AUTHOR(S): BANI, N.A., ABDUL-MALEK, Z., MUHAMMAD-SUKKI, F., MASUD, A.A., MUHTAZARUDDIN, M.N., KAMARDIN, K., JAMIAN, J.J. and AHMAD, H.

TITLE: Modelling the effect of applied voltage and frequency on electroluminescence in polymeric material.

YEAR: 2016

Publisher citation: BANI, N.A., ABDUL-MALEK, Z., MUHAMMAD-SUKKI, F., MASUD, A.A., MUHTAZARUDDIN, M.N., KAMARDIN, K., JAMIAN, J.J. and AHMAD, H. 2016. Modelling the effect of applied voltage and frequency on electroluminescence in polymeric material. International journal of electrical and computer engineering [online], 6(3), pages 1375-1384. Available from: https://dx.doi.org/10.11591/ijece.v6i3.9573

OpenAIR citation: BANI, N.A., ABDUL-MALEK, Z., MUHAMMAD-SUKKI, F., MASUD, A.A., MUHTAZARUDDIN, M.N., KAMARDIN, K., JAMIAN, J.J. and AHMAD, H. 2016. Modelling the effect of applied voltage and frequency on electroluminescence in polymeric material. International journal of electrical and computer engineering, 6(3), pages 1375-1384. Held on OpenAIR [online]. Available from: https://openair.rgu.ac.uk

International Journal of Electrical and Computer Engineering (IJECE)
Vol.x, No.x, September 201x, pp. xx~xx
ISSN: 2088-8708

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

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Article Info

Article history:

Received Jun 12th, 201x
Revised Aug 20th, 201x
Accepted Aug 26th, 201x

Keyword:

Dimensional Analysis
Electrical discharge
Electroluminescence
Modelling

ABSTRACT

Electroluminescence method has been used by several researchers to observe the behaviour of an aged polymeric material. Electroluminescence 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 electroluminescence 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 electroluminescence 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.

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1. 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. Several studies have come into agreement [3-4] that EL measurement can be used as an indicator for electrical degradation in polymeric 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. Several researchers [5-7] have developed a mathematical model associated with EL intensity incorporating these factors in order to observe the process of electrical aging in insulating material. 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 [8]. One major advantage of using DA is the reduction of the number of variables in a set of problem. Several researchers have used DA to form reasonable hypotheses about complex physical situations and tested them through laboratory experiments. DA have been used in finding effective implementation of line and station insulation coordination in contaminated conditions [9], predicting polymer tube life for solar hot water systems [10], scaling and instrumented indentation measurements [11] and more. 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.

2. RESEARCH METHOD

2.1. The electroluminescence measurement

The experimental setup for EL measurement has been explained in details elsewhere [12]. 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 coated on both sides of the sample. For EL measurement, the uniform field configuration is shown in Figure 1. The detection system utilizes a Peltier cooled electron multiplying charge coupled device (EMCCD) camera and is 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.

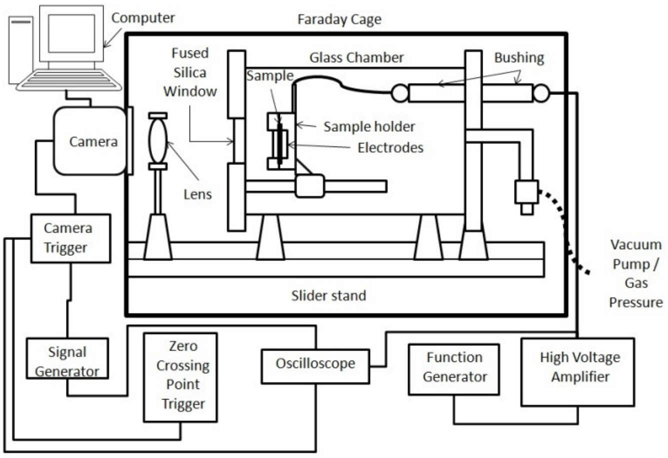


Figure 1. Experimental setup for EL measurement on LDPE samples

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 results of the EL simulations are validated by regression analysis using Minitab software by obtaining the R^2 value. A high value of R2 indicates that a model has a good fit. The relationship between these variables can be written as:

$$EL = \Phi (V, T, R_{eh}, \varepsilon o \varepsilon r, \omega, X) \tag{1}$$

where EL is the electroluminescence intensity, V is the applied voltage, T is the aging temperature of material, R_{eh} 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 used are indicated in Table 1.

Table 1. 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_{eh}	L^{-3}
$\varepsilon_o\varepsilon_r$	$L^{-3}M^{-1}T^4A^2$
ω	T^{-1}
X	L^1

The dimensional matrix of the above variables can be written as:

$$\begin{array}{c|ccccccc}
 & k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & k_7 \\
 & EL & V & T & R_{eh} & \varepsilon_o\varepsilon_r & \omega & X \\
\hline
L & 0 & 2 & 2 & -3 & -3 & 0 & 1 \\
M & 0 & 1 & 1 & 0 & -1 & 0 & 0 \\
T & -2 & -3 & -2 & 0 & 4 & -1 & 0 \\
A & -1 & -1 & 0 & 0 & 2 & 0 & 0
\end{array}$$

where k_1, k_2, k_3, k_4, k_5, k_6, and k_7 are the exponents of variables EL, V, T, R_{eh}, $\varepsilon_o\varepsilon_r$, ω and X respectively. The rank of the dimensional matrix is 4 ($\neq 0$) hence the dimensionless product of the whole set is 3 (number of variables minus rank). The homogeneous linear algebraic equations corresponding to the respective exponents can be written as:

$$2k_2 + 2k_3 - 3k_4 - 3k_5 + k_7 = 0 \tag{2}$$

$$k_2 + k_3 - k_5 = 0 \tag{3}$$

$$-2k_1 - 3k_2 - 2k_3 + 4k_5 - k_6 = 0 \tag{4}$$

$$-k_1 - k_2 + 2k_5 = 0 \tag{5}$$

The expression for k_4, k_5, k_6 and k_7 in terms of k_1, k_2, and k_3 can be derived from Equations (2)-(5) by using simultaneous equation technique resulted in 4 unknowns with 3 equations. To solve this, one of the exponents is assigned as constant n, in this case k_7, hence resulted in:

$$k_4 = -\frac{1}{3}k_2 - \frac{1}{3}k_3 + \frac{n}{3} \tag{6}$$

$$k_5 = k_2 + k_3 \tag{7}$$

$$k_6 = -2k_1 + k_2 + 2k_3 \tag{8}$$

$$k_7 = n \tag{9}$$

The value of n will be determined by experiments. Since there are three sets of dimensionless products; π_1, π_2 and π_3, the solutions can be arranged in the matrix form as below;

$$
\begin{array}{c|ccccccc}
 & k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & k_7 \\
 & EL & V & T & R_{eh} & \varepsilon_o\varepsilon_r & \omega & X \\
\hline
\pi_1 & 1 & 0 & 0 & \frac{n}{3} & 0 & -2 & n \\
\pi_2 & 0 & 1 & 0 & -\frac{1}{3}+\frac{n}{3} & 1 & 1 & n \\
\pi_3 & 0 & 0 & 1 & -\frac{1}{3}+\frac{n}{3} & 1 & 2 & n
\end{array}
$$

From the matrix form, we can deduce that:

$$\pi_1 = EL\, R_{eh}^{\frac{n}{3}}\, \omega^{-2} X^n \tag{10}$$

$$\pi_2 = V\, R_{eh}^{-\frac{1}{3}+\frac{n}{3}}\, \varepsilon \omega X^n \tag{11}$$

$$\pi_3 = T\, R_{eh}^{-\frac{1}{3}+\frac{n}{3}}\, \varepsilon \omega^2 X^n \tag{12}$$

By dimensional analysis,

$$\pi_1 = \phi(\pi_2^{\alpha_2}, \pi_3^{\alpha_3}) \tag{13}$$

where α_2 and α_3 will be determined experimentally. This means that the function for each dimensionless product is unknown and any function can be performed on them. For identifying the effect of varying applied electrical stress and frequency on virgin LDPE sample, we applied the Buckingham's π-theorem and taking into consideration the general relationship between light intensity and applied voltage, we deduced that $\alpha_2 = 2$ and $\alpha_3 = 0$. This resulted in:

$$\pi_1 = (\pi_2)^2 \tag{14}$$

$$EL\, R_{eh}^{\frac{n}{3}}\, \omega^{-2} X^n = \left(V R_{eh}^{-\frac{1}{3}+\frac{n}{3}}\, \varepsilon \omega X^n \right)^2 \tag{15}$$

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

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 [6]. From equation (15), the effects of applied voltage, recombination rate, permittivity of material, angular frequency and thickness of sample on EL intensity can be deduced.

3. RESULTS AND ANALYSIS

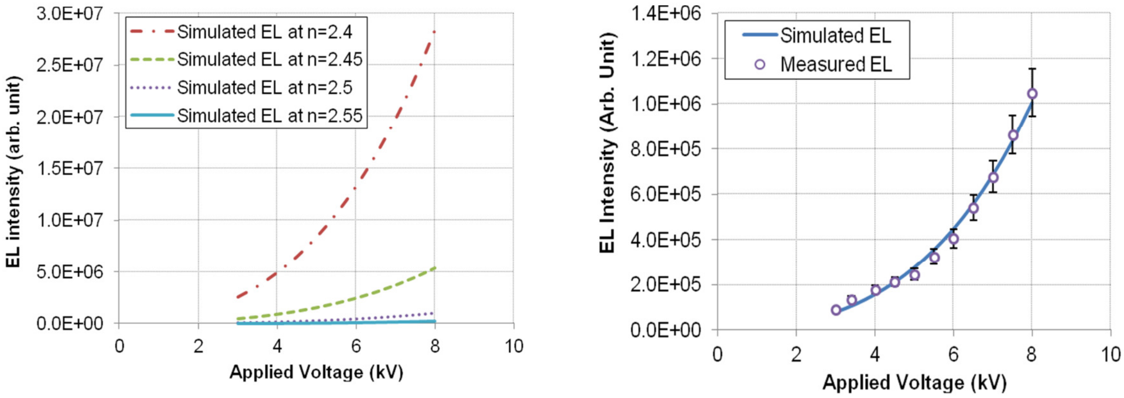
3.1. Voltage Dependency of EL Intensity

The main goal of the modelling is to reproduce the experimental EL phenomena for better understanding of the behaviour of EL phenomena. From Equation 15, the effect of applied voltage and applied frequency on EL intensity can be deduced. 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. 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.

Table 2. Set of parameters and its value

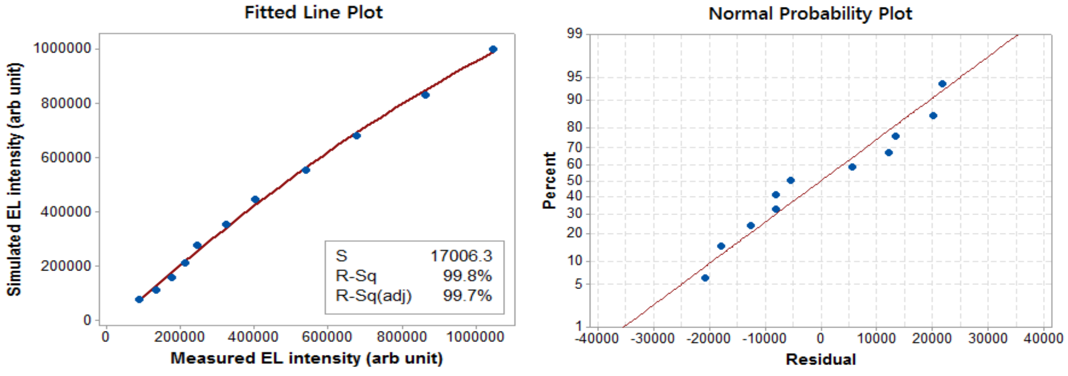
Parameters	Physical Units
$\boldsymbol{D_{c1}}$	$\mathbf{1x10^{-12}}$
$\boldsymbol{D_{c2}}$	$\mathbf{7x10^{12}}$
V	3kVp – 8kVp
$\boldsymbol{n_1 = n_2}$	2.5
R_{eh}	Assume 0 at 0kVp
$\varepsilon_o\varepsilon_r$	$1.992\text{x}10^{-11}$F/m (ε_r= 2.3)
ω	100π (f = 50Hz)
X	100µm

Figure 2(a) shows the model simulation of EL emission. 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. It can be seen that the variance of EL intensity is larger at higher applied field. The value of *n* also plays an important role. Higher *n*-value produces lower EL intensity. Figure 2(b) compares the simulation data of EL intensity due to varying electric field for virgin LDPE with that of the experimental data. Comparison is made in terms of the changes in EL intensity at varying electric field. The model is reasonably in good agreement with experimental data as depicted in Figure 2(b). There is slight variation in the simulation from 3kVp to 8kVp. Slightly bigger differences can be observed at 8kVp. The experimental data is trending towards exponential-like behaviour which explains the high EL intensity at higher applied voltage. The R^2 value in Figure 3(a) shows a very high value of 99.8% which means the model is found to fit the measured data very well. This is also supported with the spread of the data that is normally distributed as depicted in Figure 3(b).



(a) (b)

Figure 2: (a) Simulation of EL measurement with varying electrical field, and (b) comparison between simulation and experimental data for virgin LDPE with 10% standard error



(a) (b)

Figure 3: (a) Best fitted line plot, and (b) normal probability plot of virgin LDPE

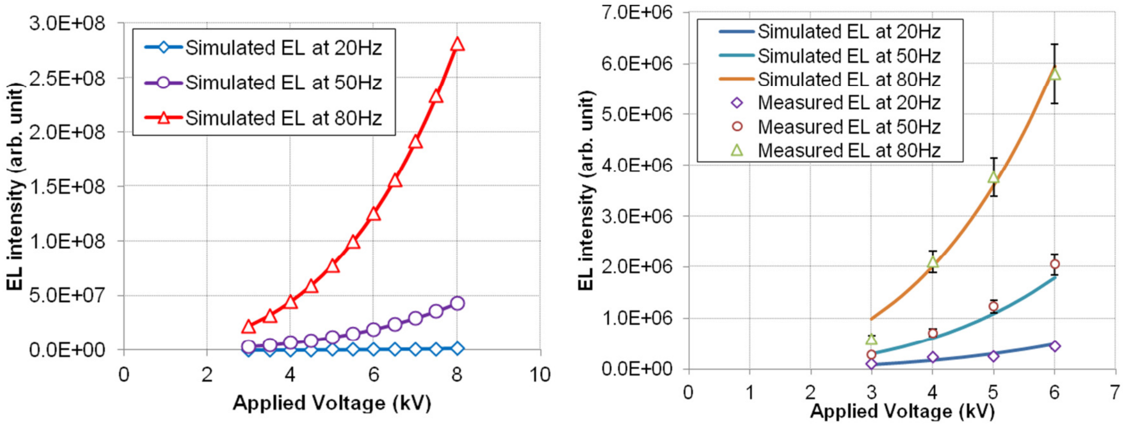
3.2. Frequency Dependency of EL Intensity

In modelling the frequency variation, Equation 15 is opted as well. The same procedure is used in calculating R_{eh} but with a new set of parameters as in Table 3. In this experiment, samples are subjected to varying field of 3kVp to 6kVp at 20 Hz, 50Hz and 80Hz.

Table 3. Set of parameters and its value

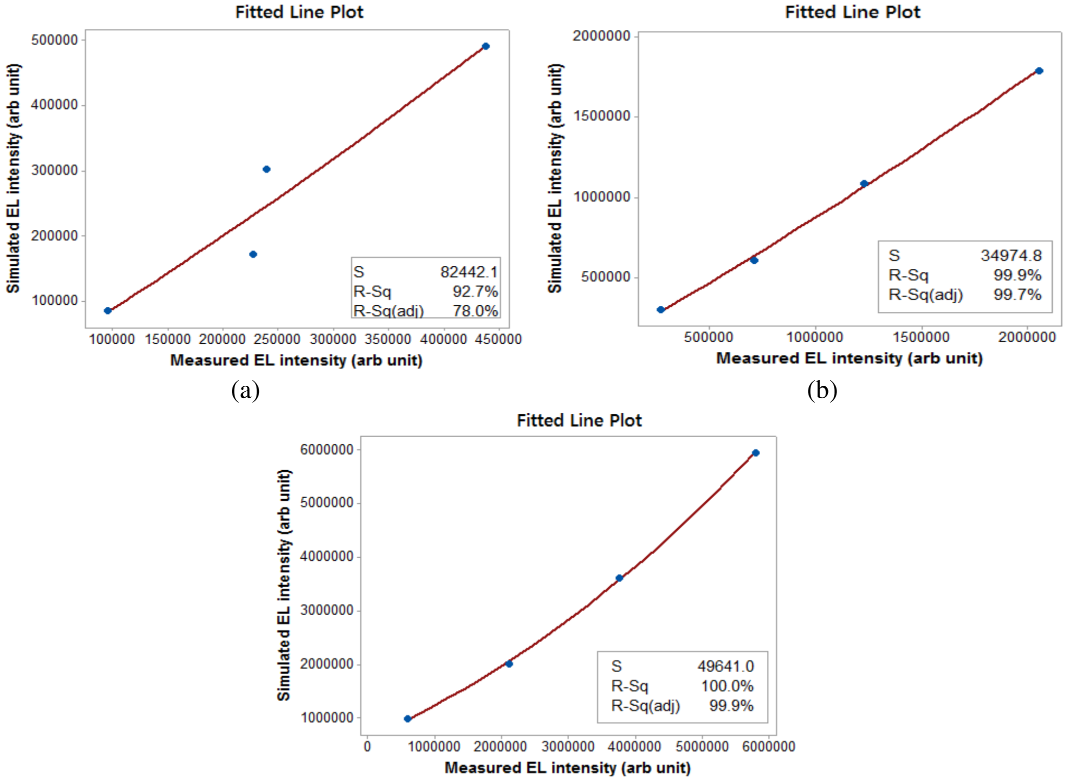
Parameters	Physical Units
$\boldsymbol{D_{c1}}$	**1x10^{-12}**
$\boldsymbol{D_{c2}}$	**3x10^{14}**
V	3kVp – 6kVp
$\boldsymbol{n_1 = n_2}$	2.5-2.6
R_{eh}	Assume 0 at 0kVp
$\varepsilon_o\varepsilon_r$	1.992x10^{-11}F/m (ε_r= 2.3)
ω	2πf (f = 20Hz, 50Hz, 80Hz)
X	100μm

Fig. 4(a) shows the model simulation of EL emission with varying electrical field at applied frequency of 20Hz, 50Hz and 80Hz. The values of n used in this model are 2.5, 2.57 and 2.59 for 20Hz, 50Hz and 80Hz respectively. The value of n is higher for higher applied frequency. The EL intensity is also 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. Figure 4(b) compares the simulation data of EL intensity due to varying electric field at applied frequency of 20Hz, 50Hz and 80Hz for virgin LDPE with that of the experimental data. The simulated data are scaled to fit the experimental data for comparison purposes using the parameters value as tabulated in Table 3. Comparison is made in terms of the changes in EL intensity at varying electric field. The model is in good agreement with the experimental data for all applied frequencies as depicted in Figure 4(b) with very slight variation. As applied voltage increases to 6kVp, the variations are observed getting larger. 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. The R^2 value in Figure 5 shows a very high value of 92.7% at 20Hz, 99.9% at 50Hz and 100% at 80Hz. This means the model is found to fit the measured data very well especially at higher frequency. This is also supported with the spread of the data that is normally distributed for all measured applied frequency as depicted in Figure 6.



(a) (b)

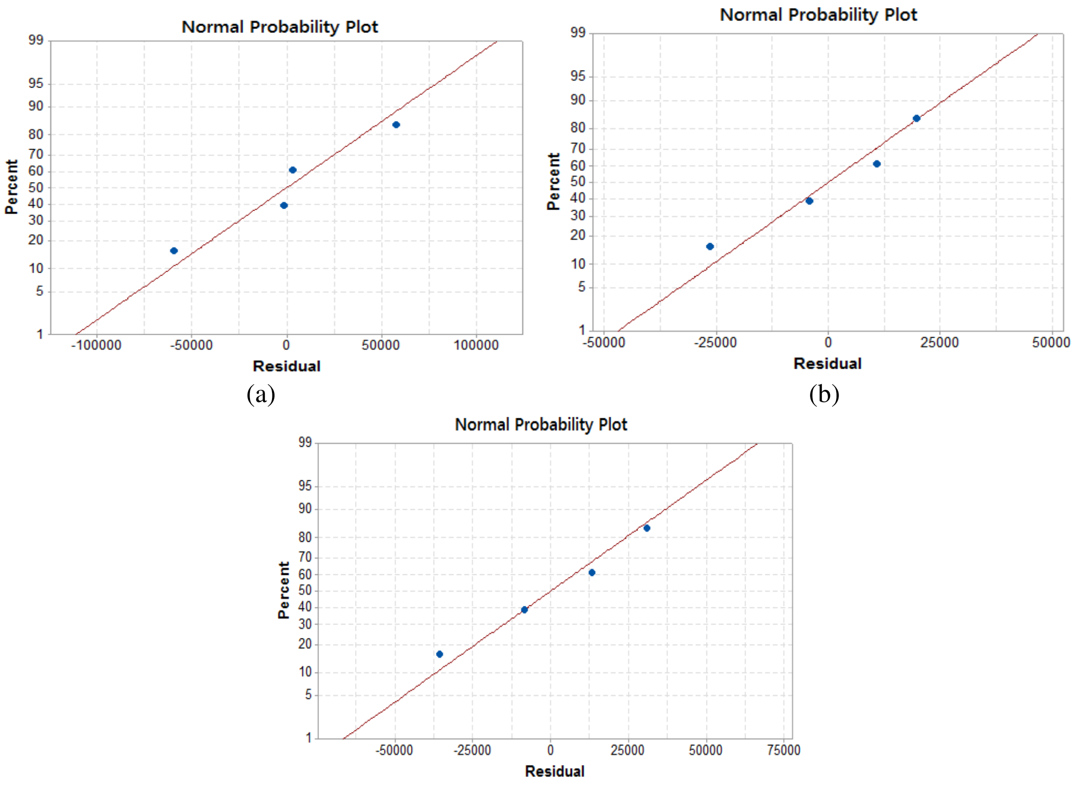
Figure 4: (a) Simulation of EL measurement at varying frequencies, and (b) comparison between simulation and experimental data for virgin LDPE with 10% standard error



(a) (b)

(c)

Figure 5: Fitted line plot of simulated versus measured EL intensity at: (a) 20Hz, (b) 50Hz and (c) 80Hz.



(a) (b)

(c)

Figure 6: Normal probability plot of simulated versus measured EL intensity at: (a) 20Hz, (b) 50Hz and (c) 80Hz

4. CONCLUSION

This paper has presented the development of a mathematical model using DA 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 for virgin samples. In both cases, the model exhibit quadratic and exponential-like behaviour that correlates to the experimental data with very slight variation. Some major differences that can be detected in all simulations are the value of D_{c2} and n_2 that need to be changed when applying varying frequency on virgin samples. However, the n-value for virgin sample is still within 2.5-2.6 and the change in D_{c2} value is necessary to produce a good correlation between experimental and modelling data. In this paper we have provide statistical evidence using Minitab to conclude that the model is sufficiently accurate for specific conditions with high R^2 value but can also be used in various cases by using different parameters values. This is sufficiently useful for researchers as a reference in carrying out real experiments at high fields or high frequency that would have been costly to conduct without the model. Although the model described here is empirical at this stage, the information yielded from this model is valuable for future predictions. This model shows that DA is a powerful mathematical tool that helps to further understand the physical processes controlling the EL emission phenomenon. This study believes that the same procedures are also necessary for simulating aged samples at different ageing temperature and ageing durations that could be useful to predict the electrical breakdown in aged samples.

ACKNOWLEDGEMENTS

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. Authors wish to thank Ministry of Science, Technology and Innovation (MOSTI), Ministry of Education (MOE), and Universiti Teknologi Malaysia.

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