



## A New Statistical Approach for Analysis of Tree Inception Voltage of Silicone Rubber and Epoxy Resin under AC Ramp Voltage

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**Abstract:** Weibull distribution has been used widely by many researches around the world especially in the analysis of high voltage experimental data. Unfortunately, the statistical techniques used to analyse the high voltage experimental data are not highly accurate. In view of the foregoing, this paper presents a new statistical approach to analyze the tree inception voltage of silicone rubber and epoxy resin. The tree inception voltage of silicone rubber and epoxy resin was measured via camera-equipped online monitoring system. The leaf-like specimen was used as test sample. AC ramp voltage was applied to obtain the tree inception voltage of silicone rubber and epoxy resin. It was observed that, the electroluminescence emission and ultraviolet (UV) radiation occurred indicating the early stage of tree occurrence. The obtained results were analysed statistically by using fitting method. Anderson-Darling goodness-of-fit test was performed in order to obtain the best fitting distribution. Comparison was made between the best-fitted distribution and Weibull distribution. Based on Anderson-Darling tests, the tree inception voltage of silicone rubber and epoxy resin was best fitted with Johnson  $S_B$  distribution. Based on this fitted distribution, the value of tree inception voltage for silicone rubber and epoxy resin was calculated and equalled to 11.80 kV and 20.11 kV respectively. From this study, it was found out that the best-fitted distribution for the value of tree inception voltage for silicone rubber and epoxy resin is the Johnson  $S_B$  distribution by means of Anderson-Darling goodness-of-fit test.

**Keywords:** Electrical Treeing, Johnson  $S_B$  Distribution, Anderson- Darling goodness-of-fit Test, Weibull Distribution, Electroluminescence.

### 1. Introduction

Polymer-based materials such as polyethylene (PE), crosslinked polyethylene (XLPE), epoxy resin (ER), silicone rubber, polyvinyl chloride (PVC) etcetera are widely used for electrical insulating materials in underground distribution and transmission cables because of their excellent electrical, thermal, and mechanical properties. However, voids, impurities, asperities, cracks, defects, grazes and protrusion can exist inside these insulating materials. From the presence of foreign particles and insulation physical imperfection, electrical treeing can be initiated which results in insulation breakdown [1]. Electrical tree is defined as labyrinthine structures of narrow gas-filled tubules being created by localized partial discharge activity [2]. It consists of a filamentary pattern of hollow channels and is initiated at the regions of high electric stress and is visible under optical microscope in transparent dielectrics [3].

In view of this, there are many research reports concerning about this phenomenon in terms of modelling, experiment, and simulation [4-8]. Besides that, statistical approach has been used for the analysis of characteristic value of tree parameters such as time to breakdown, tree length, tree inception voltage, tree inception time, and tree growth time. Up to date, Weibull distribution is widely accepted in the insulation performance analysis for its capability in

extreme values phenomena. It is widely used by various researchers around the world especially for high voltage engineering application [4-6].

Interestingly, till date, there has been no further study on new statistical technique to obtain a more accurate estimation of electrical tree inception voltage since the introduction of Weibull distribution. This paper describes a more accurate technique of data analysis to estimate electrical tree inception voltage by introducing the fitting method using Anderson-Darling goodness-of-fit test. The sample materials used for this test were silicone rubber and epoxy resin.

## 2. Sample preparation

Two types of insulating material were used in this study: a commercial silicone rubber and an epoxy resin. The test specimens were prepared in the form of leaf-like specimen [12-14]. The significance of preparing the test samples in the form of leaf-like specimen is the usage of small amount of dielectric material. The test cell used for this test is a pair of point-to-plane electrode. The material used for the point electrode was Sigma-Aldrich's tungsten wire of 0.25 mm in diameter. The point electrode is actually a needle with sharp tip. The needle tip and tip angle were 5  $\mu\text{m}$  radius and 30 degrees respectively. Cleansing of needle electrode was accomplished with acetone. This was done before the polymer casting process. The above mentioned point-to-plane has 2 mm gap distance. Aluminium foil was used as the plane electrode which was connected with ground (earth electrode). The formation of the needle tip was accomplished with the aid of Sodium Hydroxide (NaOH). Briefly, the tungsten wire was deepened into the sodium hydroxide solution with 30 V and 3A DC supply connected to it. The schematic diagram for needle tip formation is shown in Figure 1.

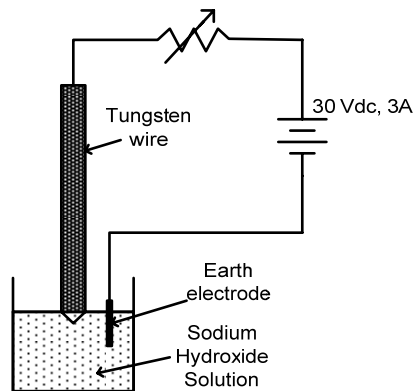


Figure 1. Schematic diagram for the needle tip formation processes using Sodium Hydroxide (NaOH) solution.

The first material was derived from a combination of Farnell's Sylgard 184 silicone rubber with a special hardener. It has a low viscosity of 3900 MPa.s and large temperature range within 50  $^{\circ}\text{C}$ -200  $^{\circ}\text{C}$  [15]. Therefore, the silicone rubber can be processed at room temperature. It also has a good optical property in order to produce the transparent specimen for allowing tree observation. The base and the hardener were thoroughly mixed using a weight ratio 10:1 and degassed at room temperature under vacuum of 760 mmHg for 10 minutes. Then, it was casted onto the slide glass and the thin cover was placed on the silicone rubber. This step was handled carefully to avoid the formation of voids. The silicone rubber was covered using thin cover glass. After further casting process, the specimen was placed in an oven for about 45 minutes at a maintained temperature of 100 $^{\circ}\text{C}$  to cure the silicone rubber.

The second material was derived from a combination of Hexion's Epikote 1006 epoxy resin with hardener which has high degree of hardness, good chemical resistance and mechanical properties was used. The resin also has good optical properties for allowing treeing observation

via stereomicroscope. The resin/hardener was mixed thoroughly in the recommended 10:6 weight ratio. Next, the resin was degassed at room temperature using vacuum set for about 20 minutes at 760 mmHg. After evacuation, the resin was casted onto the slide glass and the thin cover glass was used to cover the resin. This step was also handled carefully to avoid the void formation. Afterwards, the specimen was cured under room temperature for 3 hours. 30 samples of silicone rubber and 30 samples of epoxy resin were prepared in this study. The top and side view of leaf-like specimen is shown in Figure 2.

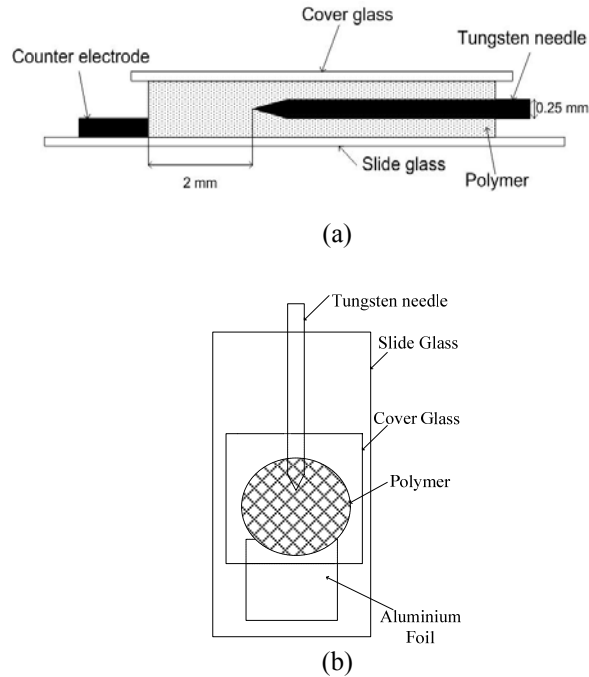


Figure 2. Configuration of leaf-like specimen (a) side view and (b) top view

### 3. Treering Apparatus

In this work, to study electrical treeing, an online monitoring system was developed. The monitoring system consisted of a stereomicroscope, a personal computer, and a charge-coupled device (CCD) camera. A schematic diagram of the set-up is shown in Figure 3. The based system consisted of an Olympus SZX16 Research Stereomicroscope equipped with auxiliary Olympus Xcam-Alpha CCD camera with 115x magnification capability. The given magnification level was sufficient to capture magnified images of electrical tree initiation and propagation. The Darkfield illumination mode was employed in order to observe the light emission due to electrical treeing. The samples were enclosed inside a clamped acrylic cell and were immersed in the silicone oil to prevent premature surface tracking and flashover. The acrylic cell was placed directly under the microscope lens to monitor the inception process of electrical treeing. An AC ramp voltage was applied to measure tree inception voltage for all samples [9]. The tree inception voltage was defined as the voltage when the observed tree length has roughly exceeded  $10\ \mu\text{m}$  [16]. The observation of tree initiation was done by using the camera-equipped microscope connected to the personal computer. As soon as a tree has initiated, the tree inception voltage was recorded and the applied voltage was kept constant to monitor the tree propagation. The experiment was executed for both silicone rubber and epoxy resin samples. All the 30 samples of silicone rubber and epoxy resin specimen were subjected to high voltage. The tree inception voltages of all the specimens were recorded.

The experimental procedure is based on the block diagram shown in Figure 4. It starts with identifying suitable insulation material which is transparently enough to render visible under

microscopy observation. Next, the test cell as well as the specimen is prepared for the tree testing. The prepared specimen is then subjected to AC ramp voltage. If failure or insulation breakdown occurs or treeing does not occur on the specimen a new specimen is used. The tree inception voltage of treed or successful specimen is then recorded and analyze.

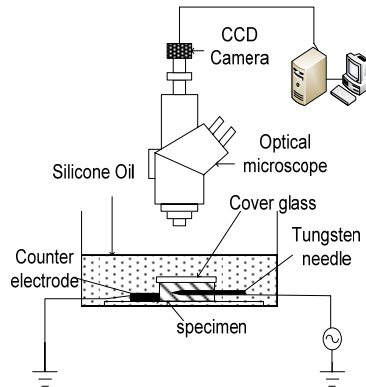


Figure 3. Set-up of camera-equipped online monitoring system for electrical treeing studies schematic diagram

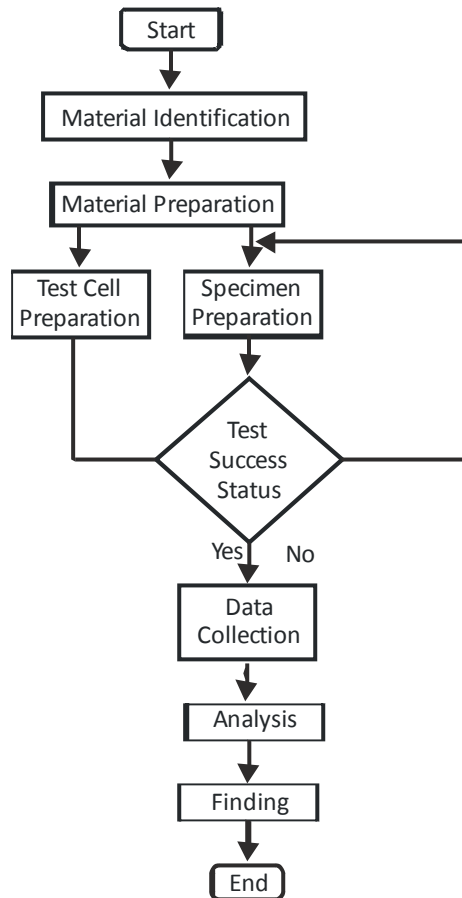
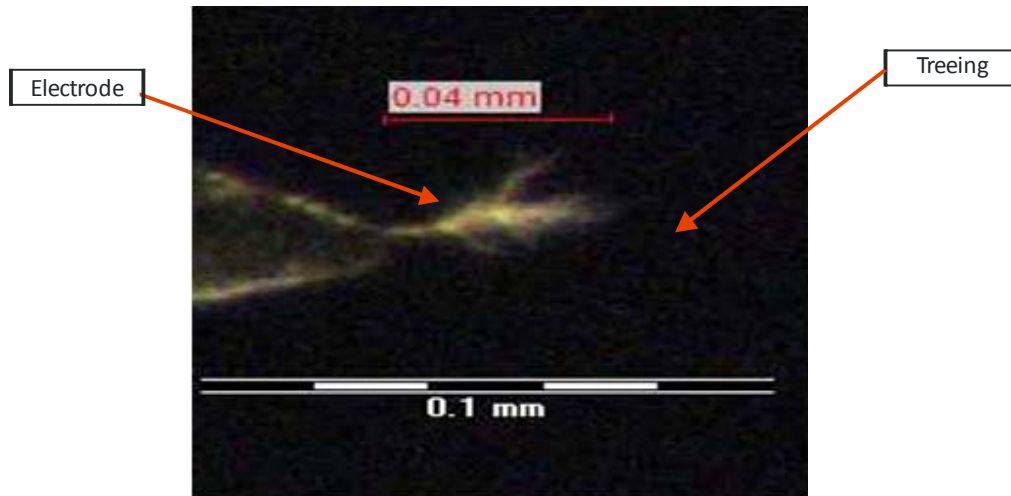


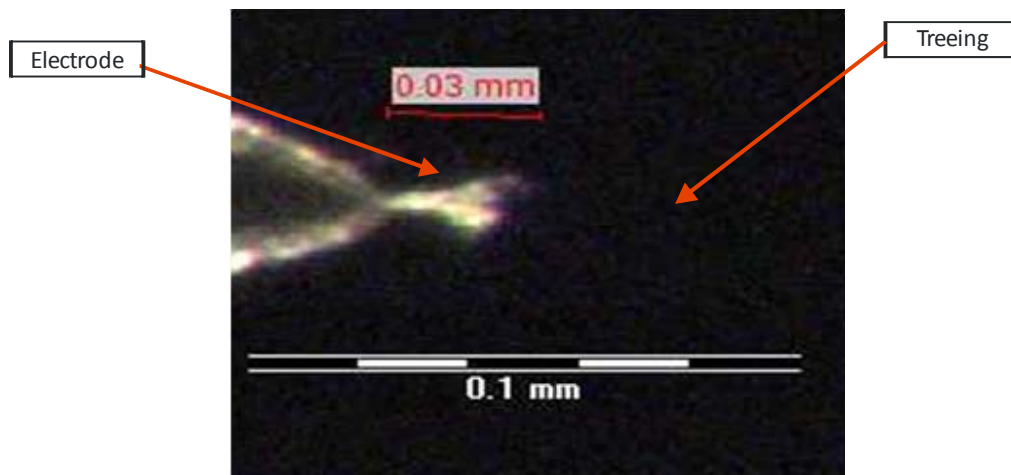
Figure 4. Block diagram of experimental process

### 5. Results and discussion

Figure 5(a) and Figure 5(b) show the electrical tree initiated channels in epoxy resin and in silicone rubber respectively. Treeing initiated in epoxy resin at 18.5 kV and in silicone rubber at 16.5 kV. The tree lengths for epoxy resin and silicone rubber were 40  $\mu\text{m}$  and 30  $\mu\text{m}$  respectively.



(a)



(b)

Figure 5. Electrical tree initiation in (a) epoxy resin at 18.5 kV, tree length = 40  $\mu\text{m}$  and (b) silicone rubber at 16.5 kV, tree length = 30  $\mu\text{m}$

The experimental results were analysed statistically using fitting method. The best-fitted distribution was determined using commercial fitting software. From the software, the Anderson-Darling goodness-of-fit test was performed and the results of distribution analysis were compared. The values of tree inception voltage for silicone rubber and epoxy resin were determined at probability 0.5 by calculating inverse cumulative distribution function (CDF) of

the best fitted distribution. Comparison was made based on fitted distribution and Weibull distribution. The experimental result is shown in Table 1.

Table 1. Tree Inception Voltage in the Single-Needle Treeing Test with Silicone Rubber (SiR) and Epoxy Resin (Er) As Insulating Materials. (Stressing Condition: AC Ramp Voltage)

No. of Sample	Tree Inception Voltage of SiR (kV)	Tree Inception Voltage of ER (kV)
1	10	14
2	7.5	15
3	9.5	13
4	12.5	17
5	11	14
6	8.5	11
7	8	17.5
8	10	20
9	11	20
10	9.5	21
11	8.5	16
12	11.5	20
13	12.5	22.5
14	12.5	15
15	14.5	21.5
16	14.5	20.5
17	12	18.5
18	13.5	22
19	11.5	18.5
20	10	20.5
21	15	26
22	15.5	28.5
23	12.5	16.5
24	16.5	23
25	13.5	23.5
26	11	23
27	11	28
28	12.5	25
29	14.5	26.5
30	14	29

The experimental data from Table 1 were then used in determining the best-fit statistical distribution to describe the tree inception voltage for both silicone rubber and epoxy resin. It was found that the tree inception voltage of silicone rubber was best described by the Johnson  $S_B$  distribution based on the goodness-of-fit ranking using Anderson-Darling goodness-of-fit test.

The 59 statistical distributions which have been sorted according to Anderson-Darling goodness-of-fit test are shown in Table 2. Generally, it shows that the tree inception voltage of silicone rubber is best fitted with Johnson  $S_B$  distribution based on Anderson-Darling goodness-of-fit test. It also shows Weibull is ranked 28<sup>th</sup> place with higher error as compared to Johnson  $S_B$  with the lowest error and the 1<sup>st</sup> in the ranking. Anderson-Darling goodness-of-fit test error for Johnson  $S_B$  distribution equalled to 0.17837 which shows the minimum error while for Weibull distribution the error was 0.31177. Therefore, it obviously shows that the experimental data of tree inception voltage for silicone rubber is best fitted with Johnson  $S_B$  distribution as compared to Weibull distribution.

The fitting test was performed based on Anderson-Darling goodness-of-fit test for data of tree inception voltage for epoxy resin. The Anderson-Darling goodness-of-fit test has shown that the experimental data was best fitted with Johnson  $S_B$  distribution with the lowest error which equal to 0.14117 while the error value for Weibull distribution equalled to 0.2399. Based on this goodness-of-fit test, the error value for Johnson  $S_B$  is lower than Weibull distribution. The ranked table based on Anderson-Darling goodness-of-fit test is shown in

Table 3. Table 3 shows the experimental data of tree inception voltage for epoxy resin is best fitted with Johnson  $S_B$  at first ranking based on Anderson-Darling goodness-of-fit test.

Table 2. Summary of Fitting Distribution for Experimental Data of Tree Inception Voltage for Silicone Rubber

Distribution	Anderson-Darling	
	Error	Rank
Johnson SB	0.17837	1
Wakeby	0.18356	2
Error	0.18393	3
Gen. Extreme Value	0.19764	4
Pert	0.21429	5
Log-Pearson 3	0.23001	6
Normal	0.23073	7
Burr (4P)	0.24647	8
Weibull (3P)	0.24652	9
Pearson 6 (4P)	0.24877	10
Lognormal (3P)	0.24880	11
Fatigue Life (3P)	0.24885	12
Gamma (3P)	0.24896	13
Pearson 5 (3P)	0.24899	14
Inv. Gaussian (3P)	0.24982	15
Erlang (3P)	0.25082	16
Nakagami	0.25721	17
Burr	0.26119	18
Gamma	0.27811	19
Pearson 6	0.27846	20
Gen. Gamma (4P)	0.27857	21
Gen. Gamma	0.28003	22
Log-Logistic (3P)	0.28561	23
Gen. Logistic	0.28749	24
Dagum	0.29066	25
Rice	0.29332	26
Beta	0.29452	27
Weibull	0.31177	28
Lognormal	0.32578	29
Fatigue Life	0.32598	30
Logistic	0.36475	31
Log-Gamma	0.37634	32
Triangular	0.37657	33
Rayleigh (2P)	0.38962	34
Inv. Gaussian	0.39415	35
Pearson 5	0.39508	36
Frechet (3P)	0.42430	37
Log-Logistic	0.42772	38
Phased Bi-Weibull	0.43160	39
Erlang	0.48541	40
Hypersecant	0.49136	41
Cauchy	0.63605	42
Chi-Squared (2P)	0.65514	43
Laplace	0.74342	44
Gumbel Max	0.79537	45
Gumbel Min	0.82053	46
Frechet	1.01360	47
Kumaraswamy	1.19520	48
Power Function	1.42170	49
Reciprocal	1.52730	50
Exponential (2P)	3.48140	51
Chi-Squared	4.03190	52
Uniform	4.06170	53
Gen. Pareto	4.06810	54
Rayleigh	4.34290	55
Levy (2P)	4.99260	56
Dagum (4P)	5.14360	57
Pareto	5.52980	58
Pareto 2	8.93840	59

Table 3. Summary of Fitting Distribution for Experimental Data of Tree Inception Voltage for Epoxy Resin

Distribution	Anderson-Darling	
	Error	Rank
Johnson SB	0.14117	1
Wakeby	0.14403	2
Gen. Extreme Value	0.14672	3
Log-Pearson 3	0.16136	4
Error	0.16720	5
Burr (4P)	0.17005	6
Weibull (3P)	0.17006	7
Pert	0.17294	8
Normal	0.17511	9
Gamma (3P)	0.18216	10
Fatigue Life (3P)	0.18248	11
Lognormal (3P)	0.18273	12
Pearson 6 (4P)	0.18296	13
Pearson 5 (3P)	0.18296	14
Nakagami	0.18635	15
Erlang (3P)	0.18835	16
Inv. Gaussian (3P)	0.19154	17
Dagum	0.20358	18
Gen. Logistic	0.20517	19
Gen. Gamma	0.20564	20
Triangular	0.20706	21
Gamma	0.20756	22
Log-Logistic (3P)	0.20828	23
Burr	0.21798	24
Weibull	0.23990	25
Gen. Gamma (4P)	0.24023	26
Lognormal	0.25962	27
Rice	0.2606	28
Fatigue Life	0.26108	29
Pearson 6	0.26543	30
Logistic	0.27433	31
Log-Gamma	0.31354	32
Rayleigh (2P)	0.31709	33
Frechet (3P)	0.32810	34
Pearson 5	0.34867	35
Log-Logistic	0.36410	36
Hypersecant	0.37316	37
Inv. Gaussian	0.37475	38
Cauchy	0.51435	39
Laplace	0.55970	40
Chi-Squared (2P)	0.57514	41
Gumbel Max	0.62064	42
Chi-Squared	0.68415	43
Power Function	0.93106	44
Frechet	0.94168	45
Erlang	0.94895	46
Gumbel Min	0.95861	47
Kumaraswamy	1.3280	48
Beta	1.4061	49
Reciprocal	2.7158	50
Rayleigh	3.3413	51
Exponential (2P)	3.8328	52
Gen. Pareto	4.0590	53
Uniform	4.7874	54
Levy (2P)	5.5578	55
Pareto	6.3150	56
Exponential	8.1061	57
Phased Bi-Weibull	8.4876	58
Pareto 2	9.8627	59



In [17], light was emitted at electrode tip of high local stressed in the polymer prior to electrical tree initiation. The light was not caused by partial discharge but was due to electroluminescence and, it was shown that the light inception voltage was the threshold voltage at which the polymer starts to degrade. Besides, the light is caused by electrons injected into the polymer and this phenomenon of light emission is called electroluminescence [3]. In this study, light emission was detected within visible and ultra-violet ranges. This ultraviolet radiation can occur when the voltage applied to the polymer exceeds the threshold voltage of light inception and this will lead to the photodegradation [18]. The photodegradation causes the photons to break the polymer and create a microcavity which lead to tree initiation and propagation [19]. Thus, Figure6 shows that light emission or electroluminescence and ultraviolet radiation have occurred at the needle tip during the initiation of electrical tree.

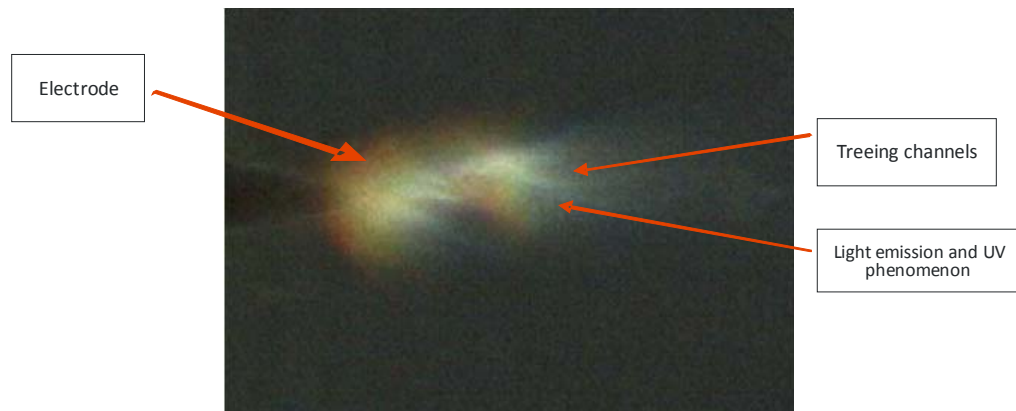


Figure 6. Light emission (electroluminescence) and UV radiation occur due to tree initiation phenomenon

The tree inception voltage,  $V_t$  depends on material, the radius of curvature  $r$  of the point electrode tip, the electrode separation,  $d$  and the form of the applied stressing voltage [20]. Based on these influenced factors, the distinct factor that can be clarified is material composition since the other factors were kept constant. Material composition plays a main role in this electrical treeing phenomenon [21]. From online monitoring of electrical treeing, it can be said that the initiation of electrical tree in silicone rubber was extremely fast than epoxy resin. This is due to lower resistivity of silicone rubber compared with epoxy resin. The emission of electroluminescence also has been observed using the online monitoring system. This phenomenon indicates the preliminary stage of electrical treeing. However, the tree inception voltage was recorded when the tree length had exceeded  $10 \mu\text{m}$ . Interestingly, this monitoring system has shown that the ultraviolet radiation has occurred instead of the electroluminescence emission. Thus, it indicates a chemical deterioration has occurred caused by partial discharge. The chemical deterioration could erode the channel tips which lead to tree propagation [1].

Electrical treeing is a stochastic phenomenon. Thus, a statistical analysis is essential for interpretation of the experimental data and hence estimates the tree inception voltage. As a result, Anderson-Darling goodness-of-fit test was employed in this analysis in order to fit the data with the best fitted distribution. Based on the results from the fitting via Anderson-Darling goodness-of-fit test, the data of tree inception voltage of silicone rubber and epoxy resin were best fitted with Johnson  $S_B$  distribution.

The voltage required to initiate the formation of a tree, which is referred as tree inception voltage, is usually measured as mean 50% inception voltage,  $V_t$  [20]. Based on the Johnson  $S_B$  distribution, the probability of 0.5 is calculated by taking inverse CDF of this distribution. The values of both inverse CDFs, at  $F(x)=0.5$  are estimated as tree inception voltage,  $V_t$  for silicone rubber and epoxy resin. Based on this distribution, the tree inception voltage was estimated at  $F(x)=0.5$  and was calculated and equalled to 11.80 kV. Meanwhile, the experimental data of

epoxy resin was also fitted well with Johnson  $S_B$  distribution which tree inception voltage equalled to 20.11 kV. The comparison between fitted distribution and Weibull has been done. Thus, it shows that Weibull is not fitted well with both experimental data for tree inception voltage of silicone rubber and epoxy resin based on results from Anderson-Darling goodness-of-fit test. The best fitting distribution was Johnson  $S_B$  for both data of tree inception voltage for silicone rubber and epoxy resin.

### Conclusions

The main results of this paper can be summarized as follows:

1. The material composition plays an important role in electrical treeing phenomenon particularly in terms of tree inception voltage. A material having higher dielectric strength level exhibits higher tree inception voltage.
2. The statistical analysis is essential for large population of high voltage insulation data interpretations. The tree inception voltage data can be examined via the best fitted distribution. The fitting process is executed since the analysis of data based on the best-fit statistical distribution is essential.
3. Based on Anderson-Darling goodness-of-fit test, it can be concluded that the empirical tree inception voltage of silicone rubber and epoxy resin are best fitted with Johnson  $S_B$  distribution. This is based on the rank grading which correlates with the error of Anderson-Darling goodness-of-fit test. From the rank grading, it shows that Johnson  $S_B$  statistical distribution was more accurate compared with Weibull distribution in term of degrees of fitness to the experimental data. As a result, the tree inception voltage of silicone rubber and epoxy resin are estimated and equalled to 11.80 kV and 20.11 kV respectively.
4. This study contributes to a comparative study between the best-fitted statistical distribution and Weibull distribution. It shows that an accurate method is applied based on fitting method. As a result, the best-fitted statistical distribution is more suitable than using Weibull distribution for treeing data analysis. The treeing parameters such as tree inception voltage, tree inception time, tree breakdown voltage, tree length, and etcetera could satisfy certain statistical distribution and further research could be done to prove this. Interestingly, this study shows that the tree inception voltage for silicone rubber and epoxy resin satisfies Johnson  $S_B$  distribution at statistical rank 1.
5. Electroluminescence which is accompanied with the tree initiation can be used as future diagnostic method for condition monitoring of insulation material.

### Acknowledgment

The authors gratefully acknowledge Universiti Teknologi Malaysia and Malaysia Ministry of High Education (MOHE) for the fully supported by Short Term Grant, 4D019, Fundamental Research Grant Scheme (FRGS), 4F022 and Research University Grant, 03J15 to carry out this work.

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