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Statistical Analysis of Electrical Tree Inception Voltage, Breakdown Voltage and Tree Breakdown Time Data of Unsaturated Polyester Resin

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Abstract – This paper presents a statistical approach to analyze electrical tree inception voltage, electrical tree breakdown voltage and tree breakdown time of unsaturated polyester resin subjected to AC voltage. The aim of this work was to show that Weibull and lognormal distribution may not be the most suitable distributions for analysis of electrical treeing data. In this paper, an investigation of statistical distributions of electrical tree inception voltage, electrical tree breakdown voltage and breakdown time data was performed on 108 leaf-like specimen samples. Revelations from the test results showed that Johnson SB distribution is the best fit for electrical tree inception voltage and tree breakdown time data while electrical tree breakdown voltage data is best suited with Wakeby distribution. The fitting step was performed by means of Anderson-Darling (AD) Goodness-of-fit test (GOF). Based on the fitting results of tree inception voltage, tree breakdown time and tree breakdown voltage data, Johnson SB and Wakeby exhibit the lowest error value respectively compared to Weibull and lognormal.

Keywords: Electrical treeing, Statistical model, Weibull distribution, Johnson SB distribution, Anderson-Darling goodness-of-fit test.

1. Introduction

Numerous papers have been published investigating various electrical treeing parameters in polymeric insulating material [1-5]. Such parameters include tree inception voltage, tree breakdown voltage, tree length, tree inception time, tree breakdown time, fractal dimension and number of branches. Weibull [6-10] and lognormal [1, 11, 12] distributions are widely used models for statistical analysis of electrical tree parameters. However, not all the treeing parameters data could be treated adequately by Weibull and lognormal and it depends on the empirical data. The wrong treatment could lead to wrong analysis of results. A correct selection of statistical models for the collected experimental data is a key factor in electrical tree studies. Treating the data by comparing the mean and standard deviation is very straightforward and this simple way is insufficient and can lead to erroneous results [12]. The treeing data should be analyzed imperatively in order to know the type of statistical distribution which represents the electrical tree data.

In this paper, selection of statistical models which fitted with the collected tree data was performed. Anderson Darling (AD) Goodness-of-fit (GOF) test was chosen as a technique to determine the best distribution that represents the original data.

From the AD GOF test, comparisons were done between the best fitted distribution and Weibull and also lognormal distribution for the purpose of proving that Weibull and lognormal are not the best distributions to represent the original data but an imperative statistical technique should be performed. With this technique and knowledge, the accuracy of statistical inferences could be improved.

2. Experiment

The test samples were prepared in the form of leaf-like specimen with point-to-plane electrode [13-14]. The significance of using leaf-like specimen is the usage of small amount of insulating material. The material used for the point electrode was Sigma-Aldrich's tungsten wire with 0.25 mm in diameter. A needle with sharp tip was formed from the tungsten wire by electro-chemical etching process with the aid of sodium hydroxide (NaOH) solution. The tungsten wire was briefly deepened into the sodium hydroxide solution with 30 V and 30 A DC supply connected to the tungsten wire.

The schematic diagram for needle tip formation is shown in Fig. 1. All needle tips were examined under microscope in order to ensure their needle tip radius and needle tip angle are 5 μm and 30°C respectively for

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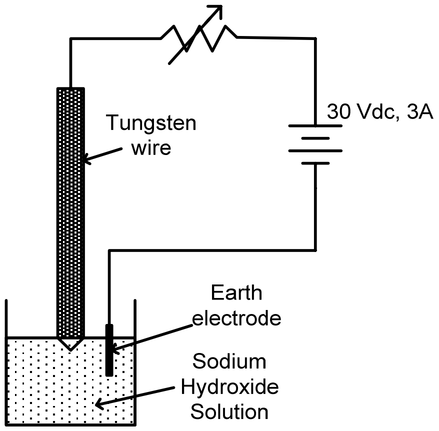

Fig. 1. Schematic diagram for the needle tip formation using Sodium Hydroxide (NaOH) solution.

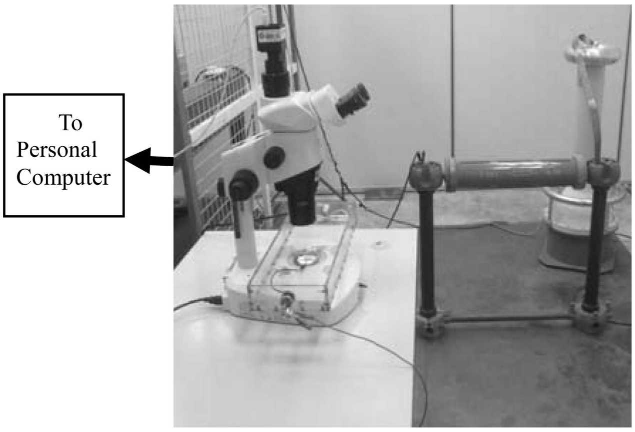

Fig. 3. Pictorial view of online monitoring system for electrical tree studies.

uniformity. One side of the needle tip was wrapped with aluminium foil. The gap distance between the needle tip and the plane electrode was adjusted to 2±0.05 mm.

BIP2700AT, unsaturated polyester resin was employed in this work. It consists of two parts which are resin and hardener. The mixing ratio between resin and hardener is 50:1. After mixing the resin and hardener, the mixture was degassed using a vacuum set for 15 minutes to remove bubbles. After ensuring no bubbles remained in the mixture, the polymer was casted onto the electrode gap to cover the whole gap between both electrodes and covered by a thin glass. The completed sample was cured at room temperature for 24 hours. In this work, 50 leaf-like specimen samples were prepared for treeing inception voltage and breakdown voltage tests while 58 samples were prepared for treeing breakdown time tests. The schematic drawing configuration of leaf-like specimen sample is shown in Fig. 2.

An online monitoring system has been established which consists of an Olympus SZX16 research stereomicroscope, a personal computer, and an Olympus Xcam-α charge-coupled device (CCD) camera. This research stereo-microscope has magnification of up to 115x. This magnification ability is enough to observe the initiation and propagation of electrical tree optically via computer monitor. The online monitoring system is shown in Fig. 3. There are two types of test methodologies for tree inception and growth which are short term test and long term test. For short term test, linearly increasing sinusoidal voltage was applied. In this condition, it is possible to measure the tree inception voltage and tree breakdown voltage [15, 16]. The long term test is performed with constant AC value sinusoidal voltage. Under this condition, measurement of the tree inception time and tree breakdown time are possible [15].

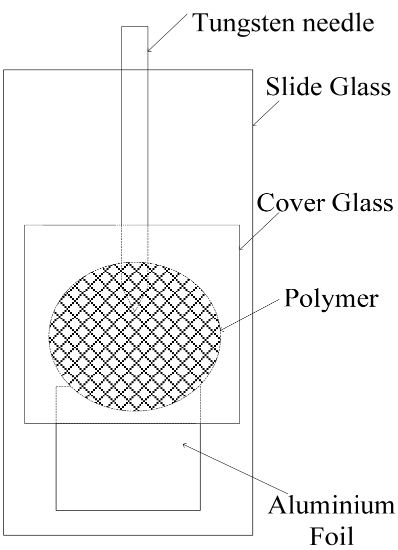

Fig. 2. Configuration of leaf-like specimen.

In this work, the short term test method was chosen by applying 0.5 kV/s AC ramp voltage. The applied voltage was increased linearly at the rate of 0.5 kV/s until breakdown occurred. The tree inception voltage was measured at the instance of treeing inception while the breakdown voltage was measured when breakdown occurred. This short term tests were performed on all the 50 samples.

On the other hand, the treeing breakdown time of unsaturated polyester resin insulating material was studied under constant voltage as well. The 0.5 kV/s AC ramp voltage was applied to each of the 58 samples until trees initiated. After the tree initiation, the voltage was kept constant to study the growth of electrical tree until the trees have bridged the electrode gaps and breakdown occurred. The tree breakdown time of all 58 samples were measured and recorded.

3. Results and Discussion

Precise interpretation of an obtained data set in electrical tree studies should be studied thoroughly, thus there is a need of employing statistical analysis for this purpose. An essential part of the statistical analysis is the application of different distributions of the experimental data providing a broad background for unbiased estimates as well as improved estimates of the mean and variance [17]. Furthermore, the analysis also depends on the number of samples. Small sample size might lead to a masking of the significant levels and to a bias in outcomes. Thus, in this work, 50 samples were chosen for short term test and another 58 samples were tested under constant voltage. The obtained experimental results of tree inception voltage, tree breakdown voltage and tree breakdown time were analyzed statistically using commercial fitting software called Easy-fit software (version 5.5, MathWave Technologies). Distribution fitting was used to specify the most appropriate distributions and as estimators of variation [18].

The Anderson-Darling (AD) Goodness of Fit (GOF) test was used to determine whether the data set comes from a specified distribution. This test typically summarizes the discrepancy between the observed values and the values expected under the model in question. It makes use of the cumulative distribution function where the Anderson-Darling (AD) statistic is given by the following formula:

$$AD = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left[\ln F(X_i) + \ln(1 - F(X_{n-i+1}))\right] \quad (1)$$

Where n is the sample size, *F(X)* is the cumulative distribution function for the specified distribution and *i* is the i^{th} sample when the data is sorted in ascending order. Hence, the data is said to fit the distribution well if the value of the Anderson-Darling statistic is small. This AD statistic is referred as the error in this study. A rank selection of distribution was performed based on the AD GOF results. Comparative studies were performed between the best-fit distribution, Weibull and lognormal distribution. The experimental result is shown in Table 1 and Table 2.

The experimental data presented in Table 1 and Table 2 were used in determining the best fit statistical distribution which adequately describes the distribution of electrical tree inception voltage, tree breakdown voltage and tree breakdown time. Based on AD GOF test calculated by fitting software, the tree inception voltage and tree breakdown time distributions were best described by Johnson SB distribution whereas Wakeby distribution was the best fit for the tree breakdown voltage distribution. For tree inception voltage and tree breakdown time distributions, Johnson SBs were found to be more flexible and random variables bound by extremes. Thus, the null hypothesis of the sample drawn from Johnson SB distribution was not rejected but accepted. This result support that the hypothesis should be accepted; hence the Johnson SB function can adequately describe the tree inception voltage and tree breakdown time data whereas Wakeby function fit well with tree breakdown voltage data.

The Johnson's SB shape, scale and location parameters were estimated based on Maximum Likelihood Estimation (MLE). Cumulative distribution function (CDF) of Johnson SB distribution is shown as follows [19]:

$$F(z) = \Phi\left(\gamma + \delta \ln\left(\frac{z}{1-z}\right)\right) \quad (2)$$

Where Φ is the CDF of the standard normal random variable, δ and γ are shape parameters, ξ is a location parameter, λ is a scale parameter and *z,* is referring to following transformation:

Table 1. Tree inception voltage and tree breakdown voltage for 50 samples of unsaturated polyester resin

Number of Sample	Tree Inception Voltage (kV)	Tree Breakdown Voltage (kV)
1	22.5	26
2	21.5	25.5
3	14	24.5
4	18	24.5
5	17.5	31
6	19	25.5
7	17.5	30.5
8	20.5	27
9	21.5	25.5
10	20.5	28
11	14.5	25.5
12	18	22.5
13	21.5	27
14	18.5	22
15	19	30
16	19	22.5
17	18	23.5
18	18.5	20.5
19	17	26
20	15	18
21	14.5	21
22	13	22.5
23	12	17
24	13	23
25	16.5	20
26	15.5	21.5
27	20	22
28	17	27
29	13	22.5
30	13.5	23
31	15	19.5
32	20	25.5
33	16	20.5
34	17	22
35	17	20
36	13.5	28.5
37	14	30.5
38	15.5	27.5
39	23	29.5
40	14	23.5
41	19.5	22
42	20	23.5
43	17.5	21
44	19	27
45	15	20.5
46	16	27.5
47	17	21.5
48	17.5	25
49	16	23.5
50	18	23

$$z = \frac{x-\zeta}{\lambda} \tag{3}$$

In the literature, Weibull and lognormal distributions were applied to the estimation of breakdown-time, breakdown-voltage, water and electrical tree length in solid insulating materials [5-8, 20-22]. The CDF of 2-parameter Weibull distribution is shown in Eq. (3).

Table 2. Tree inception voltage and tree breakdown time for 58 samples of unsaturated polyester resin.

Number of Sample	Tree Inception Voltage (kV)	Tree Breakdown Time (s)
1	14	121
2	16	253
3	18	257
4	13	323
5	18	115
6	18	21
7	19	73
8	18.5	147
9	23.5	24
10	17	127
11	20	31
12	19.5	53
13	17	62
14	15	78
15	14.5	69
16	19	19
17	26	13
18	18.5	5
19	23.5	165
20	13.5	315
21	24.5	9
22	22.5	115
23	25	42
24	18.5	16
25	19.5	19
26	18.5	76
27	25.5	13
28	18.5	187
29	17.5	84
30	18	6
31	18.5	27
32	20.5	17
33	16	309
34	18	17
35	22	9
36	21	14
37	22	15
38	16.5	135
39	19.5	68
40	13.5	67
41	15	118
42	19	8
43	19.5	27
44	13.5	416
45	21	30
46	19	18
47	25	5
48	15	17
49	20	5
50	18	5
51	20	6
52	18	43
53	17	10
54	23	13
55	24	5
56	17	19
57	20	8
58	21	5

$$F(x) = 1 - \exp\left\{\left(-\frac{x}{\beta}\right)^{\alpha}\right\} \tag{4}$$

Where, α is shape parameter and β is scale parameter. Furthermore, the CDF for 2-parameter lognormal distribution is expressed as follows:

$$F(x) = \phi\left(\frac{\ln x - \mu}{\sigma}\right) \tag{5}$$

Where μ is scale parameter, σ is shape parameter and ϕ is Laplace integral which is expressed as:

$$\phi = \frac{1}{\sqrt{2\pi}}\int_0^x e^{-\frac{t^2}{2}}dt \tag{6}$$

The Wakeby distribution is mostly defined as an inverse distribution function which is with quantile estimation equation. The equation is shown as follows [23]:

$$x(F) = \xi + \frac{\alpha}{\beta}(1-(1-F)^{\beta}) - \frac{\gamma}{\delta}(1-(1-F)^{-\delta}) \tag{7}$$

Where F is the uniform (0, 1) variate, ξ and α are location parameters and also β, γ, and δ are shape parameters. Based on MLE, the Johnson's SB shape, scale and location were calculated as follows:

Shape parameter, γ= 0.2014
Shape parameter, δ= 1.1936
Location parameter, ζ= 15.024
Scale parameter, λ = 10. 236

Meanwhile for Weibull distribution, the shape parameter, α and scale parameter, β were 7.3622 and 18.186 respectively. The shape parameter, σ and scale parameter, μ for lognormal distribution were 0.15918 and 2.8324 respectively. The ranked table based on AD GOF test is shown in Table 3.

It can be seen from Table 3 that Johnson SB exhibited the lowest fitting error and is ranked at first place compared with lognormal and Weibull which ranked 27th and 36th places respectively. It can therefore be pointed out that lognormal and Weibull are not the best fit for the original data. The error for Johnson SB distribution was 0.18197 whereas lognormal exhibited fitting error of 0.35164 and Weibull with higher error of 0.47595. The histogram of tree inception voltage of polyester resin is shown in Fig. 4 and comparison was performed for lognormal and Weibull distributions.

Table 3. Ranking of fitting distribution of tree inception voltage data based on AD GOF test

Distribution	Anderson-Darling	
	Error	Rank
Johnson SB	0.18197	1
Gen. Gamma (4P)	0.1872	2
Dagum (4P)	0.19554	3
Error	0.20911	4
Kumaraswamy	0.21137	5
Beta	0.21345	6
Gen. Extreme Value	0.22108	7
Pert	0.22599	8
Normal	0.26688	9
Nakagami	0.2721	10
Weibull (3P)	0.28064	11
Burr (4P)	0.28074	12
Log-Pearson 3	0.28084	13
Pearson 5 (3P)	0.29208	14
Lognormal (3P)	0.29355	15
Pearson 6 (4P)	0.29365	16
Fatigue Life (3P)	0.29569	17
Gamma	0.29881	18
Burr	0.30002	19
Gamma (3P)	0.30057	20
Pearson 6	0.30664	21
Gen. Gamma	0.30723	22
Triangular	0.31678	23
Inv. Gaussian (3P)	0.32321	24
Fatigue Life	0.34928	25
Log-Logistic (3P)	0.35086	26
Lognormal	0.35164	27
Dagum	0.35233	28
Erlang (3P)	0.36396	29
Gen. Logistic	0.36566	30
Log-Gamma	0.38533	31
Pearson 5	0.41688	32
Rayleigh (2P)	0.42884	33
Inv. Gaussian	0.43893	34
Log-Logistic	0.4691	35
Weibull	0.47595	36
Logistic	0.47698	37
Frechet (3P)	0.57078	38
Erlang	0.65643	39
Hypersecant	0.67705	40
Cauchy	0.9182	41
Laplace	1.0471	42
Gumbel Max	1.1389	43
Frechet	1.283	44
Gumbel Min	1.3673	45
Reciprocal	1.9173	46
Power Function	1.9578	47
Phased Bi-Weibull	2.3942	48
Chi-Squared (2P)	3.7407	49
Wakeby	4.0195	50
Chi-Squared	5.0189	51
Exponential (2P)	5.0242	52
Gen. Pareto	7.8302	53
Uniform	7.871	54
Pareto	7.99	55
Levy (2P)	8.9505	56
Rayleigh	9.101	57
Exponential	16.351	58
Levy	21.584	59
Pareto 2	21.668	60

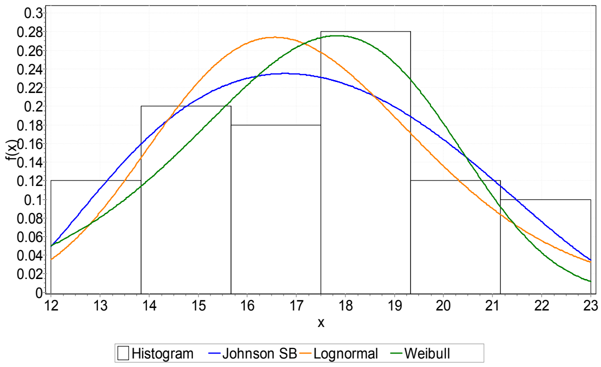

Fig. 4. Calculated distribution frequency by AD GOF test with comparison between best fit (Johnson SB), Weibull and lognormal distribution in case of tree inception voltage.

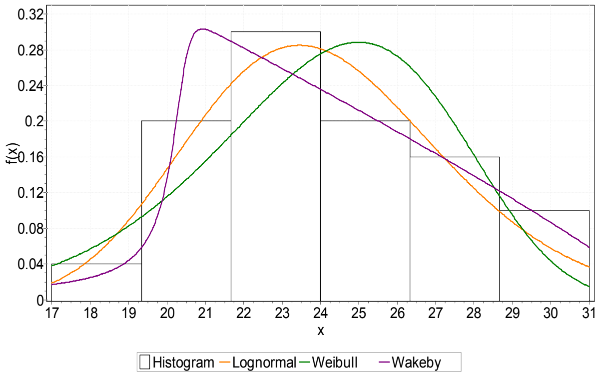

Fig. 5. Wakeby distribution fitted to the histogram of tree breakdown voltage of polyester resin and comparison with Weibull and Lognormal.

For the tree breakdown voltage data, the fitting done showed that Wakebys' location parameters α, and ζ, shape parameters, β, γ, and δ were 263.2, 45.156, 6.9921, -0.5342, and 13.87 respectively. By using MLE, the values of Weibull's shape parameter, α and scale parameter, β were estimated and equaled to 8.4604 and 25.367 respectively. Whereas, lognormal's shape parameter, σ and scale parameter, μ were equaled to 0.1379 and 3.174 respectively. Based on Table 4, it can be seen that the Wakeby distribution was first ranked according to AD GOF test fitting error. The Weibull and lognormal distribution were ranked at 41st and 7th places respectively. This proves that Wakeby function better describes the tree breakdown voltage compared to Weibull and lognormal. The histogram of experimental data of tree breakdown voltage for polyester resin is shown in Fig. 5.

Further analysis was performed for tree breakdown time data. Data of 58 samples of polyester resin were analyzed statistically. The results have shown that Johnson SB was the best that fitted well with the experimental data of tree breakdown time. This was referred to the calculated error. The Johnson SB's scale parameter, λ, shape parameter, δ

Table 4. Ranking of fitting distribution of tree breakdown voltage data based on AD GOF

Distribution	Anderson-Darling	
	Error	Rank
Wakeby	0.18631	1
Gen. Extreme Value	0.25513	2
Log-Gamma	0.27183	3
Johnson SB	0.27364	4
Pearson 5	0.27829	5
Fatigue Life	0.28654	6
Lognormal	0.28822	7
Log-Pearson 3	0.29017	8
Gamma (3P)	0.29565	9
Fatigue Life (3P)	0.29979	10
Gamma	0.30198	11
Lognormal (3P)	0.30322	12
Weibull (3P)	0.30403	13
Burr (4P)	0.30425	14
Pearson 5 (3P)	0.30616	15
Pearson 6 (4P)	0.30692	16
Gen. Gamma (4P)	0.31382	17
Gen. Gamma	0.31459	18
Nakagami	0.33374	19
Dagum	0.33559	20
Pert	0.35011	21
Frechet (3P)	0.35538	22
Log-Logistic (3P)	0.35586	23
Log-Logistic	0.36512	24
Error	0.36584	25
Inv. Gaussian (3P)	0.38264	26
Inv. Gaussian	0.38735	27
Burr	0.39054	28
Beta	0.39403	29
Gen. Logistic	0.39645	30
Normal	0.40417	31
Kumaraswamy	0.4224	32
Triangular	0.42713	33
Erlang (3P)	0.44936	34
Gumbel Max	0.58303	35
Logistic	0.61062	36
Erlang	0.62806	37
Rayleigh (2P)	0.71553	38
Frechet	0.78039	39
Hypersecant	0.84946	40
Weibull	0.91172	41
Chi-Squared (2P)	1.2557	42
Cauchy	1.3383	43
Laplace	1.4067	44
Gumbel Min	2.1243	45
Pearson 6	3.3186	46
Reciprocal	3.3448	47
Phased Bi-Weibull	3.7482	48
Chi-Squared	4.649	49
Power Function	5.4989	50
Exponential (2P)	6.7148	51
Gen. Pareto	7.9602	52
Pareto	9.7946	53
Rayleigh	10.277	54
Levy (2P)	10.969	55
Uniform	15.077	56
Pareto 2	16.198	57
Exponential	17.186	58
Levy	22.254	59
Dagum (4P)	40.833	60

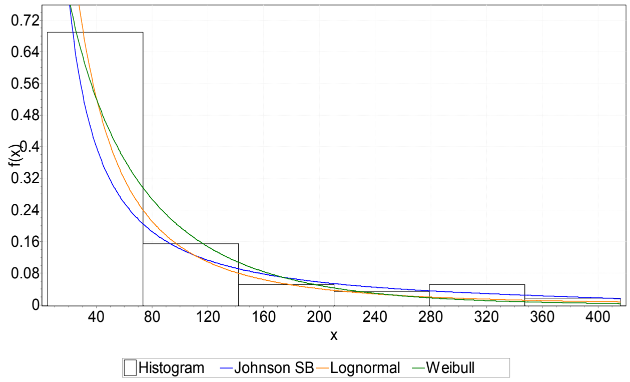

Fig. 6. Johnson SB distribution fitted to the histogram of tree breakdown time of polyester resin and comparison with Weibull and Lognormal.

and γ and also location parameter, ξ are 481.06, 0.5165, 1.401 and 2.0289 respectively. The Weibull scale parameter, β and shape parameter, α are equaled to 60.378 and 0.8773 respectively. Meanwhile, the lognormal's scale parameter, μ and shape parameter, σ are equaled to 3.5165 and 1.2923 respectively.

The smallest error value was 0.62155. Meanwhile, error values of 0.85755 and 1.5424 were possessed by lognormal and Weibull respectively. By referring to Table 4, the fitting ranking for Johnson SB, lognormal and Weibull are 1st, 5th and 21st respectively. The smallest error value exhibited by Johnson SB has proved that the most appropriate or the best distribution that fit to the tree breakdown time data is Johnson SB distribution. The histogram of time to breakdown data with fitted curves of Johnson SB, Weibull and lognormal was plotted in Fig. 6.

Koa [24] has mentioned that, the voltage required to initiate the formation of electrical tree, called the tree inception voltage, is commonly measured as mean 50% inception voltage, V_i. By referring to the Johnson SB distribution, the probability of 0.5 is calculated by taking inverse CDF of the distribution. Thus, the value of inverse CDF, at $F(x)$ = 0.5 is estimated as tree inception voltage. The similar estimation is applied to estimate the breakdown voltage of polyester resin. Therefore, the estimated values of tree inception voltage, tree breakdown voltage and tree breakdown time of polyester resin are 17.12 kV, 23.75 kV and 32 seconds respectively. The summaries of estimated parameters for Johnson SB, Wakeby, Weibull and Lognormal are tabulated in Table 6, Table 7 and Table 8. Based on the ranking, it obviously shows that Weibull and lognormal are not suitable to represent the tree inception voltage, tree breakdown voltage and tree breakdown time.

Therefore, an imperative statistical analysis based on fitting approaches should be performed in order to obtain the most accurate distribution that can describe the original data adequately. The wrong selection of statistical distribution that best fit to the data would lead to wrong

Table 5. Ranking of fitting distribution of tree breakdown time based on AD GOF

Distribution	Anderson-Darling	
	Error	Rank
Johnson SB	0.62155	1
Fatigue Life	0.67226	2
Log-Pearson 3	0.76403	3
Dagum	0.82519	4
Lognormal	0.85755	5
Log-Gamma	0.85891	6
Frechet	0.86865	7
Pearson 6	0.87463	8
Burr	0.88644	9
Log-Logistic	0.89969	10
Pearson 5	0.90369	11
Frechet (3P)	0.93846	12
Pareto 2	0.94726	13
Pearson 5 (3P)	0.96561	14
Inv. Gaussian (3P)	1.0519	15
Fatigue Life (3P)	1.055	16
Levy (2P)	1.2967	17
Gen. Pareto	1.3149	18
Wakeby	1.3149	19
Gamma	1.3662	20
Weibull	1.5424	21
Gen. Gamma	1.6839	22
Gen. Extreme Value	1.8055	23
Gen. Logistic	1.9852	24
Levy	2.1179	25
Exponential	3.4563	26
Gumbel Max	3.8399	27
Logistic	5.5659	28
Chi-Squared (2P)	5.6117	29
Hypersecant	5.6853	30
Normal	5.7281	31
Beta	6.0219	32
Inv. Gaussian	6.052	33
Error	6.2659	34
Laplace	6.2659	35
Rayleigh (2P)	6.6803	36
Gen. Gamma (4P)	6.7733	37
Weibull (3P)	7.5702	38
Gamma (3P)	7.856	39
Cauchy	10.304	40
Pareto	10.933	41
Reciprocal	11.315	42
Gumbel Min	13.182	43
Pert	13.338	44
Phased Bi-Exponential	15.186	45
Lognormal (3P)	16.089	46
Error Function	17.338	47
Kumaraswamy	21.837	48
Log-Logistic (3P)	23.012	49
Power Function	25.744	50
Uniform	25.88	51
Pearson 6 (4P)	26.107	52
Exponential (2P)	27.179	53
Burr (4P)	27.381	54
Phased Bi-Weibull	33.209	55
Rayleigh	33.292	56
Dagum (4P)	39.993	57
Triangular	41.087	58
Rice	46.613	59
Student's t	305.3	60

Table 6. Summary of parameters for Johnson SB and Wakeby distribution

Estimated Parameters	Tree Inception Voltage, Weibull	Tree Breakdown Voltage, Weibull	Tree Breakdown Time, Weibull
Scale parameter	$\beta = 18.186$	$\beta = 25.367$	$\beta = 60.378$
Shape parameter	$\alpha = 7.3622$	$\alpha = 8.4604$	$\alpha = 0.8773$
Location parameter	$\gamma = 0$	$\gamma = 0$	$\gamma = 0$
Error	0.47595	0.91172	1.5424
Ranking	36th	41st	21st

Table 7. Summary of parameters for Weibull distribution

Estimated Parameters	Tree Inception Voltage, Lognormal	Tree Breakdown Voltage, Lognormal	Tree Breakdown Time, Lognormal
Scale parameter	$\mu = 2.8324$	$\mu = 3.1740$	$\mu = 3.5165$
Shape parameter	$\sigma = 0.1592$	$\sigma = 0.1379$	$\sigma = 1.2923$
Location parameter	$\gamma = 0$	$\gamma = 0$	$\gamma = 0$
Error	0.35164	0.28822	0.85755
Ranking	27th	7th	5th

Table 8. Summary of parameters for lognormal distribution

Estimated Parameters	Tree Inception Voltage, Johnson SB	Tree breakdown Voltage, Wakeby	Tree Breakdown Time, Johnson SB
Scale parameter	$\lambda = 3.4755$	-	$\lambda = 481.06$
Shape parameter	$\delta = 1.0555$ $\gamma = -0.1490$	$\delta = -0.5342$ $\gamma = 6.9921$ $\beta = 45.156$	$\delta = 0.5165$ $\gamma = 1.401$
Location parameter	$\xi = 1.2928$	$\xi = 13.87$ $\alpha = 263.2$	$\xi = 2.0289$
Error	0.67473	0.18631	0.62155
Ranking	1st	1st	1st

description and analysis of the empirical data. Therefore, in the context of this study, it can be pointed out that Johnson SB function and Wakeby function could be useful in the analysis of electrical tree inception voltage, tree breakdown time and tree breakdown voltage data respectively. However, a better statistical way should be adopted in order to select a best-fit distribution that represents the original data. With the aid of AD GOF test, the best-fit distributions were obtained.

The failure of insulating material could bring severe effect to the reliability of energy distribution and hence could give many losses. Therefore, every single failure data should be analyzed correctly in order to estimate the failure probability and estimated breakdown parameter values that occurred due to electrical treeing. It is suggested, correct ways of statistical analysis could give a better solution to the reliability of electrical insulation system.

4. Conclusion

This paper has demonstrated some useful methods for the estimation of electrical tree inception voltage, tree breakdown time and tree breakdown voltage using statistical tools. The qualitative determination of the distribution of electrical tree inception and breakdown voltage and also tree breakdown time data contribute to the models with better accuracy and consistency. The findings from this study suggest that Johnson SB distribution is the most appropriate fitting distribution that estimates tree inception voltage and tree breakdown time while Wakeby distribution is a more appropriate fitting distribution that estimates treeing breakdown voltage for unsaturated polyester resin (BIP2700AT); Weibull and lognormal were not suitable to represent the tree inception voltage, tree breakdown voltage and tree breakdown time of the unsaturated polyester resin insulating material under test. It also contributes to a comparative study between the best fit distribution, Weibull and lognormal distribution. Therefore, a further development of this study could be done which can reveal ways for applying better statistical analysis in order to model the treeing parameters. The treeing parameters such as tree inception voltage, tree breakdown voltage, tree length, tree inception time, tree breakdown time and etcetera could satisfy certain statistical distributions. However, further studies are required to prove this and more insulation materials could be tested in order to gather more treeing data and definitely a better statistical approach is required to analyze those data.

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