2.5-2.6
R	Assume 0 at 0kVp	Assume 0 at 0kVp
$\varepsilon_o\varepsilon_r$	1.992×10^{-11}F/m (ε_r= 2.3)	1.992×10^{-11}F/m (ε_r= 2.3)
ω	100π (f = 50Hz)	2πf (f = 20Hz, 50Hz, 80Hz)
X	100μm	100μm

3.1 Frequency Dependency of EL Intensity

In modelling the frequency variation, a set of parameters as in Table 2 for frequency dependency is used. In this experiment, samples are subjected to varying field of 3kVp to 6kVp at 20 Hz, 50Hz and 80Hz. The model is in good agreement with the experimental data as depicted in Fig. 1(b) with very slight variation. The EL intensity is higher at higher frequency level. Since injection and recombination takes place at the first quadrant of the positive and negative half cycle, charges have lesser time to transport deeper into the material at higher frequency due to the half cycles stay above the threshold level of EL emission for a shorter time. This resulted in increasing number of injected and trapped charges at the metal-polymer interface and increases the chances of charge recombination, thus higher EL intensity. Nonetheless, the model exhibits an exponential-like behaviour especially at high frequency level. If the value of the EL intensity is not taken into consideration, the model displays similar behaviour and in good agreement with the experimental data.



(a) (b)

Figure 1: Comparison between simulation (with 10% standard error) and experimental data for virgin LDPE for (a) voltage dependency and (b) frequency dependency.

Conclusion

This paper has presented the development of a mathematical model using Dimensional Analysis method to reproduce the experimental EL phenomenon in virgin LDPE in order to observe the factors that have an impact on the EL emission. The model shows a satisfactory agreement with the experimental data for both voltage dependency and frequency dependency model and lower applied voltage. The model exhibit exponential-like behaviour that correlates to the experimental data with very slight variation. This model shows that Dimensional Analysis is a powerful mathematical tool that helps to further understand the physical processes controlling the EL emission phenomenon.

ACKNOWLEDGMENT

The first author wishes to express her deepest gratitude to Professor Paul Lewin, David Mills and all staff at The Tony Davies High Voltage Laboratory for their guidance and support throughout the research undertaken at University of Southampton.

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