Article

Evaluation of Electrical Tree Degradation in Cable Insulation using Weibull Process of Propagation Time

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Abstract: The main purpose of this paper is to evaluate electrical treeing degradation for cable insulation. To effectively deal with the currently facing issues, I endeavor to find the most optimal methods by means of applying signal process. First, we made three type models of electrical tree for PD generation to show the distribution characteristics and applied voltage to acquire data by using a PD detecting system. These acquired data presented distribution and four 2D distributions. Hn(q), Hn(Φ), $Hq_n(\Phi)$, and $Hq_{max}(\Phi)$ were derived from the distribution of partial discharge. From the analysis of these distributions, each PD model is proved to hold its unique characteristics and the results were then applied as basic specific qualities for insulation conditions. In order to recognize the progresses of an electrical tree, we proposed methods using scale parameter by means of Weibull distribution. We measured the time of tree propagation for 16 specimens of each model from initiation stage, middle stage, and breakdown respectively, using these breakdown data, we estimated the shape parameter, scale parameter and MTTF (Mean Time To Failure). The results of this study recognize the sources of PD by applying acquired data from PD signals to pre-acquired data. If the cause of PD is degradation, in other words, electrical tree, we can determine the replacement time of devices at the initiation stage of tree growth progress or no later than the middle stage and use it as a basic methods analysis diagnosis system. That is, pattern recognition and Weibull distribution can be employed to get the reliability of diagnosis.

Keywords: partial discharge; Weibull distribution; XLPE cable; electric tree; diagnosis

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1. Introduction

Maintenance technology for diagnosing electric power equipment has shifted from time-based maintenance to both condition-based and reliability-centered maintenance in Korea. Among various methods of implementing condition-based diagnosis, the partially discharge-based diagnosis method is most widely used because it is easy to derive parameters for insulation diagnosis. This is thanks to sufficient information on the insulation condition of the electric power equipment that is contained in signals arising from the occurrence of partial discharge in the equipment [1,2]. Construction of a number of electric railroads incorporating high-speed rail has recently taken place, and a lot of railway sections involving long tunnels have also been constructed in Korea. Whereas insulated cables are rarely utilized in the general sections of electric railroads due to the overhead catenary lines being used there, the minimalized construction of insulated cables in tunnel sections is operated from the perspective of the cross-sectional area of a tunnel on the grounds of construction costs. So, feeder wires are installed inside tunnels as insulated cables on overhead catenary lines. The

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condition diagnosis and degradation evaluation of the insulated cables installed in tunnels emerge as important factors.

Electrical treeing in cable insulation is a pre-breakdown phenomenon for insulation failure and the main factor in the insulation degradation of solid insulators. Therefore, discerning any electrical tree and grasping its propagation status is undoubtedly most crucial because it is directly related to the lifespan of the equipment [3-11].

To determine the propagation of electrical trees, this paper came up with three types of simulated electrical tree specimens and presented a method of revealing it by estimating the shape and scale parameters using the Weibull distribution [12-17]. As a method of using Weibull distribution analysis, partial discharge sizes were employed to uncover the propagation of electrical trees by estimating the shape and scale parameters step by step and analyze their change characteristics. In addition, by using 16 specimens for each model, the failure time in the event of any tree propagation was measured and presented. The failure times were then identified and categorized into three relevant tree propagation stages, thereby estimating the shape parameters, the scale parameters and the mean time to failures (MTTF) at each stage.

2. Evaluation of Electrical Tree Degradation

2.1. Specimen and test methods

2.1.1. Electrical tree discharge models

The specimens for the electrical tree discharge were secured by cutting some cross-linked polyethylene (XLPE) insulating material portions off a power distribution cable, three different types of tree models were made as shown in Figure 1. Each specimen was made by inserting a needle into the relevant insulating material after heating it to 100°C in order to inhibit the occurrence of any nonessential electric discharge due to the complete adherence of the interface between the needle and the insulating material during the needle insertion. The made specimens were tested in the insulation oil condition in order to prevent any surface discharge that could possibly occur on surface and outside.

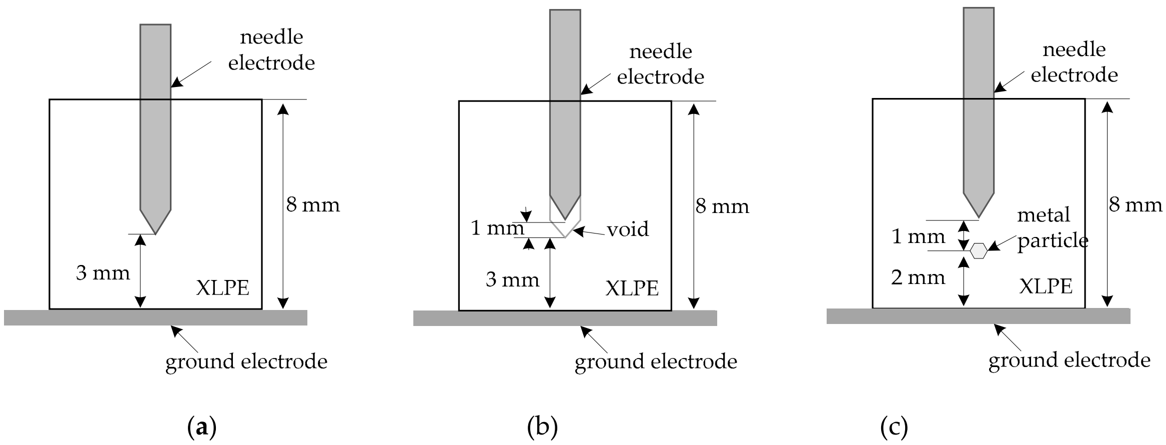

Figure 1. Artificial electric tree models: (**a**) tree model 1 was only needle electrode; (**b**) tree model 2 with void on needle electrode surface; (**c**) tree model 3 with metal particle between needle and ground electrode [18].

2.1.2 Experimental method and data processing

The experimental apparatus for the occurrence of partial discharges and the obtainment of relevant data consists of a PD-free transformer, a partial discharge acquisition, storage, a display system (PDASDS), and a microscope for observing electrical trees. The apparatus is designed in such a way so that voltage application, data acquisition and data processing are all possible with it. Partial discharge pulses were detected using a partial discharge detector (Biddle Instruments, AVTM 662700Ja), and the data was derived from the Φ-q-n distribution.

(a) (b) (c)

Figure 2. This is the test process of the experimental setup to detect the PD: (a) test process; (b) Partial discharge detector; (c) microscope and test oil tank [18].

3. Experimental results by electric tree models

Partial discharge distribution characteristics according to the electrical tree model specimens. The propagation stages of each electrical tree were distinguished from one another by selecting the actual time of its 20–30% growth as the initiation stage, the time of its 50–60% growth as the middle stage, and the time of its 80% or higher growth as the final stage.

3.1. Partial discharge distributions for tree modle 1

Figure 3 show the partial discharge distributions during the tree propagation in tree model 1. In the case of model 1 as shown in Figure 3, if AC voltage is applied, the breakdown voltage is lower (the voltage at which corona occurs is lower) in general when the needle in the needle-to-plane electrode is negative than when it is positive, and the tree growth is fast when the needle is positive, therefore, insulation failure may occur much more easily when the needle electrode has entered the positive half cycle. For these particular reasons, it can be concluded that the size of any electric discharge occurring is larger in the positive half cycle.

The distribution related to the frequency of discharge occurrence (i.e. the number of times it occurs) tends to decrease as the electrical tree propagation proceeds from the initiation stage towards the final stage, whereas in the cases of the discharge size-related distributions, Hq_n (Φ) and Hq_{max} (Φ), their values tend to increase as the electrical tree propagation proceeds towards the final stage of its propagation. This reveals that the quantity of electric discharge is a more important factor than the frequency of discharge occurrence in understanding the characteristics of both the insulation degradation and failure.

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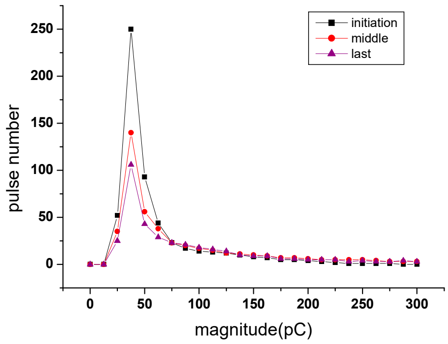
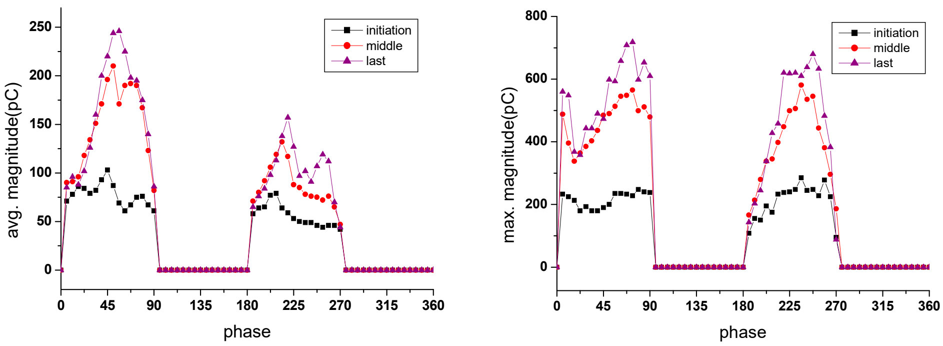


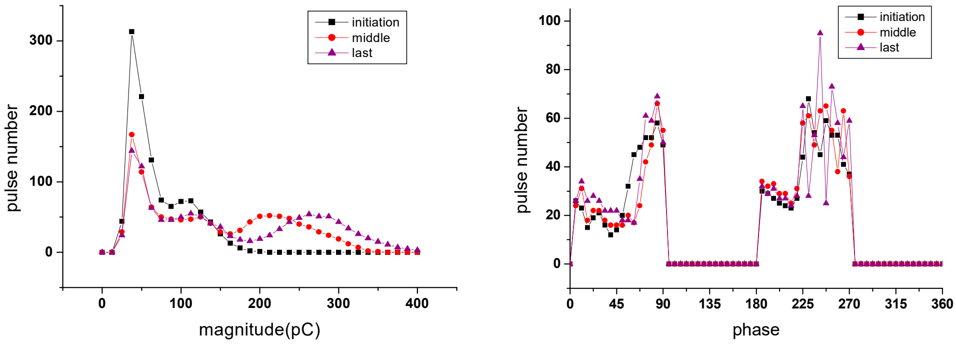
(a) (b)



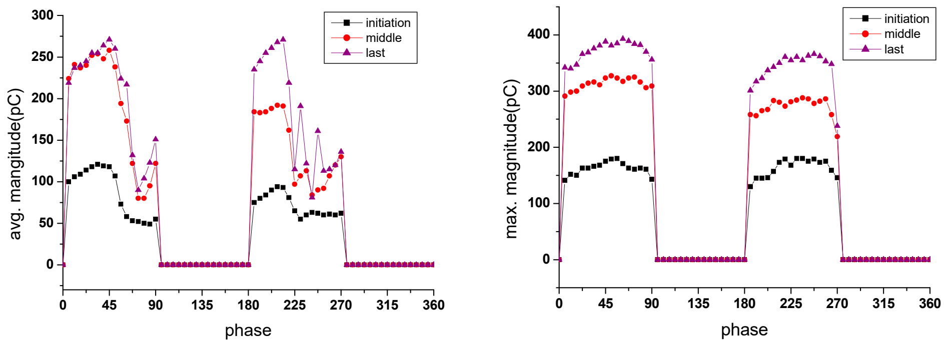
(c) (d)

Figure 3. PD distribution of tree model 1: (a) Hn(q) distribution; (b) Hn(Φ) distribution; (c) $Hq_n(\Phi)$ distribution; (d) $Hq_{max}(\Phi)$ distribution

(a) – (d) in Figure 4 reveal electric discharge distributions during the tree propagation in Tree Model 2. Much like in the case of Model 1, the occurrence of the electric discharge is more frequent in the positive half cycle than in the negative half cycle in Model 2. The discharge size has shown to be greater in the positive half cycle than in the negative half cycle. Both the mean and largest discharge sizes are greater in the positive half cycle. This seems to be the result of the existence of a void in the needle tip in Model 2, unlike in the case of Model 1. This phenomenon also showed the same characteristics even when there was a metallic foreign material in Model 3. Model 2 shows similar characteristics in the frequency of electric discharge occurrence (i.e. the number of times it occurs), its growth is clearly classified into the initiation stage, the middle stage, and the final stage in terms of the size of the electric discharge. In addition, as the tree propagation proceeds further towards the middle and final stages, the data on the discharge sizes above 300 show the greater frequency of the discharge occurrence.



(a) (b)



(c) (d)

Figure 4. PD distribution of tree model 2: (a) Hn(q) distribution; (b) Hn(Φ) distribution; (c) Hq_n(Φ) distribution; (d) Hq_{max}(Φ) distribution

The electric discharge size characteristically does not grow when the electrical tree propagates. Figure 5 shows PD distributions during the tree propagation in Tree Model 3. Electric discharge occurred many in the negative half cycle, thus displaying a high frequency of its occurrence whereas the positive half cycle showed definitely high values in the electric discharge size in Tree Model 3. The electric discharge size discovered to be greatest in Model 3 seems to be a phenomenon appearing as a result of an electric field being concentrated near the metallic foreign material. However, both the frequency of discharge occurrence and the discharge size are characteristically shown to be greater during the initiation and middle stages rather than during the final stage.

These are considered due to the influence of the metallic foreign material. More specifically, they are considered to be a phenomena appearing not only due to the complicated occurrence of the electric discharge from the needle tip, electric discharge together with a metallic foreign material, and electric discharge starting from the metallic foreign material but also due to the reinforcement of an electric field nearby under the influence of the metallic foreign material.

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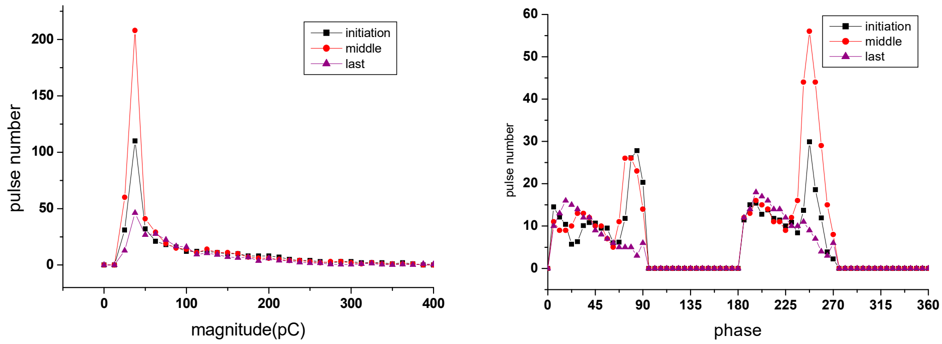
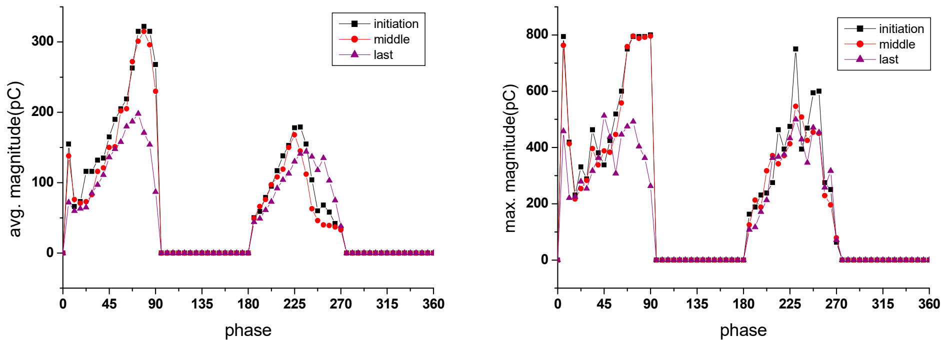


(a) (b)



(c) (d)

Figure 5. PD distribution of tree model 3: (a) Hn(q) distribution; (b) Hn(Φ) distribution; (c) $Hq_n(\Phi)$ distribution; (d) $Hq_{max}(\Phi)$ distribution

3.2 Evaluation of the degradation degree of XLPE cable

The degradation degree of the electrical trees is an important evaluation element because it is directly related to the lifespan of the cable. In order to diagnose the degradation degree of the electrical trees more accurately, this paper has processed the electrical tree propagation time by means of the Weibull distribution.

3.2.1 Examination of the electrical tree propagation time

Figure 6 shows the failure times during the electrical tree propagation for 16 specimens in each model. The tree propagation time was discovered to be shortest when there was any void in the needle tip (Model 2) whereas the tree propagation was slowest when there was metallic foreign material (Model 3). In Model 3, it was confirmed that although the electric tree propagation tended to be fast when there was any kind of metallic foreign material during the initiation stage, its propagation from the metallic foreign material until the occurrence of insulation failure proceeded so slowly that the insulation failure occurred later than in any other case.

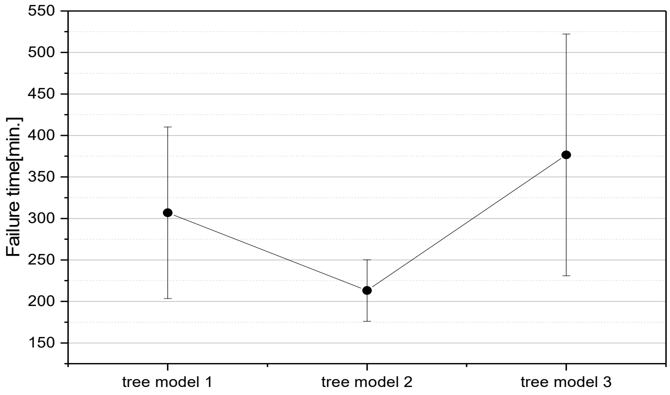


Figure 6. Time of failure according to tree models

Each failure time was measured after classifying the electrical tree propagation stages into three stages in order to estimate the parameters and the mean lifetime at each stage through the tree occurrence testing of electrical tree model specimens. The propagation stages of each electrical tree were restricted into the time of its 30% growth as the initiation stage, the time of its 60% growth as the middle stage, and the time of insulation failure as the failure stage (i.e. final stage).

Table 1 reveals the growth times for each electrical tree propagation stage of Model 1. The estimated Weibull distributions and parameters are as shown in Figure 7 and Table 2 respectively.

Figure 7 displays the results of applying failure time data based on the classification of the propagation stages in Electrical Tree Model 1 to the Weibull function. It means that some parts of the measurement data have different forms of distributions, and the shape and scale parameters for each population must be estimated by applying the data to the 5-parameter Weibull function. What we can confirm through these measurement results is that three of the 16 trees show different propagation aspects. In general, the propagation of bush-type trees proceeds slowly. Three measurement data represented the propagation of bush-type trees, and the remaining data showed a mixed form of both branch and bush types.

Table 1. Time to failure of tree model 1

specimen number	initiation (min.)	middle (min.)	failure (min.)
1	25	90	200
2	30	100	225
3	30	110	245
4	25	95	210
5	35	125	270
6	40	140	305
7	40	135	300
8	75	255	565
9	35	115	250
10	35	120	260
11	65	225	495
12	45	155	345
13	60	190	425
14	35	115	250
15	35	125	280
16	40	130	285

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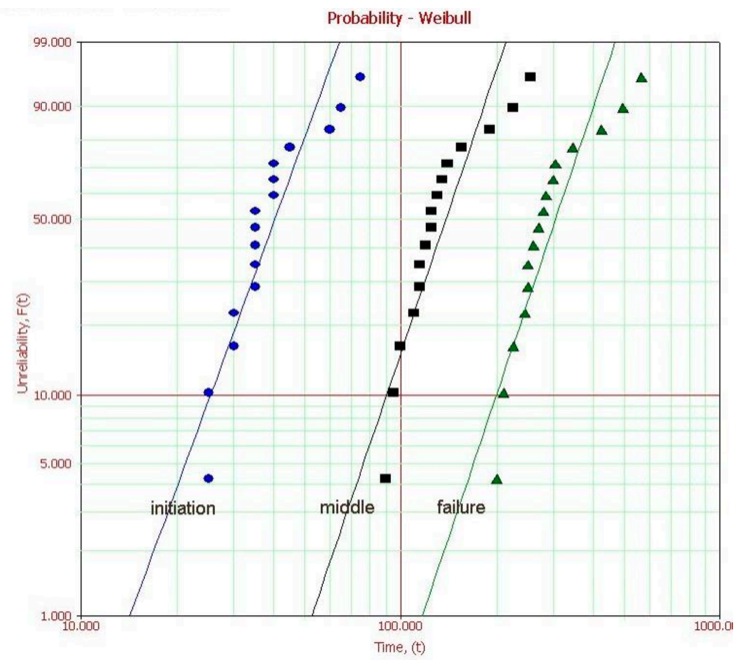

Figure 7. Time to failure of the Weibull distribution of tree model 1(divided by three progress: initiation, middle, failure)

Table 2 displays the shape and scale parameters for each tree propagation stage of Electrical Tree Model 1. All the shape parameters for Population 1 were estimated to have a value of 1 or higher, this means that the tree propagation proceeded in the form of their wear-out failure due to their degradation.

The time difference between the tree propagation stages of the scale parameters for the data on different tree propagation forms, i.e. mutually different populations, was 96 minutes between the initiation and middle stages and 147 minutes between the middle and final stages in Population 1, whereas it was 142 minutes between the initiation and middle stages and 283 minutes between the middle and final stages in Population 2. The mean lifetime was 96 minutes between the initiation and middle stages and 165 minutes between the middle and final stages.

Table 2. Shape and scale parameter of tree model 1

	initiation			middle			failure		
	shape	scale (min.)	MTTF (min.)	shape	scale (min.)	MTTF (min.)	shape	scale (min.)	MTTF (min.)
sub-population1	6.3	37	41	8.4	124	137	8	271	302
sub-population2	7.5	70		3.3	212		4.6	495	

Table 3 displays the time of each tree propagation stage for each specimen in Electrical Tree Model 2. Figure 8 reveals the results from applying the failure time data based on the classification of the tree propagation stages in Model 2 to the Weibull function. One of the measured specimens in Model 2 shows a different form of tree propagation in comparison with the other specimens. In general, at least three pieces of data are required for analyzing the Weibull function. Thus, it is necessary to use the 2-parameter estimation method, not the 5-parameter estimation method in the case of Model 2.

Table 3. Time to failure of tree model 2

specimen number	initiation (min.)	middle (min.)	failure (min.)
1	32	63	210
2	26	51	170
3	29	60	195
4	33	66	220
5	36	72	240
6	32	63	210
7	24	45	155
8	31	62	205
9	37	74	245
10	34	63	225
11	53	105	350
12	33	67	220
13	29	57	190
14	28	56	185
15	32	66	215
16	31	58	205

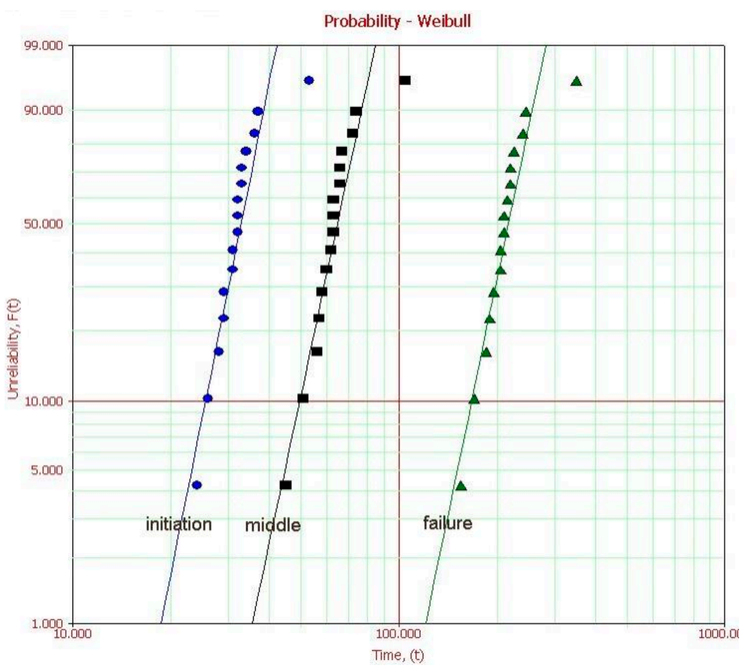

Figure 8. Time to failure of the Weibull distribution of tree model 2(divided by three progress: initiation, middle, failure)

By using the 2-parameter estimation method, the shape parameters were estimated to be 7.5, 7.03 and 7.64 according to the relevant time, the scale parameters were estimated to be 24, 68 and 226 minutes, and MTTF to be 32, 64 and 212 minutes.

In Model 2, the tree propagation proceeds very fast during the initiation stage but the tree propagation speed is similar to those from other models after the middle stage, this is considered to be because the tree propagates is fast at an early stage due to the influence of the void at the end tip of Model 2, but shows a general tree propagation aspect later. However, even if the tree propagation characteristics of Model 2 show similar aspects, what is important is that the time to failure in Model 2 is much shorter in comparison with the other models, this is vital information for understanding the lifetime of the electrical tree according to each defect.

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Table 4 reveals the respective values of the shape parameters, scale parameters and MTTF in Model 2.

The difference in the mean lifetime between the initiation and middle stages was 32 minutes, and that between the middle and final stages was calculated to be 148 minutes. When compared with Model 1, the tree propagation time between the initiation and middle stages was shown to be shorter than that in Model 1, however the tree propagation time between the middle and final stages is similar to that of Population 1.

Table 4. Shape and scale parameter of tree model 2

initiation			middle			failure		
shape	scale (min.)	MTTF (min.)	shape	scale (min.)	MTTF (min.)	shape	scale (min.)	MTTF (min.)
7.5	34	32	7.03	68	64	7.64	226	212

Table 5 displays the failure time data on each tree propagation stage in Electrical Tree Model 3, and Figure 9 shows the results from applying the failure time data based on the classification of the tree propagation stages in Model 3 to the Weibull function. Like in the case of the specimens of Model 1, some of the measurement specimens of Model 3 also reveal different tree propagation aspects in comparison with the other specimens. The shape and scale parameters for each group were estimated by applying the 5-parameter estimation method.

Table 5. Time to failure of tree model 3

specimen number	initiation (min.)	middle (min.)	failure (min.)
1	45	130	285
2	45	125	280
3	60	170	380
4	40	120	270
5	43	130	290
6	52	155	345
7	50	152	335
8	75	225	495
9	50	147	325
10	120	355	790
11	50	150	330
12	48	140	310
13	100	208	640
14	55	160	355
15	40	120	265
16	50	150	330

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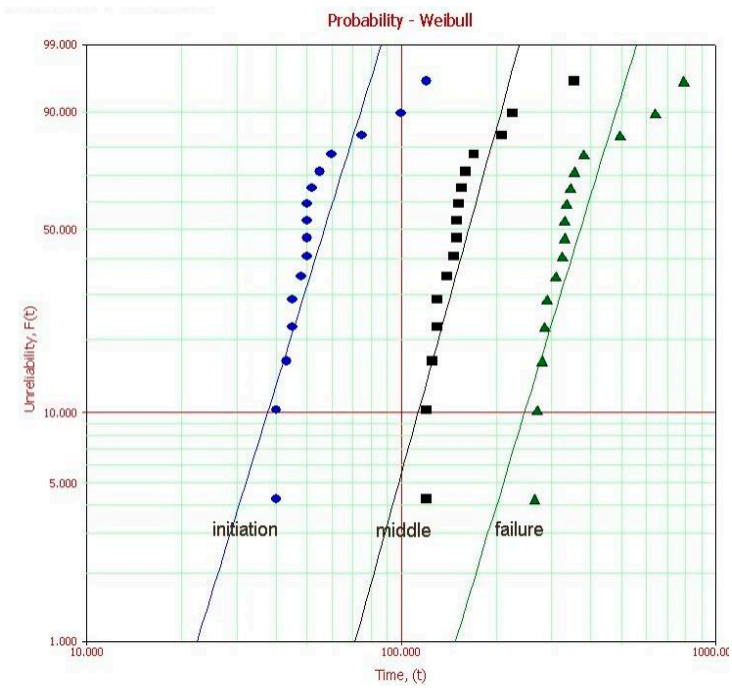

Figure 9. Time to failure of the Weibull distribution of tree model 3(divided by three progress: initiation, middle, failure)

Table 6 shows the shape parameters, the scale parameters and the MTTF in Model 3, which were respectively estimated from the measured failure times. The time difference between the tree propagation stages in Population 1 was 100 minutes between the initiation and middle stages and 206 minutes between the middle and final stages, whereas the time difference between tree propagation stages in Population 2 was 195 minutes between the initiation and middle stages and 206 minutes between the middle and final stages. It can be confirmed from the parameter estimation results in Population 2 that if a bush-type tree propagates during the initiation stage, its propagation is therefore very slow and that the tree propagates much more slowly in Model 3 containing needle-like foreign materials.

Table 6. Shape and scale parameter of tree model 3

	initiation			**middle**			**failure**		
	shape	**scale (min.)**	**MTTF (min.)**	**shape**	**scale (min.)**	**MTTF (min.)**	**shape**	**scale (min.)**	**MTTF (min.)**
sub population1	10.8	50	56	9.1	150	161	9.3	329	367
sub population2	2.9	98		2.9	293		4.1	700	

4. Discussion

When fully analyzing the failure types according to the relevant time, it can be confirmed that the failure rate increases according to the relevant time in each of the three models. In other words, all the shape parameters have a value of 1 or higher, it can be seen from this that all the three models show a wear-out failure. A curve with this form of an increasing failure rate (IFR) is characterized by the concentrated occurrence of failures anywhere due to the equipment wear-out or aging, in which case doing preventive maintenance immediately prior to the concentrated occurrence of any failure can prevent such failure in advance.

It can be confirmed through the results of the analyses conducted up until now that both the reliability and the failure rate appear to be different according to the relevant time through electrical tree-type defects, which are a failure mechanism. These can provide a lot of information for working

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out and implementing appropriate measures against failures. In other words, the time for equipment replacement can be determined during the initiation stage of tree propagation or even after the middle stage by applying the data obtained from the partial discharge signals to the data learned in advance, thereby discerning the actual causes of the occurrence of partial discharge and, if such causes are attributable to any electrical tree, by also analyzing the causes of the electrical tree. It is possible to configure a system for providing feedback as part of the design stage for discovering the causes of electrical trees through the analysis of the Weibull function and comprehensively examining the respective problems in the manufacturing process and using and installing the equipment, thereby finding out the causes of such problems. It would be possible to apply the analysis data obtained by using Weibull analysis usefully as basic data for configuring this system.

5. Conclusions

This paper analyzed the electrical tree propagation-based characteristics of the distributions of partial discharge signals occurring in cable insulation materials and has presented a degradation evaluation method, the results of this study are as follows:

1. This paper analyzed the characteristics of the partial discharge distributions at each tree propagation stage in each simulated electrical tree model.
2. Shape and scale parameters tended to increase as the electrical tree degradation proceeded in Tree Models 1 and 2, whereas the values of shape and scale parameters tended to decrease when the electrical tree propagation proceeded towards the final stage in Model 3.
3. The failure time of each specimen was measured in order to determine the degradation degree of the electrical trees by means of F(t) which uses the relevant time as a variable. The failure times in each model were measured and written by the degradation stage, and the shape parameters, the scale parameters and MTTF for each model and each stage were also estimated by means of these measurement results. The time difference between the degradation stages could be calculated, and the remaining lifetime of trees was estimated by means of such time differences.

It is considered that the research performed in this study can be utilized as basic research data for insulation diagnosis and the lifespan estimation of not only power cables but also electric power equipment which uses any different types of insulating material. It is also considered that the data based on this study can be utilized for determining the lifespan estimation and maintenance stages in the continuous monitoring and diagnosis system.

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Conflicts of Interest: The authors declare no conflict of interest.

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