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An Overview of Electrical Tree Growth in Solid Insulating Material with Emphasis of Influencing Factors, Mathematical Models and Tree Suppression

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Abstract

Nowadays, the most widely used insulating materials in high voltage equipment such as cables are polymeric insulations due to the numerous merits they possess with regards to electrical performance compared to paper insulations. However, electrical treeing, one of the dielectric pre-breakdown phenomena, has been considered as a major contribution to the failure of insulating polymeric materials. Thus, this paper provides an overview on the factors affecting the initiation and propagation of electrical tree. Discussions on parameters that affect the growth of electrical treeing such as applied voltage, electric field enhancement, partial discharge, frequency of applied voltage and temperature are given. Some discussions on the various models are also highlighted. The tree related models being discussed herein include Weibull, Lognormal, Johnson SB, Dielectric Breakdown Model, Discharge-Avalanche Model, and Field-Driven Tree Growth. In addition, discussions on the use of nano-sized fillers in polymeric insulating material to inhibit electric treeing are highlighted.

Keywords: *electrical treeing, mathematical models, partial discharge, tree suppression*

1. Introduction

Polymeric insulation materials are still widely used by power utilities as the base material for their production such as natural gas is still available in abundance. Furthermore, power utilities are replacing their impregnated insulated cables with polymeric insulation, namely cross-linked polyethylene (XLPE) and generic materials such as epoxy resin, silicone rubber, ethylene propylene diene monomer (EPDM) and etcetera due to their superior electrical performances such as high magnitude of dielectric strength in MV/cm, very low dielectric losses, high tensile strength and resistance to electrical degradation phenomena [1]. However in the long run, polymeric materials experience ageing and finally dielectric breakdown. One of the main causes of breakdown in polymeric insulations is electrical treeing [2]. And in this view, continual efforts are made to understand and characterize electrical treeing mechanisms. Treeing is observed to originate at points where impurities, gas voids, mechanical defects, or conducting projections cause excessive local electrical field stresses within small regions of the dielectric. Auckland et al. [3] characterized electrical treeing as labyrinthine structures of narrow gas-filled tubules which created by localized partial discharge activity. Barclay et al. [4] divided the process of electrical tree in insulation systems into three phases which are inception phase, propagation phase and completion phase. They described the inception phase as the undetectable damage accumulated at pre-existing defects which increases the electric field locally. At the propagation phase, a branching deterioration structure occurs from the defect and spread out across the dielectric. The completion phase occurs when the gap between the electrodes is bridged by the electrical tree due to the enlargement of the discharge.

Furthermore, Zheng et al. [5] mentioned that tree propagation is categorized in three primarily stages, initiation, stagnation and rapid propagating phases. If initiation phase is very active, the single branch tree will propagate,on the other hand if this phase is weak then the bush tree will occur more easily. Meanwhile, Wu et al. [6] characterized the development of electrical treeing as tree initiation and tree growth.

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The electrical tree shapes can be roughly characterized as branch, bush-branched and bush-shaped structures. Ding et al. [7] visualized electrical tree propagation as a process of intense localized electrical degradation, which leads to the creation of new tree channels, by the formation of sub-microscopic voids. During this phase, electrical tree grows in the function of time by following the direction of electric field. Breakdown occurs quickly after the tree has bridged the insulation [8].

The insulation lifetime depends upon the electrical tree growth. In the laboratory, the needle-plate electrode is usually used to investigate the tree growth in insulating material. The needle is used to enhance the electric field around the needle tip region. This causes the electrical tree to grow from the needle tip (local stressed region) towards the opposite electrode and hence the tree failure time is determined as the insulation lifetime [9].

Thus, due to severe effects of electrical tree on the insulation system, state-of-art study has been performed to understand clearly the tree mechanisms and this paper has taken into account to review some of the factors that influence the electrical tree induction and growth in polymeric insulating materials and examines the effects of applied voltage, local electric field enhancement, partial discharge, frequency of applied voltage, and temperature on electrical treeing. Besides, several mathematical models have been reviewed in this paper. These include Weibull model, lognormal model, Johnson SB model, Dielectric Breakdown Model (DBM), Discharge Avalanche Model (DAM) and Field-Driven Tree Growth Model (FDTG). Despite numerous studies on electrical tree, a full understanding of this phenomenon is yet to be achieved due to complexity and various factors. In view of the foregoing, this paper attempts to give a general understanding of electrical tree studies through this review.

2. Electrical Tree Formation Mechanisms

In literature, electrical tree is initiated by charge carriers injection and extraction from embedded electrode into the polymer. The charge carriers are classified as electron, hole and ions. These charge carriers are recognized as “space charge” from the context of dielectric material. They are also known to move around on the dielectric material by the electric field and become trapped in the bulk of material [10]. However, electron is considered or assumed as charge carrier in the most situations. Under negative half cycle of AC voltage, a number of electrons will be injected into the polymer material from an electrode for a short distance. Meanwhile, during the positive half cycle of AC voltage, the electron will be extracted backwards into the polymer material. This injection and extraction process will be repeated during negative and positive half cycle of AC voltages. During the positive or negative half cycle, these electrons gain sufficient energy to form polymer decomposition or to attack polymer chain in order to initiate chemical reaction to cause polymer degradation. The polymer degradation could eventually form a hollow channel that will result in the gases discharges, as a tree starts to initiate [11].

Moreover, electrical tree can be initiated by mechanical fatigue due to Maxwell stress. In details, a cracking of the polymer is produced due to the high Maxwell compressive stress at the electrode tip under AC voltage. Thus, electrical tree will start to initiate from this crack due to gas discharge. On the other hand, electrical tree can be initiated by small cavity or void which could eventually leads to the PD occurrence. As a result, this void will attract the field enhancement to locally stress on itself because it is filled with gases which has a lower permittivity compared with the polymer material which has higher permittivity. The electric field will ionize the gases and thereby forces the void to discharge [12].

3. Factors Affecting the Growth of Electrical Treeing

This section discusses the factors such as the applied voltage, electric field enhancement, partial discharge, frequency, and temperature that enhance the electrical tree formation mechanisms.

3.1. Applied Voltage

Numerous studies have shown that the initiation and growth of electrical treeing is affected by the magnitude of the voltage applied to the polymeric material whether in DC, AC or impulse voltage [13-20]. This is primarily because when high voltage is applied to insulation, the local electric field near the defect site is enhanced. If the order of magnitude exceeds the maximum electric field strength of the material, initial damage would start to induce near the defect site [21].

Maruyama et al. [22] reported that electrical tree changes from branch-type to the dense bush-type tree with the increase of applied voltage. In addition, Densley [23], Noto and Yoshimura [24]observed that the branch-type trees grew at lower voltages while the bush-type trees grew at higher voltages. Besides, Du et al. [25] performed experiments on silicone rubber (SiR) to investigate electrical tree phenomenon. Based on their results, AC voltage was found eager to initiate the electrical tree compared with DC voltage. Electrical tree grew at longer length under elevated AC voltage while under DC, short tree propagation was observed. Figure 1 shows the strong correlation between electrical tree length and applied voltage in neat room temperature vulcanized (RTV) silicone rubber.

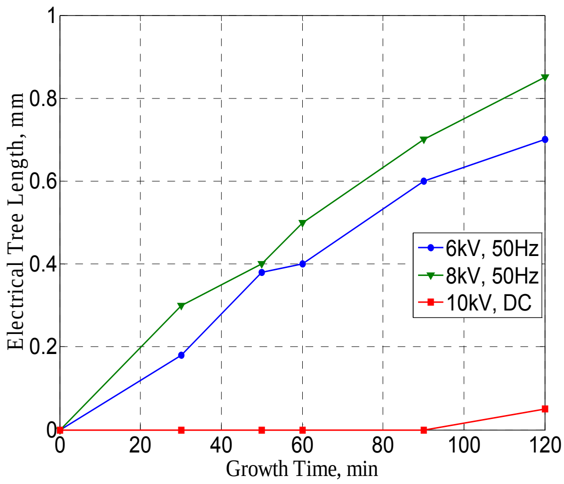

Figure 1. Growth Characteristics of Electrical Tree in SiR under Different Types of Voltage [25]

In details, during the positive and negative half cycles of AC voltage, the charges are injected and extracted into the polymer, thereby lead to the initiation of electrical tree. At some portions, the injected charges are retained in deep traps during the subsequent half-cycle which the coalescence of the luminescent gives rise to the electroluminescence. The amount of injected charges is an indicator of the intensity of electroluminescence and the light intensity changes with the values of applied voltage. Meanwhile, under DC voltage, the induction of electrical tree is caused by the homocharges which moderate the stress enhancement at the injection point. In addition, the electron avalanche causes the tree to propagate inside the polymer under DC voltage application. In other words, the injected and extracted electrons generate a first channel. Heterocharge which is deposited on the channel wall is swept out thereby transferring maximum stress to the channel region which may generate another new tree channels by electron avalanche repetition. Under impulse voltages which have risen and fall times of a few to several hundred microseconds, more electroluminescence pulses are emitted. This is due to injection of electron during the negative impulse into the polymer with the combination of trapped charges. Thus, more lights being emitted as a result of more electroluminescence. In addition, repeated impulse of the same polarity allows the space charge to being dissipated from the tree channel tips. This would result in the tree propagation by activating all the tree channel tips and thereby could develop the tree branches [12].

3.2. Electric Fields Implication

Divergent high fields have been reported as one of the causes of electrical tree [26]. Mason [27] reported that the electric field, E depends on the applied voltage, pin-tip radius and pin-plane separation distance according to the following formula;

$$E = \frac{2V}{r \ln\left(\frac{4d}{r}\right)} \quad (1)$$

Where, *d* is the distance from the needle tip to plane electrode, *r* is the needle tip radius and *V* as the applied voltage. The maximum electric field was calculated by considering *r* and *d* as depicted in Figure 2.

The size of needle tip radius plays a significant influence on the initiation of electrical treeing due to electric field enhancement [28]. Based on Mason's formula (Equation (1)), electric field is inversely proportional to the needle tip radius. Therefore according to Equation (1), smaller tip radius would result in higher electric field which is sufficient to initiate the electrical treeing.

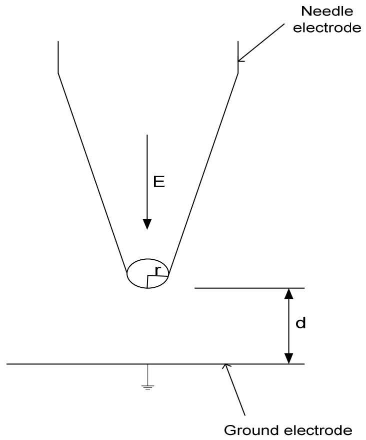

Figure 2. Simple Diagram of Needle Tip with its Corresponding Tip Radius

Champion et al. [29] reported that the inception of electrical tree depends primarily on the electric field at the pin-tip, the quality of the polymer electrode interface and the distribution of the discrete charge transfer sites at the pin surface. In addition, Noskov et al. [30] pointed out that the electrical tree growth is governed by the electric field and the damage accumulation in the dielectric material. The damage values were found to be proportional to the amount of energy being dissipated in the tree channel.

Likewise, in [31] the authors have mentioned that the electric field was required to initiate void discharges which may cause electrical tree to initiate and thereby propagate in insulation bulk materials. In case of electrical tree inception, the inception time of electrical treeing depends upon the intensity of the localized electric field which is experienced at the centre of the needle tip surface [32]. In another study by [33], it was found out that prolonged exposure to electric fields of values higher than 5 to 10kV/mm would lead to formation of voids or microcavities in the polymer (PE). With time, these microcavities may unite to form bigger-sized cavities in which PD would occur and initiate the electrical treeing. However, an electric field with value more than 200kV/mm is required to initiate an electrical tree which this level is called light inception level. The applied electric field gives sufficient energy to the free electrons inside the voids which may cause the material to ionize due to impact on the walls of the voids. The energetic electrons capture the thermal electrons which result in the formation of free radical and thus lead to the chain scission. Therefore, more microvoids would form and could coalesce to form larger voids which lead to the PD occurrence and tree to be induced [12].

3.3. Partial Discharge Implication

A partial discharge is defined as "localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor" by referring to IEC 60270: 200 standard (BS EN 60270:2001). It appears as a pulse which has duration less than 1μs. PD is normally classified as corona, surface, and internal discharges. In definition, corona discharge is a form of PD that occurs in gaseous media around conductors which are remote from solid or liquid insulation [34]. Surface discharge is defined as a type of PD that occurs on the surface of a dielectric material and internal discharge is a discharge that occurs from the cavities or inclusions which originally exist inside a dielectric material. It is also in the form of channel created due to high electric field stressing. Electrical treeing is considered as an internal discharge occurring inside an insulation material [35].

The initiation of electrical tree starts from the void in the insulation bulk. Thus, it attracts the electric field to enhance at itself because it is filled with the gases which have a lower permittivity over the rest of the dielectric. It then would lead to the ionization of the gases and cause the void to discharge. However, if the localized avalanches do not cause breakdown it would cause partial discharge to occur. The electric field for the inception of partial discharge depends on the void size and it ranges from ~3kV/mm to more than 1MV/mm for void sizes from 1mm to micrometre-sized voids [12]. This electric field values are in line with the electric field values which are required to generate electrical treeing mentioned in the previous subsection.

Noskov et al. [30] reported that partial discharge activity influenced the formation of new tree channels due to the enhancement of local electric fields near the channels. Based on the PD measurement, it was found that the partial discharge magnitude (in pC) increased with the increase of the tree length and the number of tree branches. Characteristic features based on partial discharge analysis and optical observation could identify the type and the severity of treeing [36].

Electrical tree is visible in the transparent materials such as epoxy resin, silicone rubber, polyester resin, polyurethane, PMMA and polycarbonate. The tree growth can be monitored under microscopic video images. However, for opaque materials like XLPE, LDPE, HDPE, EVA, PVC and PE, electrical tree inception voltage can be measured by measuring the PD occurring at the tree growth inception [37]. Thus, simultaneous observations of electrical tree growths and the corresponding PD occurrences are the popular and perhaps more precise method to study the initiation and propagation of electrical tree are being used nowadays [38]–[44].

In general, there are two common techniques of analyzing PD data which are widely used the phase-resolved partial discharge pattern (PRPD) and pulse sequence analysis (PSA) techniques. Probably, the most commonly used type of data for PD monitoring and insulation diagnostics in the case of ac applied voltages is the phase-resolved partial discharge pattern (φ-q-n). It represents information in 3D containing the interrelationships of ac voltage phase of PD occurrence (*φ*), discharge magnitude (*q*), and discharge rate (*n*). A typical PD pattern from an electrical treeing experiment with an alternating voltage of 50Hz was applied to the pin electrode is shown in Figure 3. Voltage phase *φ* is on the abscissa, discharge magnitude *q* is on the ordinate, and dot density in each window represents the number of discharges *n* as depicted in the Figure 3. Positive PDs are mostly present during the positive half-cycle of the applied voltage ($0 < \phi \leq 180^{o}$) while the negative PDs are mostly present during the negative half-cycle ($180 < \phi \leq 360^{o}$) [45].

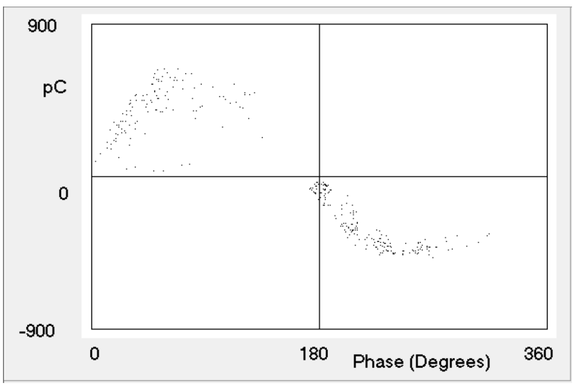

Figure 3. Typical PD Pattern from an Electrical Treeing Experiment

Based on phase-resolved PD pattern (*φ-q-n*) shown in the Figure 3, the individual PD event is denoted by dot and it contains the information of the phase of occurrence (*φ*), magnitude (*q*), and number of PD events (*n*). PDs are often regarded as stochastic processes and thus, standard statistical analysis can be employed to interpret and analyze the large PDs data [46].

3.4. Frequency

Frequency acts as repeated electrical stress in vertical direction of the electric field around the needle tip. When a centralized stress exceeds a limit of the dielectric strength of the material, a crack or void would start to produce which consequently could initiate the electrical tree. When frequency increases, the mechanical stress unites with the electrical stress applied at the needle tip thereby enhancing the initiation of electrical tree and reduces the magnitude of tree inception voltage as well. Chen et al. [47] reported that high frequency up to 500Hz could accelerate the breakdown or complete bridging of the polymeric insulation due to electrical treeing which is caused from a generation of higher number of partial discharges. Densley [23] in their work observed that electrical trees of different shapes grow under various voltages and frequencies. In addition, higher frequency accelerated time to breakdown. Du et al. [25] found that the growth rate and the tree structures were influenced by the applied frequency. The growth rate of electrical tree increased with the increase of frequency of applied voltage. The length of electrical tree also increased with the increase of voltage frequency. This is depicted in Figure 4.

The result shows that the growth speed of electrical tree in silicone rubber at the frequency of 4.5kHz was faster than that at power frequency (50Hz). The silicone rubber insulation was fully bridged by the electrical tree at duration of 90 minutes at frequency of 4.5kHz whilst at frequency of 50Hz, the tree has taken a time of 120 minutes to grow up to 0.7mm. A similar study on silicone rubber was carried out by Nie et al. [48]. They reported that tree inception voltage decreased with the increase of the frequency from 50Hz to 130kHz. At low frequency (50-500Hz), electrical tree grew in the form of branch-type and pine-type trees. At middle frequency range from 1kHz to 10kHz, the trees tend to form more in the shape of pine-type and bush-type trees, while at frequency above 10kHz, all the trees formed were bush-type trees. The findings by Nie et al. is in agreement with Chen's work whereby frequency of 500Hz accelerated the growth of electrical trees and accelerated the breakdown because the tree was a branch-typed one which has single branch and propagated in a straight line towards the ground electrode.

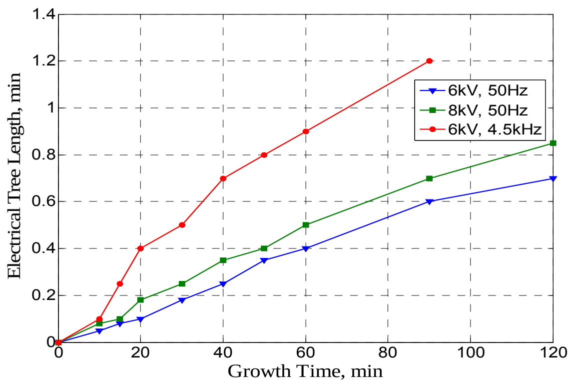

Figure 4. Growth Characteristics of Electrical Tree in SiR under AC Voltage with Different Frequencies [25]

3.5. Temperature

Studies conducted by Ieda[49] regarding to the effect of temperature on electrical tree growth has shown that the tree inception time decreased while the tree propagation rate has increased with the increase of the temperature ranging from room temperature to 100°C in Polyethylene (PE). The tree propagation rate is somehow determined by the magnitude of discharge and the extent of the damage formed at the channel tip. The increase of temperature may influence these factors which could lead to the increase of tree propagation rate [26]. Densley [23], Ieda and Nawata [50] found that at temperature greater than 80°C, only bush-type trees grew (not taking into account the value of voltage stress) whereas for temperature less than 70°C, only the branch-type trees formed at voltages of 14kV or less in PE samples. The tree propagation rate increased with increase in temperature due to the increase of degradation produced at the tree channel tip by a given discharge, since the penetration of the polymer by a charged pulse increases with temperature [26]. In ethylene-vinyl acetate copolymer (EVA), it was found that the tree inception time and breakdown time were shorter at high temperature (60°C) compared with a temperature of 20°C [51].

Temperature has also been reported to have an effect on the tree shape. In the case of room temperature vulcanized (RTV) silicone rubber, different tree characteristics had been observed by Du et al. [52]. In their work, three different ambient temperatures were selected to investigate the behavior of electrical trees. At 30°C, the trees tend to form in branch-type trees, whereas when the temperature was increased from 60°C to 90°C, the bush-type trees became the dominant. This was because when the temperature was increased, the degrees of vulcanized point also increased. Thus, this led to the formation of a uniform vulcanized net and increased the number of cross-links thereby requiring more energy to break more bonds in order to produce the cavity. In a similar work carried out by Zhou et al. [53] on electrical tree initiation in High Temperature Vulcanized (HTV) silicone rubber, temperature of 25°C resulted in the formation of branch-like and monkey-puzzle trees only. Meanwhile at 50°C, bush-like tree became dominant compared to the monkey-puzzle and branch-like trees. At higher temperature (>100°C), all the trees became bush-like trees. These results were similar to results reported by Du et al. [52]. The reason of the formation of bush-like trees at higher temperature was due to vulcanization effect which is enhanced by the increase in temperature.

In epoxy resin (BADGE) system, rapid growth of electrical tree has been observed at the temperature near the resin glass transition temperature, T_g which was 95°C. This was due to the movement of molecular chain or chain mobility has become more active and thereby led to the enlargement of electron diffusion at the needle electrode [54].

4. Statistical Models

The most appropriate method of interpreting collected data is by using statistical analysis since different results are obtained for given test condition in each test samples. Extreme-value statistics such as Weibull and log-normal distributions have been applied to describe the failure of solid insulation by fitting the experimental data to these statistical distributions via graphical and computer-based techniques. Thus, it can be said that Weibull and lognormal are commonly used in data interpretation of HV failure phenomenon. Recently Johnson SB has also been used in this field. A brief review of these models is presented in this section.

4.1. Weibull Distribution

Weibull is the most widely used distribution function in high voltage engineering to describe the failure of solid insulation. In contrast-voltage tests, time to breakdown and breakdown voltage distribution functions are determined, which are generally approximated by two-parameter Weibull distribution. In case of insulation failure due to electrical tree, Weibull has been applied principally to tree breakdown time, tree breakdown voltage problems and determining the water and electrical tree lengths in solid insulating materials. [55, 56]. The probability density function (pdf) and cumulative distribution function (cdf) of Weibull distribution are given as follow:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \quad (2)$$

$$F(x) = 1 - \exp\left[-\left(\frac{x - x_0}{\alpha}\right)^{\beta}\right] \quad (3)$$

Where,

α = scale parameter, $\alpha>0$,
β = shape parameter, $\beta>0$ or measure of dispersion,
x_0 = initial value of x or location parameter,
X = measured variable,
$F(x)$ = probability of failure at a voltage or time less than or equal to x,

For the initial value, $x_0 = 0$ the derived two-parameter Weibull is as follows;

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

The scale and shape parameters can be estimated by using least square method, maximum likelihood estimation or by plotting the probability graph on Weibull paper. From literature, several researchers have applied and modelled Weibull distribution for many purposes related to high voltage insulation.

Barclay et al. [57] have applied the two-parameter Weibull distribution to simulate the failure probability and to examine the model parameters in order to find its influences on the tree growth behaviours. Sarathi et al. [21] used Weibull distribution to understand the severity attributed to electrical stress and analysed the electrical tree processes. Dissado [31] applied the Weibull function to determine a continuous function for the cumulative probability of failure from the number of breakdowns due to electrical treeing.

Furthermore, Arainy et al. [58] have applied the Weibull to model the water-tree population and tree lengths at different temperatures. Huuva et al [59] used 2-parameter and 3-parameter Weibull statistics to model the tree inception field of LDPE with the aid of MINITAB software. In their study, 90% confidence limit was applied for fitting. However, it was found that several points had fall outside the confidence levels. Moreover, the tree inception times and tree propagation times were analysed using two-parameter of Weibull statistics for post-cure cross-linked polyester resin [60]. The 90% confident limit proved the data was fitted with two-parameter Weibull statistics. In this case, it was found that none of the short-time experimental points fall outside of the 90% confidence limits.

4.2. Log-normal Distribution

Lognormal is a statistical distribution that has been used to represent the failure data of the insulation systems. Log-normal is used to model a failure of components' life which is due to the fatigue-stress [61]. Based on the experimental results, Czaszejko [62, 63]has clarified that the water tree length data points fit very well in log-normal distribution plots. This result is consistent with the studies done by Qureshi et al. which have been published in [64-66]. Based on their studies, water tree populations and tree length distributions were fit better to log-normal model.

A variable, Y is termed log-normal when the variable produced by the transformation X= logY or X = lnY. The probability distribution function (PDF) of lognormal distribution is as follows;

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right) \quad (5)$$

Whilst, CDF of Lognormal distribution can be expressed as follows;

$$F(x) = \phi\left(\frac{\ln x - \mu}{\sigma}\right) \quad (6)$$

Where ϕ is Laplace integral which is expressed as follows:

$$\phi = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-\frac{t^2}{2}} dt \qquad (7)$$

4.3. Johnson SB Distribution

Johnson SB mostly has been applied in the fields of forest science [67], hydrology [68], exposure science and environmental epidemiological studies [69]. Recently, it has been applied in high voltage engineering by Ahmad et al. [68]. It was found that after fitting process using Anderson-Darling (AD) goodness-of-fit (GOF) tests, the tree inception voltage of silicone rubber and epoxy resin fitted well with Johnson SB model [70, 71]. They also showed that Johnson SB was more fit than Weibull and Lognormal by comparing the fitting error. PDF of Johnson SB distribution is given as follows [72];

$$f(x) = \frac{\delta}{\lambda\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\gamma + \delta \ln \frac{z}{1-z}\right)^2\right] \qquad (8)$$

Meanwhile, CDF of Johnson SB distribution is as follows [72];

$$F(z) = \phi\left(\gamma + \delta \ln\left(\frac{z}{1-z}\right)\right) \qquad (9)$$

Where δ and γ are shape parameters, ξ is a location parameter, λ is a scale parameter, and ϕ is the CDF of the standard normal random variable as shown in Equation (9). Whereas x is defined on bounded range of and z is referring to following transformation;

$$z = \frac{x-\zeta}{\lambda} \qquad (10)$$

All the Johnson SB parameters can be calculated by using Maximum Likelihood Estimation method (MLE). The Johnson SB model was found suitable for application in the analysis of electrical tree inception voltage data. This was proved by calculating the AD GOF test. Based on GOF test, the fitting error was the smallest for Johnson SB rather than Weibull and Lognormal which exhibit larger fitting error. Based on the work done by Ahmad et al. [70, 71, 73], the estimated values of tree inception voltage of silicone rubber and epoxy resin sample were calculated by taking inverse function of the Johnson SB CDF. The inverse function equation is given in Equation (11);

$$x = F^{-1}(P) = \frac{\lambda \exp\left(\frac{\Phi^{-1}(P)-\gamma}{\delta}\right)}{1+\exp\left(\frac{\Phi^{-1}(P)-\gamma}{\delta}\right)} + \zeta \qquad (11)$$

Based on the above equation, the variable x was assumed as tree inception voltage at probability of 0.5. In addition, the value of x can be calculated graphically by plotting the CDF graph.

5. Electrical Models

Electrical models are different compared with statistical models in term of analysis, data interpretation, calculation, parameters and application. In this section, several models are discussed briefly in order to differentiate them in terms of concept and application. The models such as Dielectric Breakdown Model, Discharge-Avalanche Model and Field-Driven Tree Growth Model are covered in this section.

5.1. Dielectric Breakdown Model

Dielectric breakdown phenomenon occurs by narrow discharge channels that exhibit a strong tendency to branch into complicated stochastic electrical tree patterns. The electrical tree discharge grows to the points where the electric field is highest.

Pietronero et al. [74, 75] proposed a model based on the idea of the local field discharge pattern did not govern the tree growth directly but through a stochastic process. This means that the field pattern did not just grow at the point of maximum local field but at this point exhibits the highest probability of growing. The electric field is determined by the global structure of the discharge pattern. The relation between probability and field shows the fact that the microscopic mechanism of the propagation of the discharge is modulated by its global structure. The electric field distribution is obtained from the Laplace equation by assuming the tree channel as an electrode extension or voltage drop within treeing channels. However, in [76], Weismann and Zeller modified this model by introducing a critical field for channel growth and a voltage drop along the tree channels. The stochastic model was defined on a lattice and based on the equipotential and connected discharge pattern.

DBM represents a rectangular lattice where each lattice point corresponds to a point in the dielectric. An electrode gap consists of 100 lattice units representing the dielectric breakdown. The DBM assumes that the electrical tree will grow stepwise. The growth of electrical tree will start at needle electrode with electrical potential, $\rho = 0$ and end at the counter electrode with electrical potential, $\rho = 1$. The probability, P of a tree channel growth at each site of electrical tree neighbourhood is proportional to a power, τ of electric field, E at that site. Electric field in the form of ρ is written as follows;

$$P(i, j \rightarrow i', j') = \frac{(\alpha_{i,j})^{\beta}}{\sum (\alpha_{i',j'})^{\beta}} \tag{12}$$

Where *i,j* and *i',j'* are the discrete lattice positions. The summation of denominator refers to all of the possible tree growth site (*i',j'*) which are adjacent to the electrical tree channel. By solving Laplace equation with consideration of that the tree structure has electrical potential equal to zero, the electric field, E is obtained. Then, the 2-dimensional lattice can be written as;

$$\alpha_{i,j} = \frac{1}{4}\left(\alpha_{i+1,j} + \alpha_{i-1,j} + \alpha_{i,j+1} + \alpha_{i,j-1}\right) \tag{13}$$

After iteration of this equation, the electric potential at possible tree growth site (i',j') can be obtained.

5.2. Discharge Avalanche Model

Dissado et al. [77] proposed discharged-avalanche model which described electrical tree propagation quantitatively. When the voltage is increased, it is difficult to determine the voltage dependence of tree growth whereby the shape has changed from branch to bush type. The shape changes occurred with a reduction in the length growth at a fixed time around the voltage. The total damage in bush trees was greater than branch trees. Thus, the electrical tree damage was formulated as:

$$S = \left(L / L_b \right)^{d_t} \tag{14}$$

Where S is the number of tree channel damage, L_b as average of electrical tree length, L as the length of a tree, and $d_t$as fractal dimension. Where, d_t= 1.2 to 1.8 for branched trees and 2.4 to 3 for bush trees [26], [57]. Then, if the damage grows in a straight line (d_t= 1), then the number of newly created channels is as follows;

$$S = \left(L / L_b \right) \tag{15}$$

The above equation is only applicable to non-branched tree, for a branched tree the $d_t$value is not equal to one. In the AC voltage application, the total length, *L* of all the channels is proportional to the aging time, *t*. Thus, the tree channel damage in function of aging time is given by Equation (16) [26]:

$$S(t) = \left(L/L_b \right)^{d_t} = \frac{t}{t_{ch}} \tag{16}$$

Where t_{ch} is characteristic time for tree channel formation. Although, this model can quantitatively describe the voltage dependence of electrical tree growth in the region of the branch-bush transition however this model is quite complicated as the fractal dimension, $d_t$needs to be determined in order to obtain the total damage, *S*. Furthermore, Dissado et al. [57] himself suggested that further experimental work is required to prove the efficiency and validate the model with experimental results.

5.3. Field Driven Tree Growth Model

The Field-Driven Tree Growth model proposed by Champion et al. [78] was developed by assuming that the material damage occurred only when the local electric field, E_L within material exceeds a material-dependent critical field, E_c, if the tree structure is conducting (at least during the PD activity), it will modify the local field condition by effectively reducing the needle-plate separation and increasing the apparent needle tip radius. The growing tree can be approximated by a conducting hyperboloid of hyperbolic radius equal to tree length extent as represented by the equipotential lines. During the tree growth, the hyperboloid-plate distance de, decreases as $d_e = d_p - r_e$. Here d_p is the needle-plate distance and r_e is the tree length.
The tree growth was considered as field-driven when damage volume, ΔV is increased in amount and proportional to (E_L-E_c) which is expressed in Equation (17).

$$\Delta V = A\left(E_L - E_c\right) \tag{17}$$

Where *A* is a constant which depends on the material. As a result, FDTG model has described the parameters that primarily influence the growth of electrical treeing. Such parameters were material-dependent electric field, E_c, local electric field, E_L, fractal dimension, d_t and applied voltage.

6. Electrical Tree Suppression using Nanofillers

The improvement of electrical tree resistance by adding nanofillers to inhibit treeing was firstly studied by Ding and Varlow and Imai et al in 2004 [79, 80]. Meanwhile, partial discharge resistance on polymer nanocomposites was firstly studied by Kozako et al. in 2003 [81]. However, all of these studies and publications were inspired by Lewis in 1994 based on his paper entitled “Nanometric Dielectrics” [82]. Numerous papers have been published on their findings about the improvement given by nanocomposites in inhibiting the degradation processes in dielectric materials such as electrical and water treeing, partial discharge erosion, surface tracking, space charge and etc. Table 1 presents previous studies on PD resistance and electrical treeing in polymeric nanocomposites. Tree initiation voltage, tree breakdown voltage, tree initiation time and tree breakdown time were four parameters that have been used to investigate the effectiveness and capabilities of filler to suppress the growth of electrical treeing. Alapati et al. [83], Kurnianto et al. [84], Nagao et al. [85] and Iizuka et al. [86] found that epoxy resin with addition of silica nanofiller worked as physical barrier to retard the electrical tree growth and prolonged the tree initiation time. These results showed that the silica nanofiller could slow down and hinder the growth of electrical treeing. Besides that, Kawano et al. [87] and Tanaka et al. [88] also describe the presence of magnesium oxide nanofiller in LDPE greatly hindered electrical tree growth. They found that magnesium oxide nanofiller successful increased the tree breakdown time of LDPE. Besides, they interestingly observed that even small percentage of the magnesium oxide nanofiller suppressed electrical tree growth in the tree growth stage by 100µm. Pitsa et al. [89] discussed the potential of titanium oxide nanofiller in epoxy resin. By using simulation, they found that the tree length decrease when the nanofiller size was decreased and also increased the time for electrical tree growth to reach the ground electrode.

In addition, Guastavino et al. [90] discussed the potential of getting better tree inception voltage in LDPE-silica nanofiller. They reported that the tree inception voltage for pure LDPE was lower compared with LDPE- silica nanofiller. They also found that tree breakdown voltage for pure LDPE was lower than LDPE-Montmorillonite nanofiller indicating the effectiveness of nanofillers in retarding treeing. Furthermore, Guastavino et al. [91] reported that MMT was good nanofiller because it can retard the electrical tree growth better than silica nanofiller. A modified MMT, called organo-Montmorillonite (oMMT) nanoclay has been proposed by some researchers as nanofiller due to its good mechanical and thermal characteristics [92, 93]. However, the electrical characteristics of oMMT are yet better understood. The oMMT nanofillers are considered as improved-nanofiller that are modified organically to obtain desired degree of delamination of the individual silicate layers in the polymer matrix (intercalation or exfoliation) [94].

6.1. Role of Interface

Nanocomposites have shown to be very promising in electrical insulation science. This is because of the advantages they possessed. The main advantages of using the nano-sized filler is they provided larger surface area since the size of the particles become smaller. The surface area is related to interfacial region of filler and polymer. The surface interaction between polymer and nanoparticle becomes dominant and thereby the nanoparticle affects the electrical properties of the dielectric material. Interfaces between the polymer matrix and the filler are depicted in Figure 5 [95].

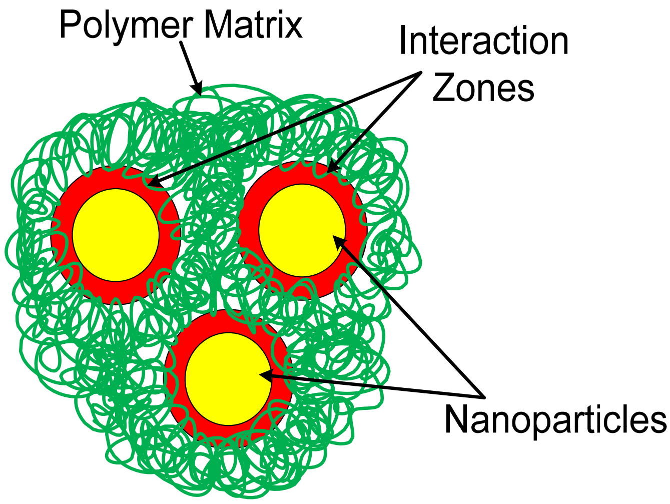

Figure 5. Diagram to Illustrate the Constituents of Polymer Nanocomposites [95]

The formation of large interaction zones as shown in Figure 5 could modify the polymer behavior, change the polymer morphology as well as reduce the internal field due to the reduction in size of the nanoparticles. Generally, the behavior of nanocomposite material is dominated by the properties of the interfaces of nanoparticles with its surrounding environment. This is because of the two forces (interatomic and intermolecular forces) that interact with the nanoparticles and polymer matrices.

The forces are important to the nanoparticles since they are varied in strength and behavior. These forces reflect the presence of bonds between the atoms and attraction or repulsion with neighboring particles (ion, atom, molecule), which are responsible for the stability [96]. In nanocomposites, the polymer chains are strongly attracted by the nanoparticle surfaces due to interatomic and intermolecular forces with high bond dissociation energy and thereby resulting in immobilized polymer interface [97].

6.2. The Role of Nanofiller on Partial Discharge Resistance and Electrical Treeing Inhibition

The term interphase is more appropriately known as a layer which forms around the filler particles rather than interface [104]. In this layer, the polymer chains are chemically and physically bounded to the nanoparticle surface. Based on Figure 6, it can be elucidated that the interface properties become increasingly dominant if the particle size has reduced or lessened. This is due to the increase in the number of surface area of the particles and the surface interaction between the host polymer and the nanoparticles. For the composite dielectric material, the first phase should be a particle with finite size and surrounded by a host material mostly polymer which possesses a layer of polymer chains with different morphology which result in the different bond types between particle surface and the polymer [101].

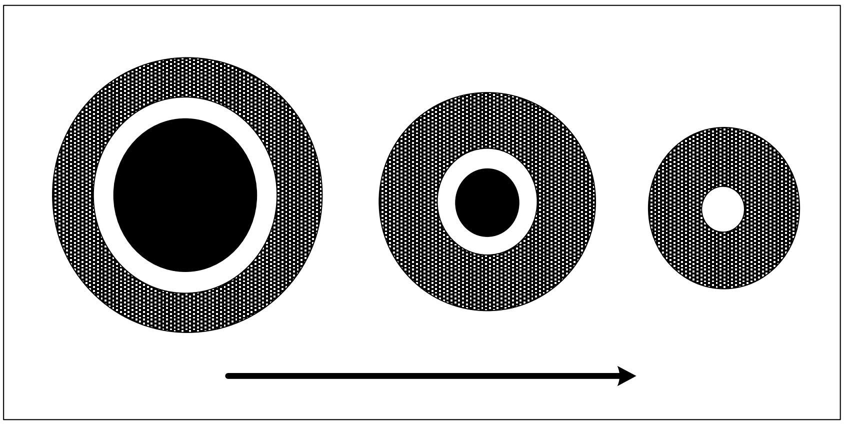

Figure 6. Nanofiller Interface Propertiesbecome more Dominant as the Particle Size Lessens [98]

A thorough explanation has been given by Tanaka in [104], and [105] regarding the interaction between tree mechanism and nanofillers. As discussed earlier, interfacial region plays a critical role in explaining its impact on dielectric properties of polymeric insulations. The addition of nanoparticles in polymer matrix changes some of its structural properties such as local charges, local conductivity distribution, free volume, charge mobility etcetera due to the increase in number of nanoparticle surface area. Thus, the interfacial region becomes very dominant because the size of filler has reduced in number.

Consequently, the density or depth of trap sites are changed and reduce the carrier mobility and energy. When the charge carriers are trapped more often, they are accelerated in shorter distances which lead to the reduction in the number of energy scattering. This would reduce the accumulated damage in the material thereby increasing the lifetime of the polymer. The carrier trapping and scattering mitigation of electric field at the electrode would increase the voltage required for charge injection and extraction resulting in the need for higher voltage to initiate the electrical treeing as longer time is required for charge build up. This charge build-up is the root cause of insulation breakdown.

The interaction between injected and extracted charge carriers (electron or hole) with the nanofiller can be more understood by referring to the Multi-core model proposed by Tanaka et al. [106]. The model is based on assumption of three layers (a bonded layer, a bound layer, and a loose layer [107] which is formed around the spherical inorganic nanoparticles. The first layer is referred to silane coupling layer. In this layer, the polymer and nanoparticle are tightly bonded by Silane Coupling Agent (SCA). The introduction of the SCA results in the surface treatment of nanoparticles. The thickness of the layer is approximately 1nm. Meanwhile, polymer chains are included in the bound layer (second layer) which is strongly bounded to the silane coupling layer. A stoichiometrical cross-linked layer is formed in this layer. It is assumed that the thickness of this layer is between 2nm and 9nm. The third layer is called a loose layer because this layer is loosely coupled with the second layer. It consists of different chain structure, chain mobility, free volume and crystallinity. The thickness of this layer is more than 10nm. The multi-core model is depicted in Figure 7.

Table 1. Literature on Nanofillers used in High Voltage Insulation System

Type Of Filler	Researcher	Base Material	Contribution/Finding
Silicon dioxide (SiO_2)	Kurnianto et al.[84]	Epoxy Resin	1. Filler particle would create an obstruction to the tree propagation. 2. Introduction of filler raised the fractal dimension due to the increase in number of branches.
	Alapati et al.[83]	Epoxy Resin	1. Tree initiation time (TIT) for pure epoxy resin was 6 hours but for epoxy nanocomposites was 10 hours. 2. Tree length less than 500µm at 1hours.
	Guastavino et al.[90]	Low Density Poly Ethylene (LDPE)	1. Tree inception voltage (TIV) of pure LDPE was 10.5 kV but TIV for LDPE nanocomposites was 13kV. 2. Tree breakdown voltage (TBV) of pure LDPE was 41.5 kV and LDPE nanocomposites was 36 kV.
	Nagao et al., [85], [99]	Epoxy Resin	1. Tree propagation in specimen without filler was faster than that with filler. Filler suppresses the tree propagation. 2. Tree growth was also influenced by filler shape. Round shape filler was most significant than rectangular shaped filler.
Montmorillonite (MMT)	Iizuka et al. [86]	Epoxy Resin	1. To obtain maximum tree breakdown time, realistic optimum size of nanofillers was around 10nm. 2. Tree breakdown time shortened due to cavities formed between filler as the size of filler was larger.
	Guastavino et al [90]	Low Density Poly Ethylene (LDPE)	1. Tree inception voltage (TIV) of pure LDPE was 10.5 kV but TIV for LDPE nanocomposites was 34.5kV. 2. Tree breakdown voltage (TBV) of pure LDPE was 41.5 kV and LDPE nanocomposites was 50kV.
	Guastavino et al [100]	Ethylene-Vinyl Acetate (EVA)	1. Tree inception voltage (TIV) of pure EVA was 14.1 kV but TIV for EVA nanocomposites was 19.8 kV. 2. Tree breakdown voltage (TBV) of pure EVA is 34.7 kV and EVA nanocomposites are 32.7 kV. 3. Tree breakdown time (TBT) for pure EVA was 6 hours and EVA nanocomposites was 9 hours
Magnesium oxide (MgO)	Kawano et al. [87]	Low Density Poly Ethylene (LDPE)	1. Tree initiation time (TIT) for pure LDPE was 3 minutes but for LDPE nanocomposite was 5 minutes. 2. Tree breakdown time (TBT) for pure LDPE was 5 minutes and LDPE nanocomposite was 7 minutes.
	Tanaka et al. [88]	Low Density Poly Ethylene (LDPE)	1. Even when nanofillers content was a low as 1 to 2 phr, nanofillers would suppress tree growth in the growth stage trees ranging several 100µm. 2. Tree breakdown time increases with the increase of nanofiller content up to 10 phr
Zinc oxide (ZnO)	Ding et al. [79]	Epoxy Resin	1. Time to breakdown increase and resistance to electric growth improves when Zinc Oxide added to epoxy resin. 2. Zinc Oxide nanofiller were far more resistive to treeing breakdown than that of microcomposites.
	Rashid et al. [101]	Polyester Resin	1. Zinc Oxide found very effective for stopping the growth of electrical trees. 2. Zinc Oxide virtually stopped the growth of electrical treeing when tree hit the barrier.
Aluminium oxide (Al_2O_3)	Li et al. [102]	Epoxy Resin	1. Tree breakdown time (TBT) for nano aluminum oxide mixed with epoxy resin is longest compared to pure epoxy resin and micro aluminum oxide mixed with epoxy resin.
	Alapati et al. [103]	Epoxy Resin	1. Addition small amount of aluminum oxide improved electrical treeing resistance. 2. The tree initiation time and tree growth resistance increased with increase in filler loading. 3. Form images of tree channel by using SEM; clearly show the presence of nanoparticles inside the tree channel. 4. Researchers confirmed by presence of nanoparticles inside the tree channel to be a possible reason for the increased treeing resistance of epoxy nanocomposites.
Titanium dioxide (TiO_2)	Pitsa et al. [89]	Epoxy Resin	1. By using simulation, researchers found that the tree length decreases if nanoparticles size decreases. 2. Consequently, electrical tree that initiates form the needle electrode cannot reach the opposite electrode and causes electric breakdown.

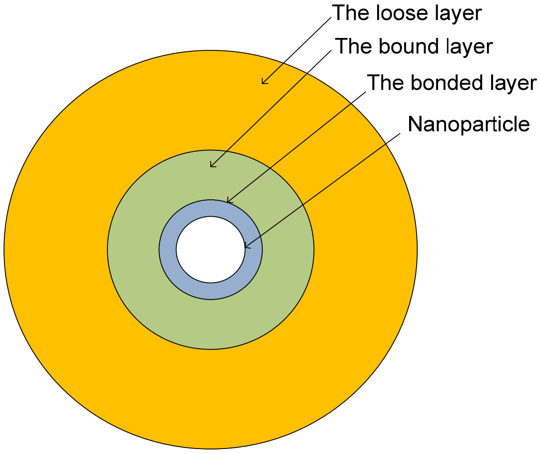

Figure 7. Tanaka's Multi-core or Multilayered Core Model which Represents Spherical-shaped Nanoparticle-polymer Interfaces [106]

Likewise, the presence of nanoparticle in polymer matrix helps to hinder the growth of electrical tree by acting as obstacle against the electrical tree propagation. Electrical tree propagation path is formed around the nanoparticles in the formed of zig-zag in which electrical tree propagates to the weaker region between adjacent nanoparticle and polymer matrix region. As aforementioned with regards to degradation of PD, electrons or holes are injected and extracted during the PD event. These electrons can be decelerated due to deep traps and shallow traps. The deep traps occur in first and second layers, whereas shallow traps occur in the third layer. If these traps catch negative charge or the nanoparticles are negatively charged, the electrons will be attracted to the interfaces of the nanoparticles thereby leading to charge trapping. On the other hand, if they catch positive charge or the nanoparticle is positively charged, electron will be repelled by the interfaces. Moreover, electrical tree must initiate and propagate towards the interfaces, but they will lose energy due to collision with the nanoparticles. This would result in the reduction of treeing since treeing is initiated by high energy electrons [105].

7. Discussions

The review on the overall perspective of electrical tree phenomena is such a huge task and does not fit this paper. So, the descriptions here are more to the various parameters affecting the electrical tree processes. However there is something quite important which the subject of electroluminescence (EL) is. EL is a phenomena occurring prior to the initiation of electrical tree.

Detection and measurement of PD and subsequently the propagation of electrical tree is rather remedial procedures because once trees have taken place, it is only a matter of time for the occurrence of insulation breakdown. On the contrary, the detection and measurement of EL is a preventative method for the prevention of electrical tree initiation. It has been accepted by many researchers that the intensity of light emission is affected by the amount of voltage applied on the polymeric material be it impulse, DC or AC. This is mainly because more charge carriers are being injected into the bulk of the polymer as applied voltage is increased, thus increases the recombination of holes and electrons injected during each positive and negative half cycle, leading to higher EL intensity.

In the presence of water, if a polymeric insulating material is subjected to high electric fields, a water tree may occur. Water tree often becomes a starting point of electrical tree. Muramoto et al. [108] found that the dried water-treed XLPE can enhance the EL properties of the material. That is because of the existence of micro-voids in the region of water tree which could accelerate the hot electrons to the higher energy. These hot electrons collide with the polymer chains and scissor the polymer bond. Therefore, the degradation region exists due to these electron bombardments [12].

With regards to statistical analysis of electrical treeing, the use of distributions that fit well with the treeing parameters should not be confined to only the breakdown data but also fitting the data such as inception process, channels expansion and distribution, tree elongations and dielectric breakdown data. Therefore, other types of statistical distribution should be integrated to produce more suitable results such as work conducted by by Ahmad et al. [70], [71]. Electrical models like the Discharge-Avalanche Model (DAM) proposed by Dissado basically using electronic theory to describe the mechanism of tree propagation. Cooray in his book, “The Lightning Flash” uses the theory of gas breakdown to explain the formation of lightning flash in atmosphere [109], Therefore a pseudo-solid breakdown theory can be used to explain the mystery of the tree initiation, propagation and subsequently breakdown. The basic characterisation of tree inhibition is the material should have the following characteristic; the electrons pushing the elongation of tree channel should be attracted to the physical body of the fillers. This is somewhat similar to SF_6 gas which is used as insulation for high voltage apparatus like gas insulated switchgear (GIS). In the gaseous media electronegative gas can attract electrons to itself [110]. The same phenomenon, electron avalanche, is happening in gaseous media, responsible for the occurrence of gas breakdown.

8. Conclusion

This paper has presented an overview on the electrical treeing in solid polymeric insulation concentrating on the factors that influence the its growth and initiation, statistical and electronic models to describe and characterize treeing mechanisms as well as recent studies on the use of nanofillers to suppress treeing. Two main phases of electrical tree processes generally agreed by researchers are initiation and propagation stages. With regards to statistical models, although Weibull and lognormal distributions have been the most widely used and accepted models for estimating electrical treeing parameters, recent studies have shown carried out on some polymeric insulating materials have shown Johnson SB model to fit better the treeing data compared to Weibull and lognormal model. Therefore there is need to further carry out studies on more statistical models to best fit the treeing data for estimation of treeing data as well as prediction of insulation lifetime. With regards to the electrical models, FDTG is more applicable than DBM and DAM since it could predict the insulation lifetime. However the model that incorporates electronic flow dynamics in materials will be more appropriate for material analysis and modeling.

Moreover, interfacial region plays a dominant role in the improvement of dielectric properties of polymer nanocomposite. When the size of particle shrinks, the surface area of the particle becomes larger and thereby would create more interactions between the nanoparticle and the polymer region. Such interaction would alter the polymer structure, chain mobility and etcetera. Thus, it helps to improve the electrical properties and enhance the PD and electrical tree resistances. As discussed in this paper, the electron injection and extraction are among the reasons for electrical tree formation. With the presence of nanoparticle in polymer matrix, it helps to reduce the electron mobility by altering the depth and the density of charge traps. Moreover, charge carriers are blocked at the interfacial region between the nanoparticle and polymer region as well. Nevertheless, various improvements of dielectric properties have been presented in this paper. It is better to point out the effect of agglomeration in this conclusion. The agglomeration in large size would introduce the defects that could attract the field enhancement to the agglomerated particles and thereby would result in reduction of breakdown strength of the composite material. Likewise, the tactoid acts as a weak point which could induce a destructive process and thereby leading to the weaker mechanical, electrical, chemical and thermal properties. The agglomeration can be reduced by proper nanocomposite preparation by using high shear force mixer and ultrasonic mixer.

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