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# Statistical Analysis of Partial Discharge during Electrical Tree in Silicone Rubber Nanocomposites under Elevated Temperature

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Additional information is available at the end of the chapter

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## Abstract

The electric fields at the cable accessories such as jointing and termination are not uniform due to the nonuniformity structures of the accessories. Thus, it has attracted the formation of the electrical tree inside the cable accessory that is commonly made from silicone rubber. Also, the location of the cable that is exposed to the high temperature level gives severe effect to the electrical performance of the insulation. Recently, the inclusion of nanoparticles into the cable insulation has resulted in a promising outcome by resisting the discharge phenomenon such as treeing. However, the study on partial discharge during electrical trees grown in silicone rubber nanocomposites under elevated temperature is scarce including the statistical analysis of the partial discharge mechanisms. Therefore, this chapter is aiming to analyze the statistical behaviors of partial discharge during electrical tree growth in silicone rubber nanocomposites under the effect of temperature.

**Keywords:** partial discharge, electrical treeing, nanocomposites, statistics, temperature

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## 1. Introduction

Nanocomposite materials have been found to be more durable than conventional composites when subjected to high-voltage stresses due to superior thermal, mechanical, and electrical properties. Nanocomposites are defined as composites with very small amounts of homogeneously dispersed nanoparticles added to the matrix by several weight percentage (wt%). Also, the nanoparticles added to the matrix are normally less than 10 wt% in quantity. It has been found that the inclusion of nanoparticles in polymeric insulation may effectively reduce the accumulation of space charge, surface tracking, partial discharges (PD), water treeing, and

electrical treeing thereby increasing the lifespan of the insulation. Andritsch et al. [1] reported that the space charge density has been reduced by adding the Magnesia (MgO) nanoparticles to the epoxy resin matrix. Also, Bamji et al. [2] reported that the amount of injected charge in polypropylene with 2 wt% and 4 wt% organoclay was less than that found in pure polypropylene after 500 hours of aging.

A study on an epoxy resin-based nanocomposite material found that partial discharge (PD) magnitudes and PD numbers were lower than that for the unfilled epoxy resin [3]. Alumina ( $\text{Al}_2\text{O}_3$ ) nanofiller have also been shown to improve the surface discharge degradation resistance of epoxy resin [4]. Guastavino et al. [5] reported that the inclusion of 5 wt% Montmorillonite (MMT) has increased the breakdown time four times longer than the breakdown time of pure low-density polyethylene (LDPE). In another study by Sridhar and Joy Thomas [6], the inclusion of 1 and 3 wt% of silica ( $\text{SiO}_2$ ) nanofillers in polyethylene (PE) has improved the tree growth resistance and increased the electrical tree inception voltage.

The inclusion of small amounts of nanofillers to a polymer matrix has resulted in significant improvement of the electrical properties of the nanocomposites. The nano-sized particles have larger specific surface area per unit volume compared with the conventional microfillers. Also, the inclusion of nanoparticles into the polymer matrix would introduce the region so-called interaction zones at the interface between the nanoparticles and the host polymer. This interaction view has led to the development of many physical models of the interface regions. One of the models is proposed by Tanaka et al. [7] namely multi-core model to account for the observed nanocomposite behavior. Moreover, the methodology used to uniformly disperse the nanoparticles is considered very important by researchers to achieve the best results.

Furthermore, XLPE has been used widely in insulation cable to cover the voltage levels ranged from 10 to 100 kV and thus the involvement of cable joints and terminals could not be neglected. These accessories are considered as weak points that may contain voids, impurities, defects, protrusions, and so on; all of which may induce an electrical tree. One of the accessories is a stress cone that is commonly made from silicone rubber [8]. In addition, the cable operating temperature can reach up to 90°C, but the usual rated temperature is within 50–60°C [9]. Thus, the performance of insulation at high temperature is important from practical viewpoint because the failure of cable joints has relationship with the temperature due to changes of soil temperature and the presence of hotspot caused by aging process [10]. Furthermore, the high temperature affects the growth of electrical tree in Polyethylene (PE), Ethylene-vinyl Acetate (EVA), High Temperature Vulcanization (HTV), and Room Temperature Vulcanization (RTV) silicone rubbers.

However, the effects of temperature on electrical tree and relevant PD in nanocomposite materials are not discussed thoroughly and the publications on the topics are scarce. Thus, the effect of temperature on inception and propagation of electrical trees in silicone rubber-based nanocomposites was examined in this study. This study was performed because it is believed that despite the overwhelming influence of temperature on electrical tree-associated PD occurrences in silicone rubber/nanoclay nanocomposites, only a few studies have been published in relation with statistical analysis thus requiring the statistical analysis of PD during electrical tree growth in nanocomposites. Besides, the temperatures of the experiment

varied from 20°C to 60°C, which lies within the rated operating temperature of most insulated power cables; thus emphasizing the importance of this study as most of the cables have been reported to be operated within 50–60°C [9–11]. Subsequently, statistical analyses of PDs during the electrical tree growth under AC applied voltages as well as under the different temperature conditions were being comprehensively characterized in this chapter.

## 2. Statistical analysis of PD events

The PD data was analyzed statistically in order to interpret the relationship between the statistical approach and the physical parameters of PD events during the electrical tree growth. Thus, the pulse magnitude distributions  $H_n(q)$  and pulse count distribution  $H_n(\varphi)$  were considered for the analysis. In the case of  $H_n(q)$  and  $H_n(\varphi)$ , both positive and negative discharge characteristics can be determined and analyzed with four statistical moments that were calculated for each of the distributions.

In general, motivating factor that necessitated the use of conventional statistical tools for the PD analysis was based on the study done by Dodd et al. [12] and Gulski [13]. The difference is that different materials are used; while Dodd et al. [12] and Gulski [13] studied PD activities during electrical tree growth in flexible epoxy resin and PE, respectively, but this study is on the PD activities during tree growth in neat silicone rubber and silicone rubber-based nanocomposites. Thus, different materials would be expected to result in different PD characteristics with PD resistance capability that is expected in silicone rubber-based nanocomposites material.

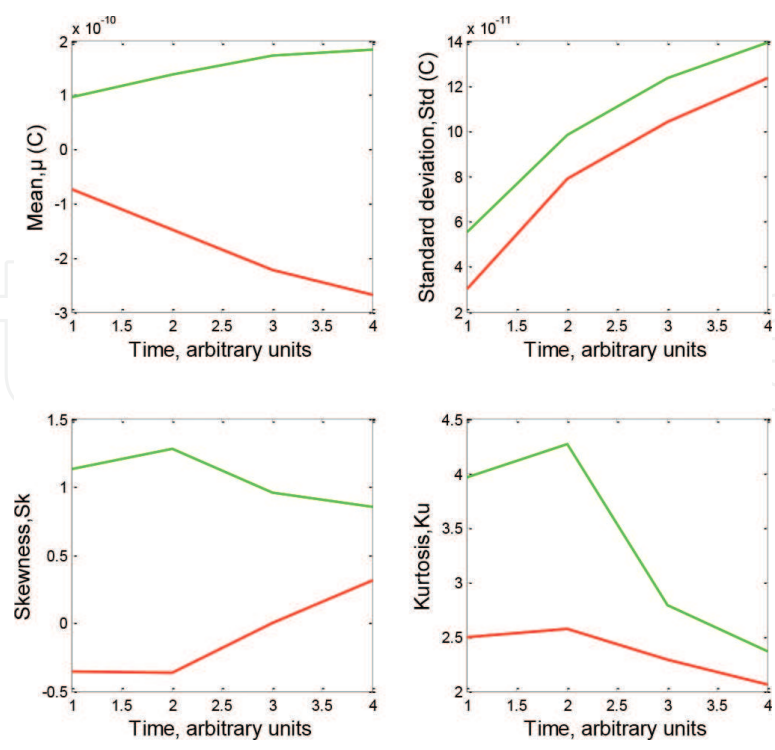
The analysis of the recorded PDs data in this study was accomplished using MATLAB software. In addition, the power that dissipated in the sample during the PD activity was also calculated based on the following formula [14, 15]:

$$P = \frac{1}{\Delta t} \sum_{i=1}^N V_i q_i \quad (1)$$

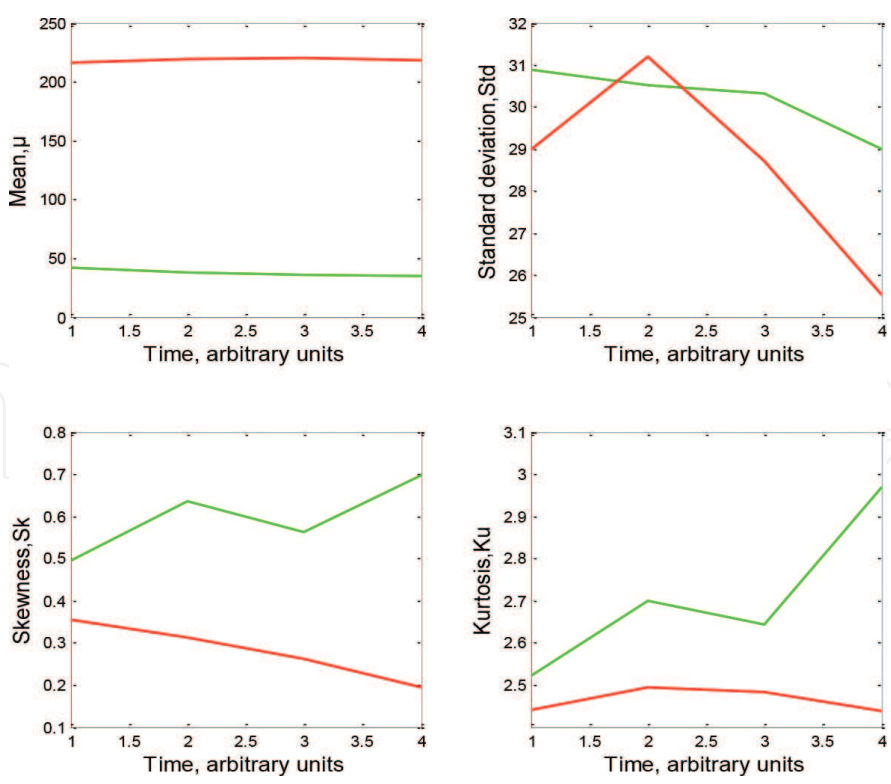
where  $\Delta t$  is acquisition time that equals to one second,  $V_i$  is the instantaneous voltage at which the  $i$ th PD event occurs with a magnitude,  $q_i$  and  $N$  are the total number of PD events in the one second of interval.

### 2.1. Analysis of PD for neat silicone rubber at temperature of 20°C, 40°C, and 60°C

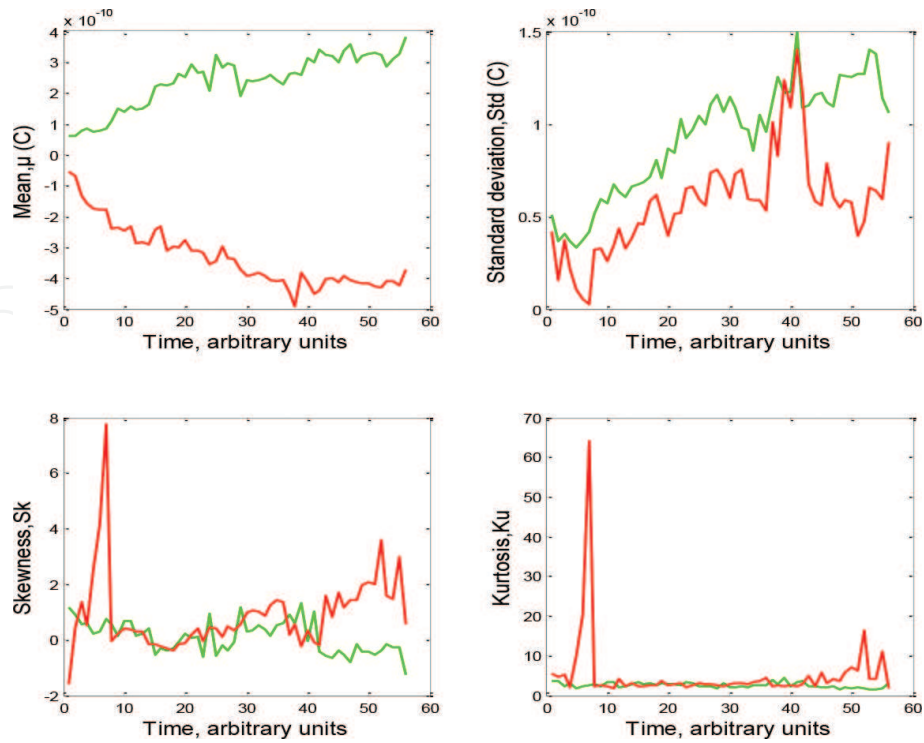
The four statistical moments, such as mean, standard deviation, skewness, and kurtosis, were computed to get the extension analysis of PDs data. The physical parameters such as average phase of occurrence, number of discharge per second, and positive and negative PD amplitudes per second of data record were also computed. The statistical moments of the pulse magnitude distributions,  $H_n(q)$  and pulse count distributions,  $H_n(\varphi)$  characterization as a function of time of neat silicone rubber tested at temperature of 20°C, 40°C, and 60°C are illustrated in **Figures 1–6**, respectively, whereas the physical parameters as a function of time of neat silicone rubber tested at 20°C, 40°C, and 60°C are depicted in **Figures 7–9** respectively.



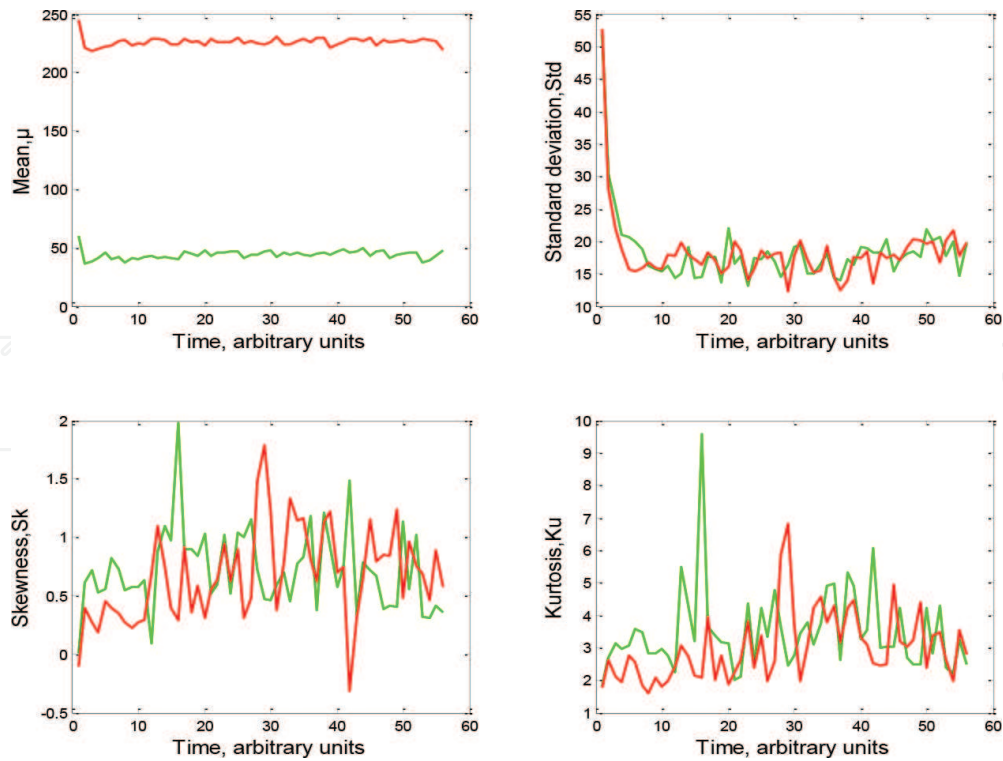
**Figure 1.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in neat silicone rubber at 20°C. Green solid line = positive PD and red solid line = negative PD.



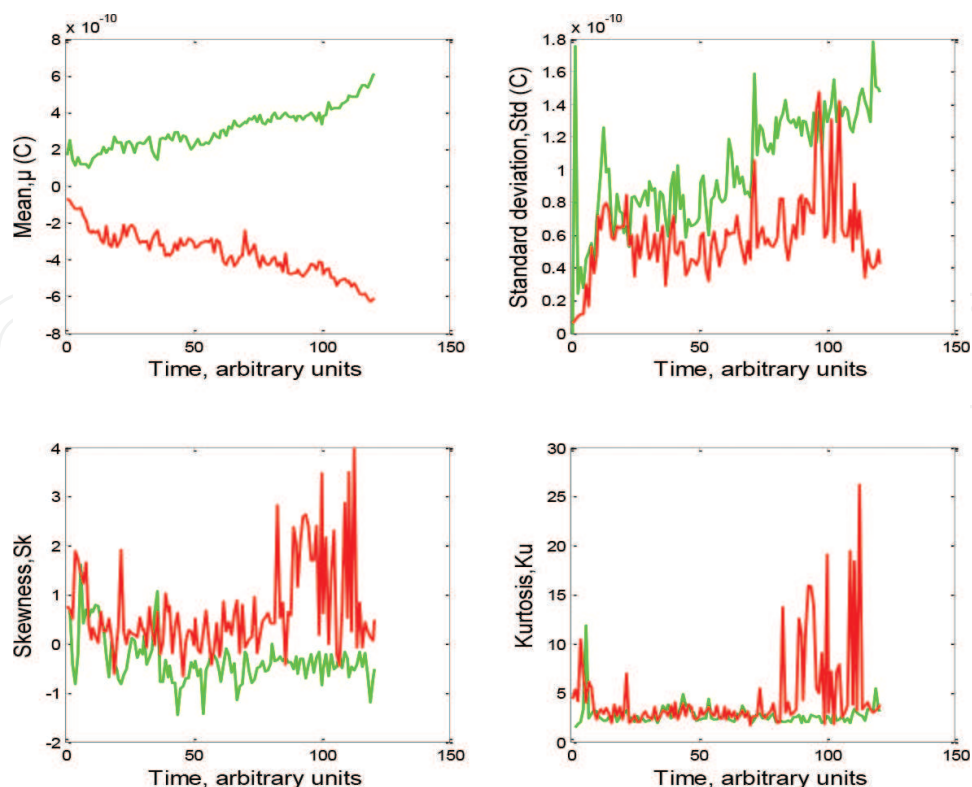
**Figure 2.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\varphi)$ , as a function of time obtained from PDs during tree growth in neat silicone rubber at 20°C. Green solid line = positive PD and red solid line = negative PD.



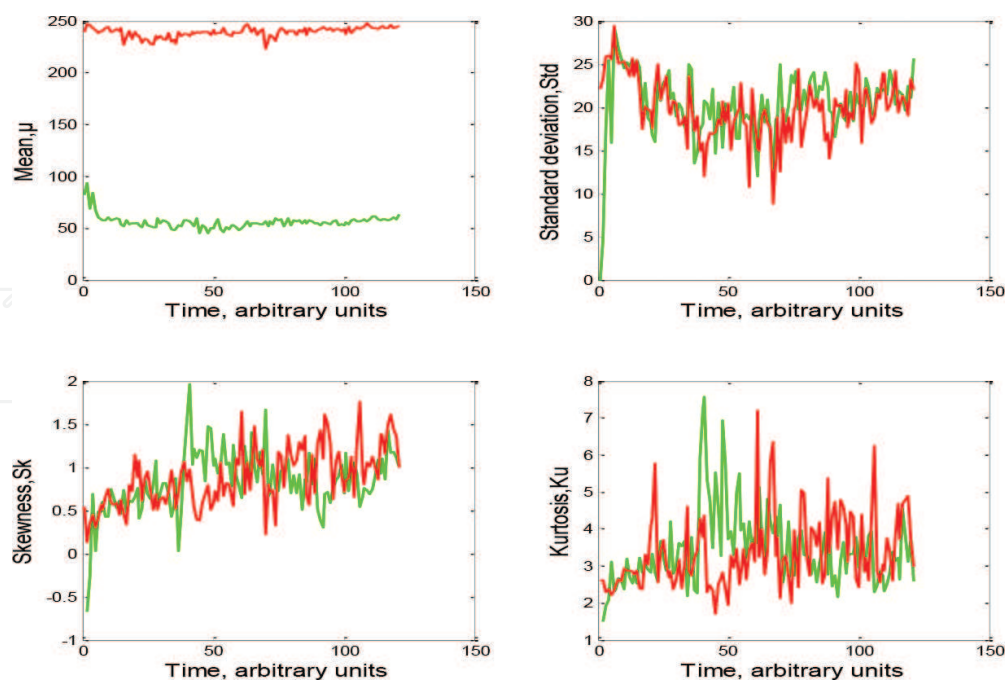
**Figure 3.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in neat silicone rubber at 40°C. Green solid line = positive PD and red solid line = negative PD.



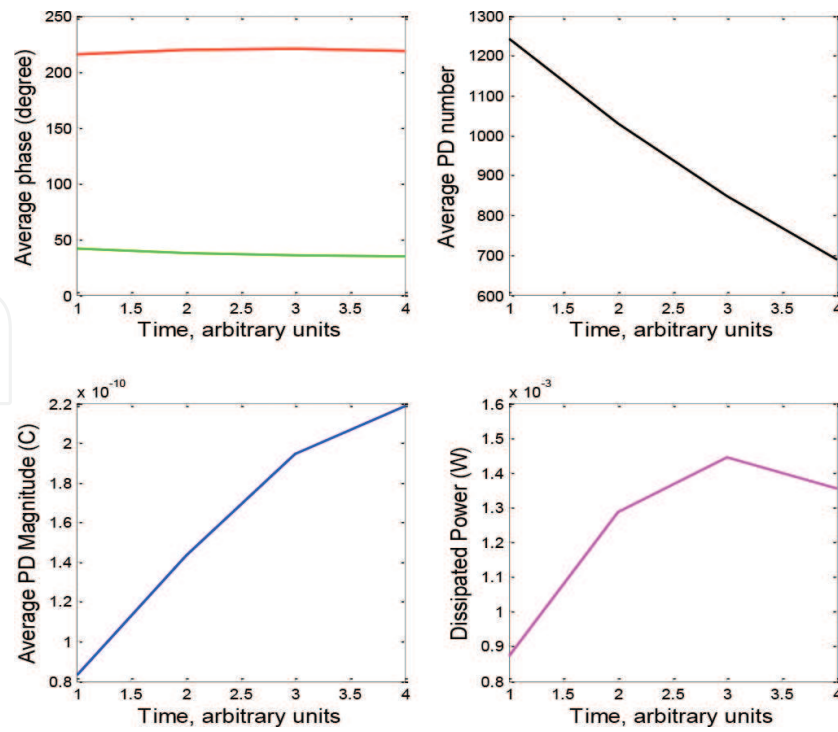
**Figure 4.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\varphi)$ , as a function of time obtained from PDs during tree growth in neat silicone rubber at 40°C. Green solid line = positive PD and red solid line = negative PD.



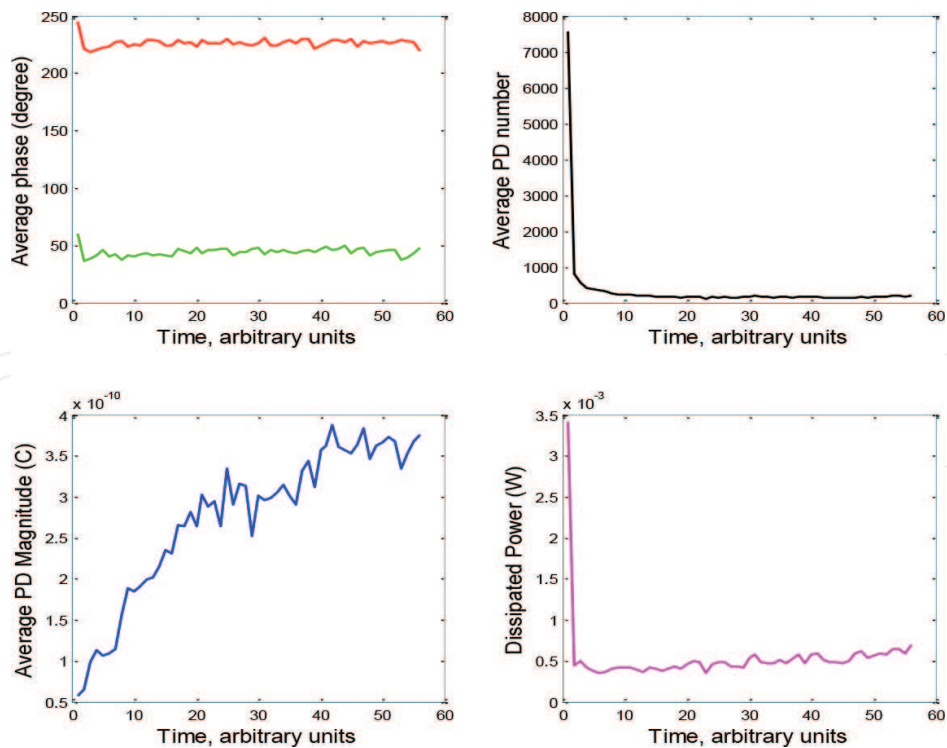
**Figure 5.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in neat silicone rubber at 60°C. Green solid line = positive PD and red solid line = negative PD.



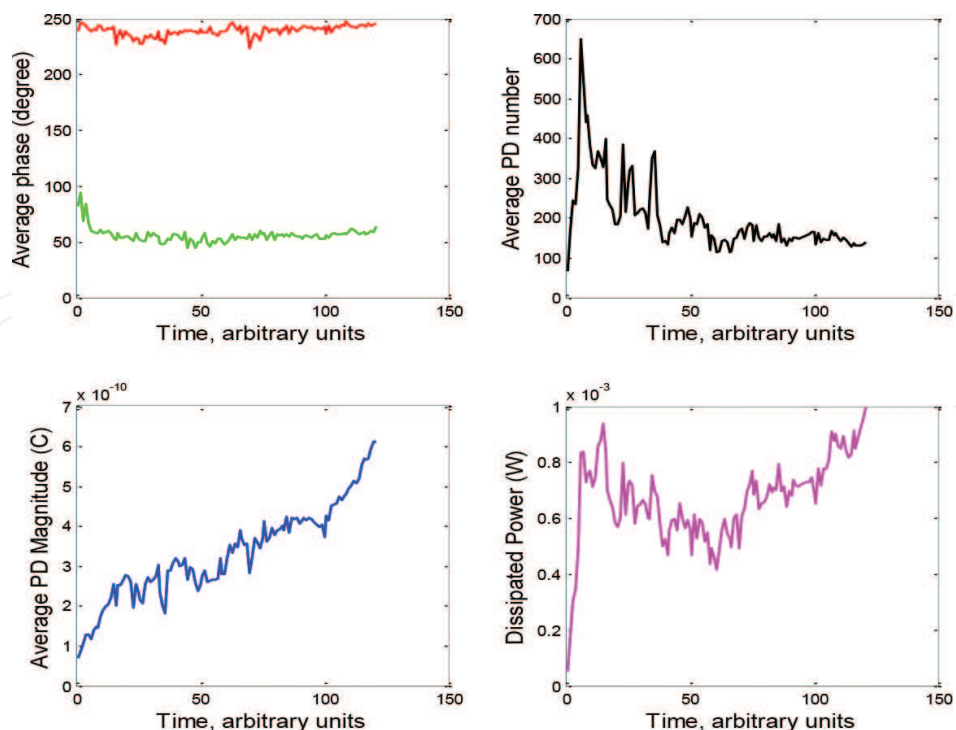
**Figure 6.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\varphi)$ , as a function of time obtained from PDs during tree growth in neat silicone rubber at 60°C. Green solid line = positive PD and red solid line = negative PD.



**Figure 7.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of times obtained from PDs during tree growth in neat silicone rubber at 20°C. Green solid line = positive PD and red solid line = negative PD.



**Figure 8.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of time obtained from PDs during tree growth in neat silicone rubber at 40°C. Green solid line = positive PD and red solid line = negative PD.



**Figure 9.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of time obtained from PDs during tree growth in neat silicone rubber at 60°C. Green solid line = positive PD and red solid line = negative PD.

PD during electrical tree growth in neat silicone rubber at temperature of 20°C, 40°C, and 60°C with 10 kV<sub>rms</sub> was subjected to the test samples at relative humidity of 45 ± 10%, and they were also subjected to statistical analyses. According to the published literatures, moisture is one of the factors that would weaken the interface between nanofiller and polymer, leading to the easier splitting of the interface. The moisture could hardly be absorbed into the filler compared with the polymer [16, 17]. In fact, a relative humidity of about 75% around the polymer seems to be necessary for the electrical tree generation [18]. Thus, in this study, we fixed the relative humidity in the range of 35–55%, which is considered low to weaken the interfacial adhesion and influence the growth of treeing. The tree growth time was depicted in arbitrary unit of time. The actual time of the entire tree growth was 80 seconds, thus the unit of time illustrated in **Figure 1** will have to be multiplied by 20 seconds. From **Figure 1**, the mean values of positive PD and negative PD magnitude distributions,  $H_n(q)$ , were increased with time during the tree growth. The standard deviations of positive and negative PDs were found to increase as well with the increase of growth time. The increase of PD magnitude was related to the increase of tree length in distance, indicating that the PD magnitude and electrical tree length are relative as PDs can propagate in the main body of electrical tree structure [19]. On the other hand, the skewness of positive PD decreases and the skewness of the negative PD increases from negative to positive values over time. Skewness and kurtosis are commonly used to describe the dispersion and shape of PD distribution. The positive skewness indicates the higher PD magnitude and PD repetition at lower phase angles, whereas the negative skewness indicates the PD with higher magnitudes and higher repetition rate at the higher phase angles. It seems that the PD distribution with negative skewness occurs at higher AC

voltage, whereas the PD distribution with positive skewness occurs at lower voltage. Thus, the PD distribution with positive skewness gives more severe effect due to greater space charge activities on the wall of the electrical treeing. In addition, positive kurtosis ( $Ku > 3$ ) describes that the PD has sharpened the distribution, whereas the  $Ku < 3$  indicates that the PD distribution was flattened. However, the kurtoses of positive and negative PDs were found to be decreased over time due to enhancement of PD repetition activities. These variations of skewness and kurtosis have indicated that the distribution is skewed.

**Figure 2** shows the pulse count distribution,  $H_n(\varphi)$ , with statistical moments. It shows that the mean phase of occurrences of positive PDs have occurred between  $34^\circ$  and  $41^\circ$ , whereas the mean phase occurrences of negative PDs have occurred between  $215^\circ$  and  $220^\circ$ . However, it is difficult to determine the burst behavior from the phase shift since the shifts are quite low in values and close to each other. Meanwhile, the other three statistical moments varied in function of time.

Similar variations of the statistical moments were found in the sample of neat silicone rubber at  $40^\circ\text{C}$ . Mean and standard deviation of positive and negative PD magnitudes increased over time. This indicated that the positive and negative PD magnitudes have increased with the increase of tree length. It was noticed that the values of positive and negative PD magnitudes were doubled with quite similar standard deviation compared with previous sample. The skewness and kurtosis were found to fluctuate over the times that indicated the skewed properties. The results can be graphically viewed in **Figure 3**. The abrupt changes of PD magnitudes that are called as bursts were noticed during the fluctuations of PDs distribution. This implied that the space charge activity became greater during bursts in the PD events [20]. However, the PD times were longer in this condition compared with the previous condition of temperature,  $20^\circ\text{C}$ .

In **Figure 4**, the statistical moments of pulse count distributions,  $H_n(\varphi)$ , were considered. The mean of positive PD phase occurrence occurred from  $36^\circ$  to  $60^\circ$  within the first quadrant of positive half-cycle of AC applied voltage, whereas the mean phase of occurrence of negative PDs occurred within the range of  $218^\circ$ – $244^\circ$ , within the third quadrant of negative half-cycle of AC applied voltage. Moreover, the standard deviation, skewness, and kurtosis of the positive and negative PDs showed fluctuations and variations over the times.

Meanwhile, **Figure 5** presents the statistical moments of PDs data obtained during the tree growth in neat silicone rubber at  $60^\circ\text{C}$ . The mean and standard deviation magnitudes of positive and negative PDs increased significantly, whereas the positive and negative PD magnitudes seem to be symmetrical. It was noticed that there are bursts of PD that indicate the rapid tree growth with reproducible behavior. The skewness and kurtosis were regularly fluctuating over time of tree growth. For comparison between PD characteristics in neat silicone rubber at  $40^\circ\text{C}$  and  $60^\circ\text{C}$ , the mean PD magnitude with its corresponding standard deviation of neat silicone rubber at  $60^\circ\text{C}$  were greater than PD magnitude of neat silicone rubber at  $40^\circ\text{C}$ . This can be elucidated that more charges are trapped at post-cure temperature of  $60^\circ\text{C}$  due to increase in number of crosslink networks. The other two parameters (skewness and kurtosis) seem to vary positively for negative PDs, whereas the skewness and kurtosis for positive PDs behave more negatively throughout the experimental time. These behaviors would give different pulse height distribution location and shape characteristics.

$H_n(\varphi)$  distributions presented in **Figure 6** denote that the average phase of occurrence of positive PDs had occurred within the values of  $44^\circ$ – $93^\circ$ , which indicated the first and second quadrants of positive cycle of AC applied voltage. Meanwhile, the average phase of occurrence of negative PD occurred at the third quadrant of negative cycle of AC applied voltage with the range of  $223^\circ$ – $247^\circ$ . The average phases of PDs occurrence fluctuated between the two levels. The first level is related to the periods between the bursts of the tree growth, whereas the second level is indicative of where the discharges occur during the bursts period when the average phase shifts to the lower value (14). These levels are noticed in **Figure 6**.

The average discharge magnitude, the average number of PDs per second, and the average phases of occurrence of positive and negative PDs were chosen as indicators of the PD activity. The average partial discharge magnitude was calculated as the average of the absolute value of all individual PD magnitudes, both positive and negative, recorded over the entire tree growth. The average number of PDs per second was calculated as the arithmetic means of all individual 1s data acquisition intervals during the entire tree growth phenomenon. Also, the average phases of occurrence of positive and negative PDs were calculated from the entire PD activities. Additionally, power dissipated in the sample due to PD was also considered. These five physical parameters of PDs during tree growth in neat silicone rubber at temperature of  $20^\circ\text{C}$ ,  $40^\circ\text{C}$ , and  $60^\circ\text{C}$  are depicted in **Figures 7–9**, respectively.

Based on **Figure 7**, the mean value of positive and negative PD phases was calculated and found to be equal to  $37^\circ$  and  $218^\circ$ , respectively. Meanwhile, the average total PD numbers that underlie within the values of 687–1244 with the mean value 952. The total PD magnitudes were found to be in the range of 83–218 pC with the mean value equal to 160 pC. For the dissipated power in the sample, the values were between 0.873 and 1.40 mW with the mean value equal to 1.24 mW. It is quite difficult to identify the phase shifts from the given figure since the phases occurred very close to each other but based on the discharge magnitudes, it can be seen that the PD magnitudes have increased linearly, which denote the increased growth of electrical tree length. However, the PD numbers have reduced over time since the bigger number of PDs has occurred at the initiation stage of electrical tree growth.

**Figure 8** presents the graphical description of the five statistical parameters of PD activity in neat silicone rubber at a temperature of  $40^\circ\text{C}$ . The average phase of positive PD value was found to be equal to  $44^\circ$ , whereas average negative PD phase was equal to  $226^\circ$ . The average total PD numbers have the values between 117 and 7571, thereby the mean value is equal to 199. For average PDs, the discharge magnitudes have the values varied from 57 to 387 pC, which results in the mean value of 280 pC. Moreover, the abrupt phase shifts occurred in the beginning of tree growth with a sharp decrease in both positive and negative PD phases. Interestingly, a similar situation was observed in PD number and dissipated power plots, which have the sudden reduction of discharge number and dissipated power. Meanwhile, the discharge magnitudes increased over times, which thereby indicated the growth of electrical tree toward the ground electrode.

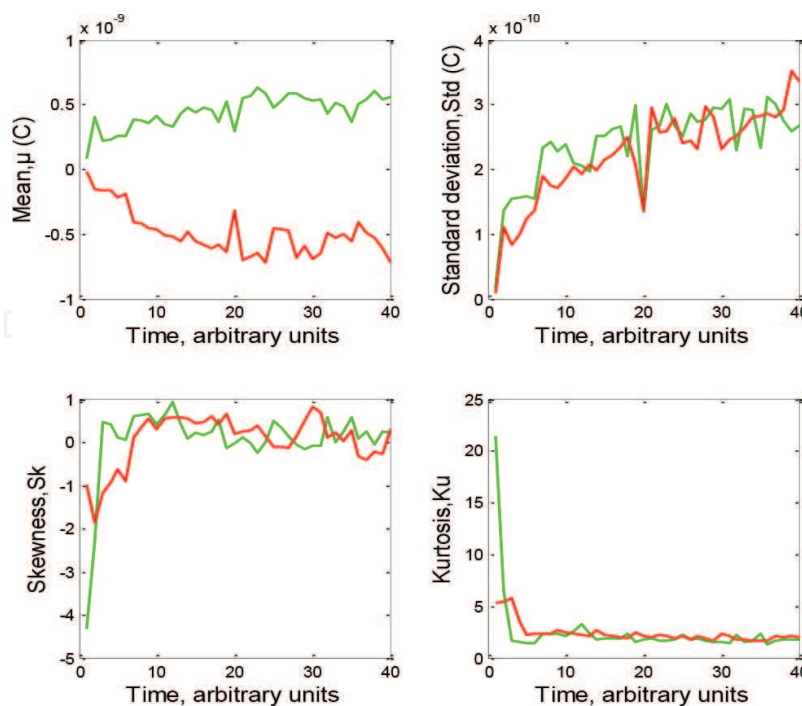
For an electrical tree grown in neat silicone rubber at  $60^\circ\text{C}$ , the corresponding plots are depicted in **Figure 9**, where it shows that the average phases of positive PDs and negative PDs are equal to  $55^\circ$  and  $239^\circ$ , respectively. Gradual phase shifts were observed for this sample. In the case of PD number, the average total PD numbers were between 65 and 649 with the mean

value 197. In addition, the average PD magnitudes were obtained within the range of 70–610 pC, and the mean value was equal to 332 pC. Meanwhile, the dissipated powers fluctuated from 51.42 to 997.4  $\mu\text{W}$  with resulting mean value of 668  $\mu\text{W}$ . The reproducible abrupt phase shifts were noticed in the dissipated at silicone rubber at temperature of 2 power plot and also in the corresponding plot of the PD number that indicated the significant increase in the number of PD during the bursts. These bursts can be related to the rapid increase in the radial extension of the tree at the inception stage as discussed before. It was noticed as well that the increased magnitudes of discharges became bigger as tree channels grew in length toward the ground electrode.

## 2.2. Analysis of PD for silicone rubber-based nanocomposite (1 wt%) at temperatures of 20°C, 40°C, and 60°C

The statistical analysis was continued for the case of silicone rubber-based nanocomposite with an addition of 1 wt% nanoclay nanofillers at temperatures of 20°C, 40°C, and 60°C. The environmental relative humidity during the test was measured and was found to have the value of  $45 \pm 10\%$ .

The statistical moments are computed and shown graphically in **Figure 10**. The mean positive and negative PD amplitude distributions,  $H_n(q)$  fluctuated from 0 to more than 500 pC with corresponding increase in standard deviation that deviated from 0 to 400 pC over time. Some regular bursts of PD activity were noticed in which the PD magnitudes increased abruptly. The skewness and kurtosis have regular fluctuations with the skewness having negative value



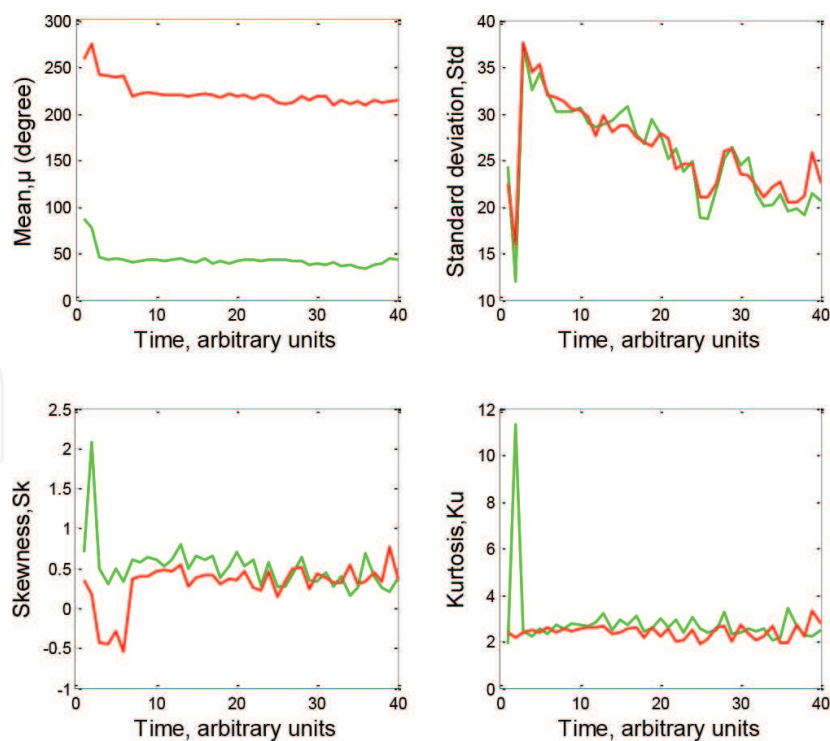
**Figure 10.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (1 wt%) at 20°C. Green solid line = positive PD and red solid line = negative PD.

( $Sk < 0$ ), which indicated the left-skewed properties, while, the kurtosis that had values more than 3 ( $Ku > 3$ ) indicated that the PD magnitude distributions have stronger peak.

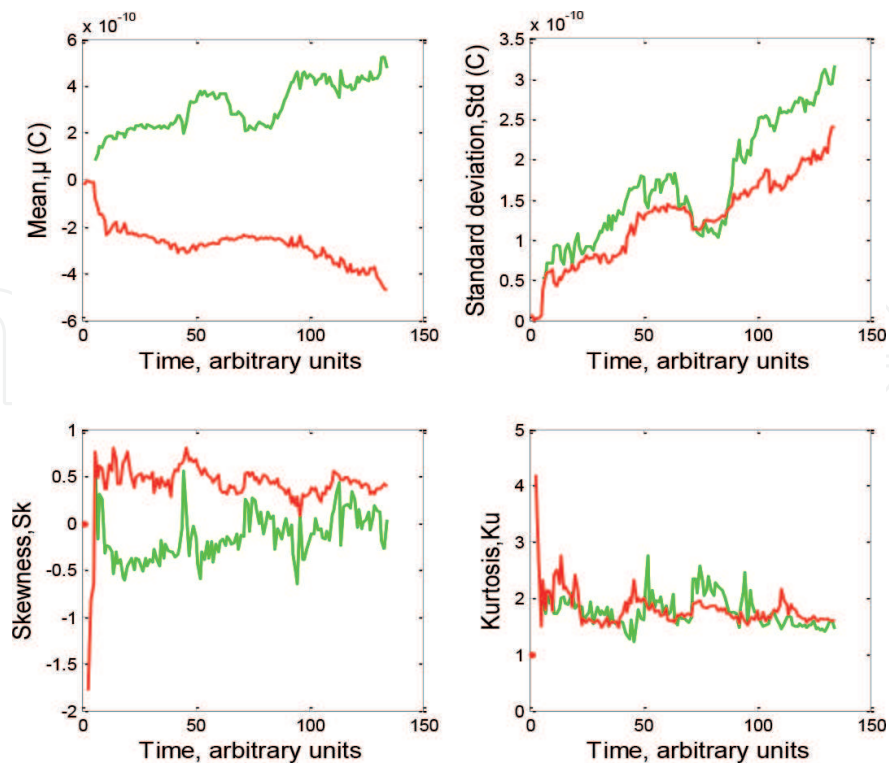
The pulse count distributions,  $H_n(\varphi)$ , are depicted in **Figure 11**. It shows that the mean phases of occurrence of positive PDs occurred between  $33^\circ$  and  $86^\circ$ , which proves that the positive PDs occurred in the first quadrant of positive half-cycle of AC voltage. Meanwhile, the mean phases of occurrence of negative PDs had the values between  $209^\circ$  and  $275^\circ$  thereby denoting that the negative PDs occurred during the third and the forth quadrant of negative half-cycle of AC voltage. Some regular phase shifts were observed from the figure, and it was also noticed that these statistical moments increased during the beginning of PDs, and after a certain period, their values had decreased over time until the last PD.

In case of PDs during tree growth in silicone rubber-based nanocomposite with 1 wt% nano-clay nanofiller under temperature of  $40^\circ\text{C}$ , the mean positive and negative PD magnitude distributions,  $H_n(q)$ , standard deviation, skewness, and kurtosis are shown in **Figure 12**. The mean PD magnitude distributions fluctuated regularly with some repeated bursts that implied the rapid propagation of electrical tree. The skewness varied between negative and positive values, which showed left and right skewness and kurtosis were found to have values  $< 3$ . Thus, the PDs magnitude distribution flattened.

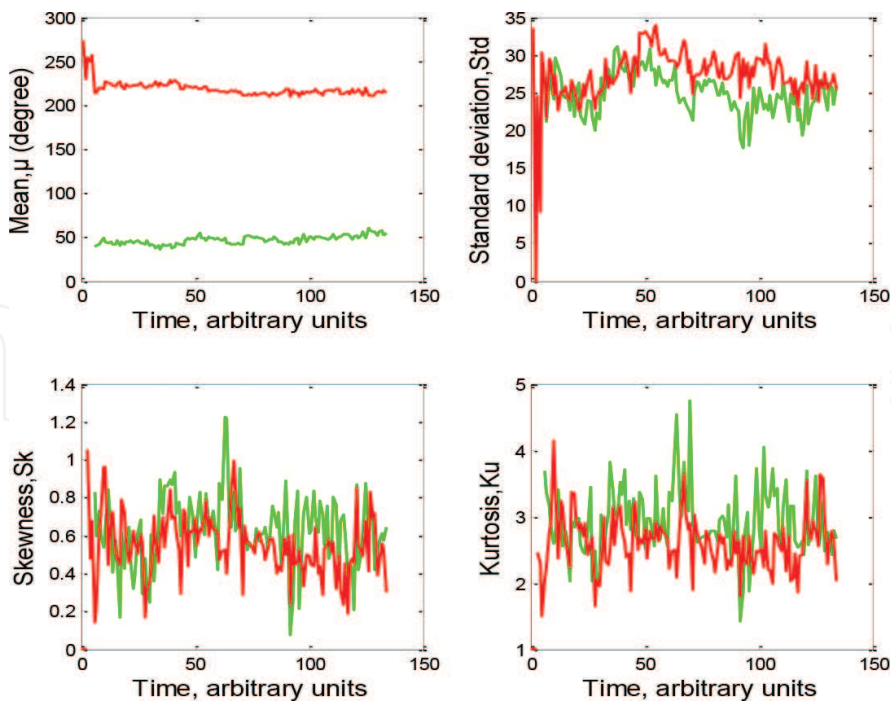
The pulse count distribution,  $H_n(\varphi)$  is depicted in **Figure 13**. For mean phase of occurrence of positive PDs, the minimum and maximum values are  $36^\circ$  and  $61^\circ$ , respectively. This implies that the PDs occurred at the first quadrant of positive half-cycle of AC voltage. Meanwhile, the mean



**Figure 11.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\varphi)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (1 wt%) at  $20^\circ\text{C}$ . Green solid line = positive PD and red solid line = negative PD.



**Figure 12.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (1 wt%) at 40°C. Green solid line = positive PD and red solid line = negative PD.

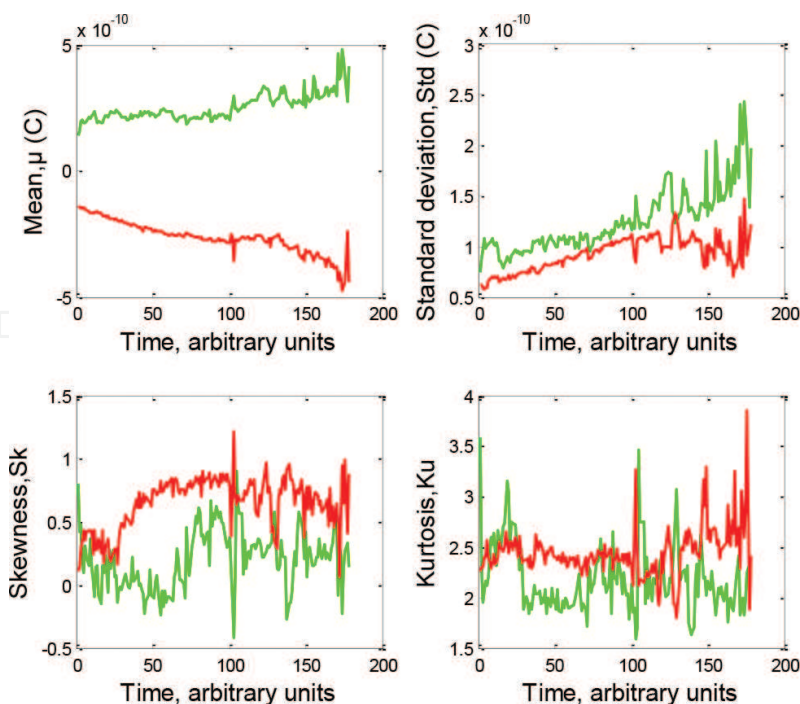


**Figure 13.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\varphi)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (1 wt%) at 40°C. Green solid line = positive PD and red solid line = negative PD.

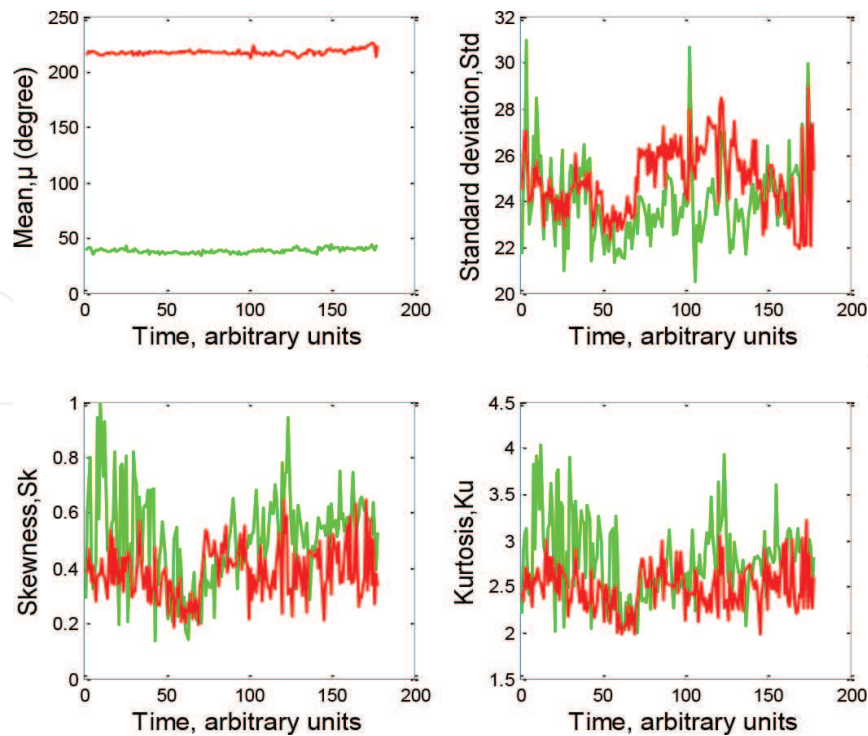
phase of occurrence for negative PDs having a range of values underlying within  $209^{\circ}$ – $274^{\circ}$  implied that these PDs occurred at the third and fourth quadrant of negative half-cycle of AC applied voltage. An apparent phase shift was observed in the beginning of PD activity as a result of the rapid growth during initiation of an electrical tree. Moreover, the standard deviation, skewness, and kurtosis had varied over time in which the phases of occurrences of positive PDs have average  $\pm 25^{\circ}$  standard deviation, whereas negative PDs possess  $\pm 27^{\circ}$  standard deviation.

The study continued in the material at  $60^{\circ}\text{C}$  temperature to investigate the PD events during an electrical tree growth in silicone rubber-based nanocomposite. As shown in **Figure 14**, the mean and standard deviation of positive and negative PD magnitude distributions,  $H_n(q)$ , had increased significantly with gradual bursts occurring rapidly within short time duration. During the burst, PDs occurred throughout the whole tree structure [20]. In terms of skewness, the negative PD magnitude distribution was skewed to the right, whereas the positive PD magnitude distribution had varied between left-skewed and right-skewed. For kurtosis, most of the kurtosis values were less than three, which indicate flattened distribution.

The pulse count distribution,  $H_n(\varphi)$ , of PD activities in silicone rubber-based nanocomposite (1 wt%) tested under condition of higher temperature ( $60^{\circ}\text{C}$ ) is shown in **Figure 15**. The mean phase of occurrence of positive PDs regularly changed from  $34^{\circ}$  to  $44^{\circ}$ , whereas mean phase of occurrence of the negative PD occurred within range of  $212^{\circ}$ – $225^{\circ}$ . It was observed that the mean phases of both positive and negative PDs have small ranges which imply accumulation of PD occurrences at closer phases. However, the other three statistical moments had fluctuated regularly over times.



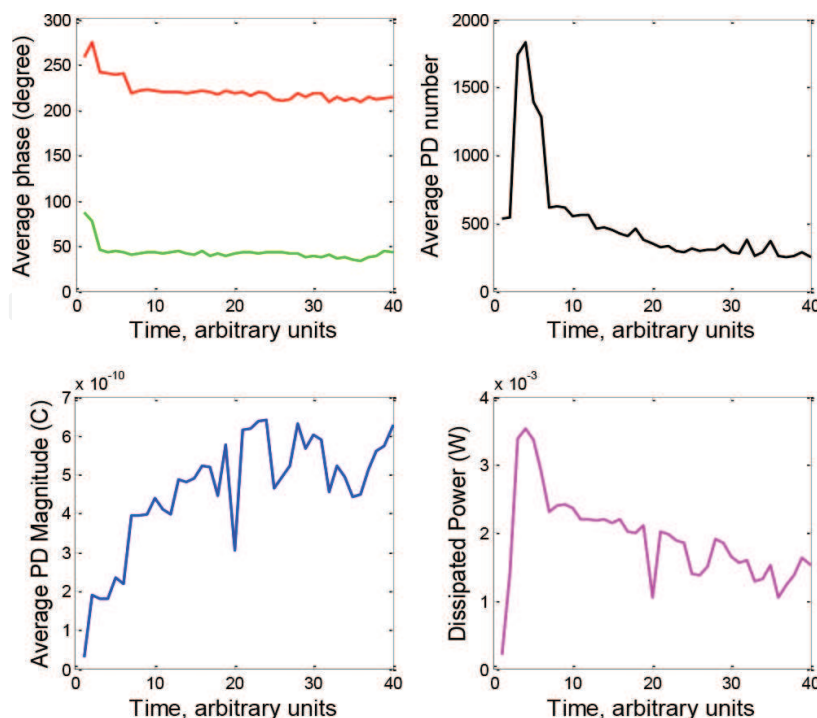
**Figure 14.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (1 wt%) at  $60^{\circ}\text{C}$ . Green solid line = positive PD and red solid line = negative PD.



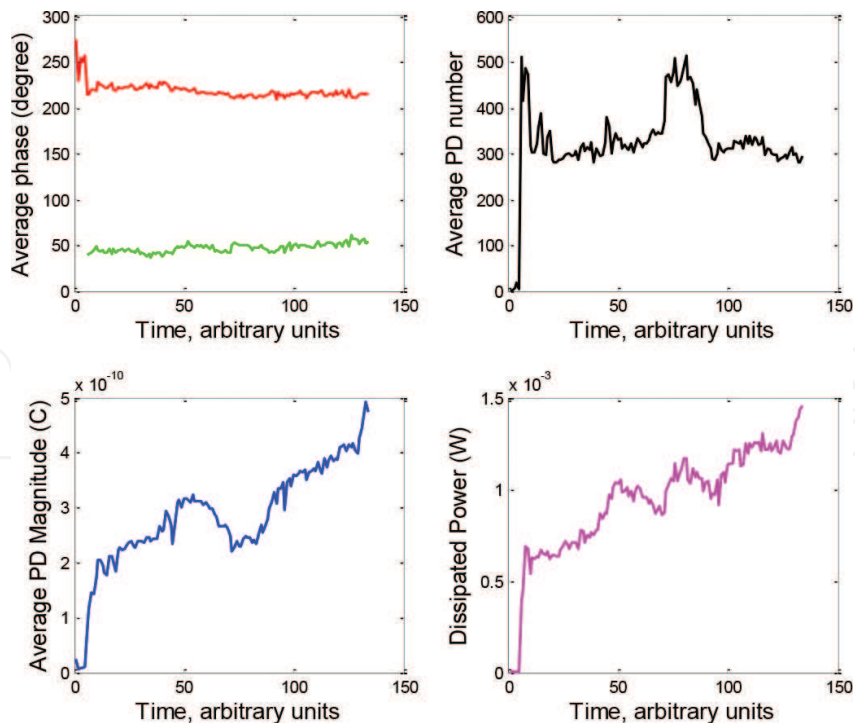
**Figure 15.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\varphi)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (1 wt%) at 60°C. Green solid line = positive PD and red solid line = negative PD.

Furthermore, the additional five statistical parameters of PD characteristics were studied for silicone rubber-based nanocomposite samples under three different temperatures (20°C, 40°C, and 60°C) as depicted in **Figures 16–18**, respectively. For silicone rubber-based nanocomposite tested under room temperature of 20°C as depicted in **Figure 16**, the mean value of phases of positive PDs was found to be equal to 44°, whereas for negative PDs at 223°, temporary and abrupt changes of phase shifts were observed to occur in the beginning of tree propagation with sharp increase in the PD numbers and dissipated power thereby indicating rapid growth of electrical tree as mentioned by Champion and Dodd [19]. It can be seen that after a temporary increase of the number of discharges, the PDs reduced over time with the total PD numbers having values between 249 and 1831 while the mean value was 495. On the other hand, the total PD magnitudes are found to change gradually within 31 and 641 pC. The mean total PD magnitudes were found to be equal to 450 pC. For the power dissipated in the sample, the minimum and maximum values were equal to 0.218 and 3.50 mW, respectively, with the mean value of 1.905 mW.

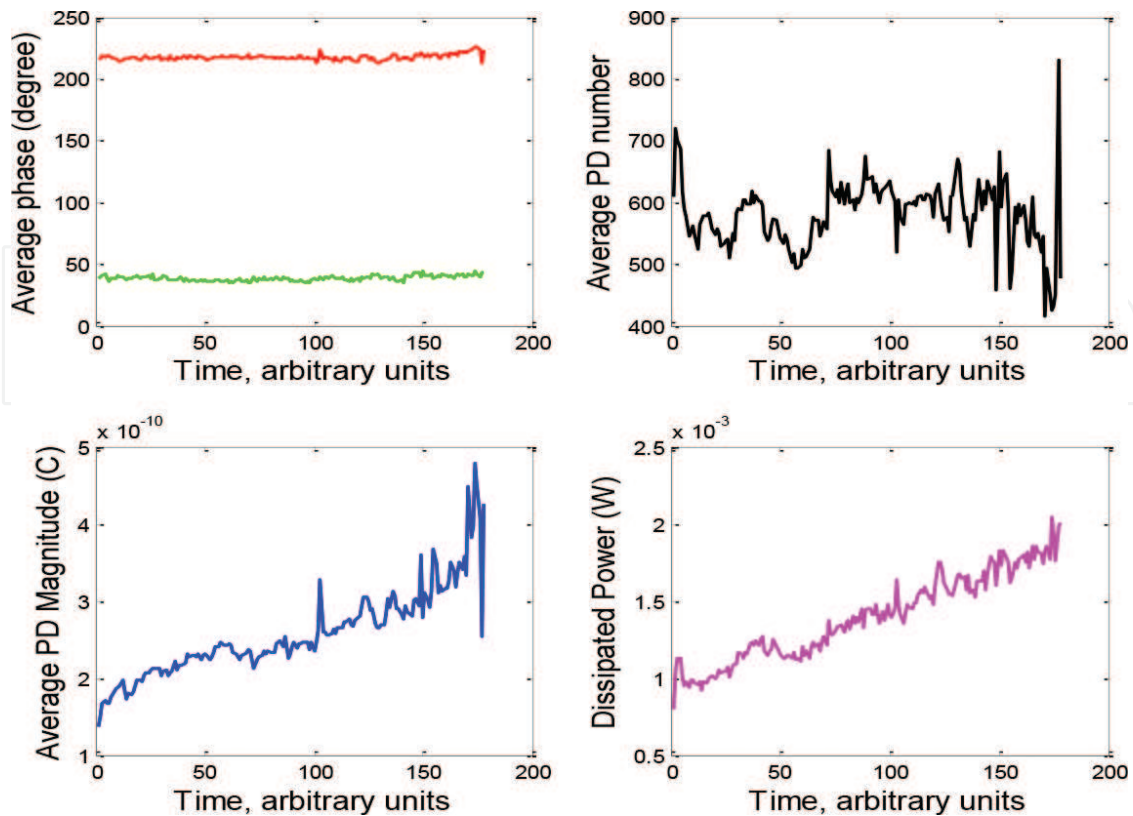
Furthermore, the results of PD activities in silicone rubber-based nanocomposite under temperature of 40°C are depicted in **Figure 17**, where it is shown that the average phase of positive PDs occurred at 47°. This implies that it occurred at the first quadrant of positive half-cycle of AC voltage, while the phase of occurrence of negative PDs occurred at 217°. The total number of discharges for both positive and negative PDs has a range of 1–515 with a mean value of 338. The total PD magnitudes had values that range from 5 to 492 pC with mean value of 294 pC. The minimum and maximum power dissipated in the sample equal to 0.061 and 1.5 mW,



**Figure 16.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of time obtained from PDs activity during tree growth in silicone rubber-based nanocomposite (1 wt%) at 20°C. Green solid line = positive PD and red solid line = negative PD.



**Figure 17.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of time obtained from PDs activity during tree growth in silicone rubber-based nanocomposite (1 wt%) at 40°C. Green solid line = positive PD and red solid line = negative PD.



**Figure 18.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of time obtained from PDs activity during tree growth in silicone rubber-based nanocomposite (1 wt%) at 60°C. Green solid line = positive PD and red solid line = negative PD.

respectively, while the mean value equals to 0.936 mW. In addition, the sudden phase shift was observed to occur at the beginning of electrical tree propagation during the burst periods. Moreover, bursts situation can be observed to have occurred in the all four graphs. The abrupt changes in the total PD numbers imply that the growth of an electrical tree was faster during inception stage that had enhanced the PD repetition events.

In the case of the sample at 60°C temperature, the PD characteristics are illustrated in **Figure 18**. The mean values of the phases of positive PD and negative PD were obtained and are equal to 38° and 217°, respectively, which imply the positive and negative PDs occurred at first and third quadrant of the AC voltage cycles. In addition, the total positive and negative PD numbers were found to have range of values between 416 and 831 with mean value equal to 580. In terms of PD magnitudes, total PDs had fluctuated in the ranges of 137–478 pC with the mean value of 257 pC. It was also found that the power dissipated in the sample has minimum, maximum, and mean values of 0.795, 2.0, and 1.395 mW, respectively. The phase shift was noticed to occur during the short time of burst. Moreover, plenty of burst-type behaviors were identified, and it can be seen that the plot of PD numbers has increased significantly during the bursts. The bursts can be seen in the plot of PD magnitudes and dissipated power as well, and the discharge magnitudes and the power increased with the time of tree propagation.

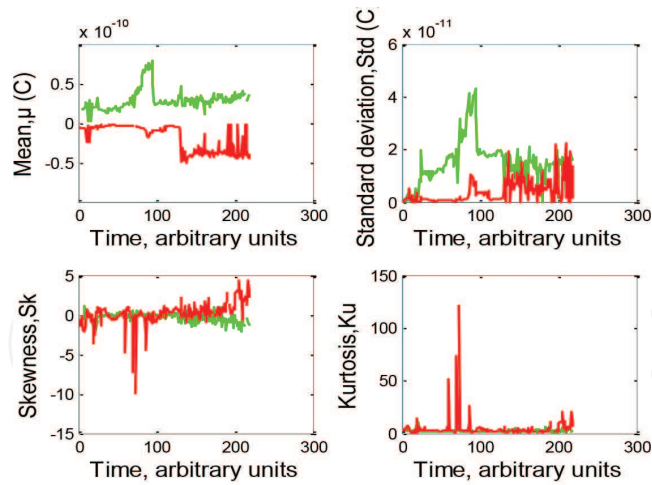
### 2.3. Analysis of PD for silicone rubber-based nanocomposite (3 wt%) at temperatures of 20°C, 40°C, and 60°C

In the case of silicone rubber-based nanocomposite with an addition of 3 wt% of nanoclay nanofiller, it was found that the PDs have occurred and were repeated at shorter time in arbitrary units of time than the actual time of voltage application (4 hours). Similarly, the statistical moments of PD magnitude distribution,  $H_n(q)$  and PD phase distributions,  $H_n(\varphi)$  in silicone rubber-based nanocomposite (3 wt%) at 20°C, 40°C, and 60°C temperature are illustrated in **Figures 19(a)–(c)**, **20(a)–20(c)**, respectively. At 20°C, the positive and negative PD magnitude distributions were found to fluctuate over time. The mean and standard deviation exhibited temporary changes of amplitudes. In terms of skewness and kurtosis, both of them fluctuated, which indicated that the distribution have skewed properties and sharper than normal distribution, respectively. In case of  $H_n(\varphi)$ , the mean, standard deviation, skewness, and kurtosis have varied values as functions of time thereby showing small amplitude of PDs and some dashed lines indicating intermittent/sporadic PDs.

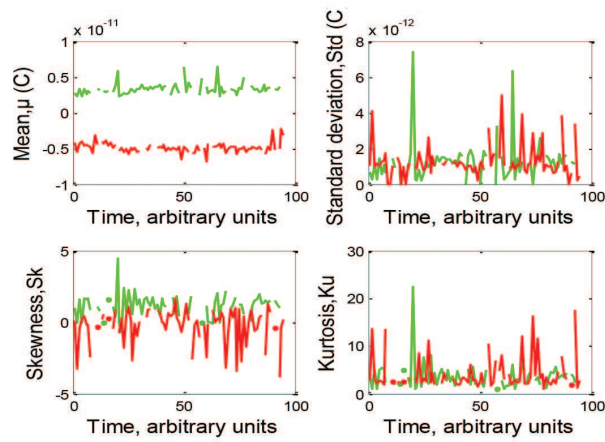
The statistical moments of pulse magnitude distributions and pulse count distributions for the test performed at a temperature of 40°C are shown in **Figure 19(b)** and **Figure 20(b)**, respectively. All the statistical moments fluctuated, and some of them have dashed lines, which show sporadic PDs. The mean of positive and negative PDs have fluctuated between the absolute values of 2 and 6 pC. Thus, the amplitudes of the mean and standard deviation were considered very low compared with the previous cases discussed in the Sections 2.1 and 2.2. The skewness and kurtosis show variations over the time. It is considered that the positive PD distribution was right-skewed and the negative PD was left-skewed, while the positive and negative PD distributions are sharper than normal distributions. The mean phases of occurrence of positive and negative PDs occurred in the whole quadrants of AC voltage cycle.

Under the temperature of 60°C, both PD magnitude and count distributions have sporadic behaviors as can be seen in **Figures 19(c)** and **20(c)**, where it shows that both negative and positive PDs only occurred at different times. It can be said that during both the half-cycle of AC voltage either positive or negative PDs occur independently at certain duration of times. The skewness and kurtosis distributions were found to have dashed lines as well. It can be said that the positive PD distributions were right-skewed and the negative PD distributions were left-skewed. Meanwhile, the kurtosis of positive and negative PD distributions was more prone to be flatter than normal distribution.

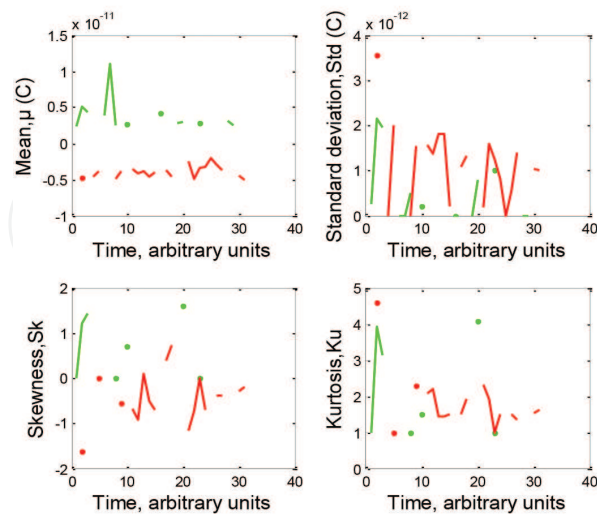
In terms of physical parameters of PD occurrences, the results are depicted in **Figures 21(a)–(c)** for the case of 20°C, 40°C, and 60°C, respectively. It was found that in the average phase of PD occurrence of all the cases (20°C, 40°C, and 60°C) were found to be relatively insensitive. The PD number and PD magnitude have shown very low values in terms of amplitudes compared with the PD results of previous two sections. The sporadic PDs affected the results. It implied that the PD occurrences were material-dependent since there were no electrical trees observed but only weak light emission, which was considered as electroluminescence. The applied AC voltage of 10 kV<sub>rms</sub> was insufficient to create an electrical tree. However, PD was detected to have occurred sporadically in very low amplitudes of number and magnitude of PDs. The reasons for all these PD characteristics are discussed thoroughly in the following sections.



(a)

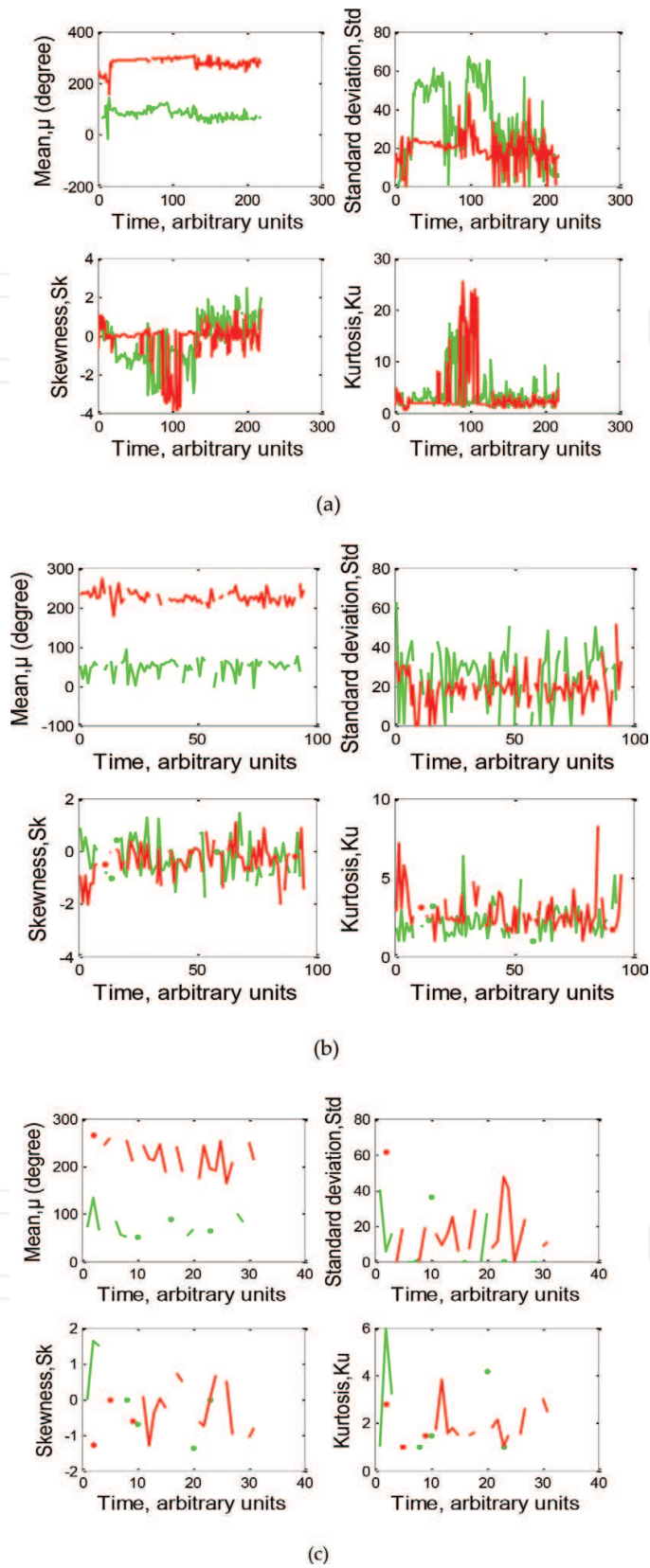


(b)

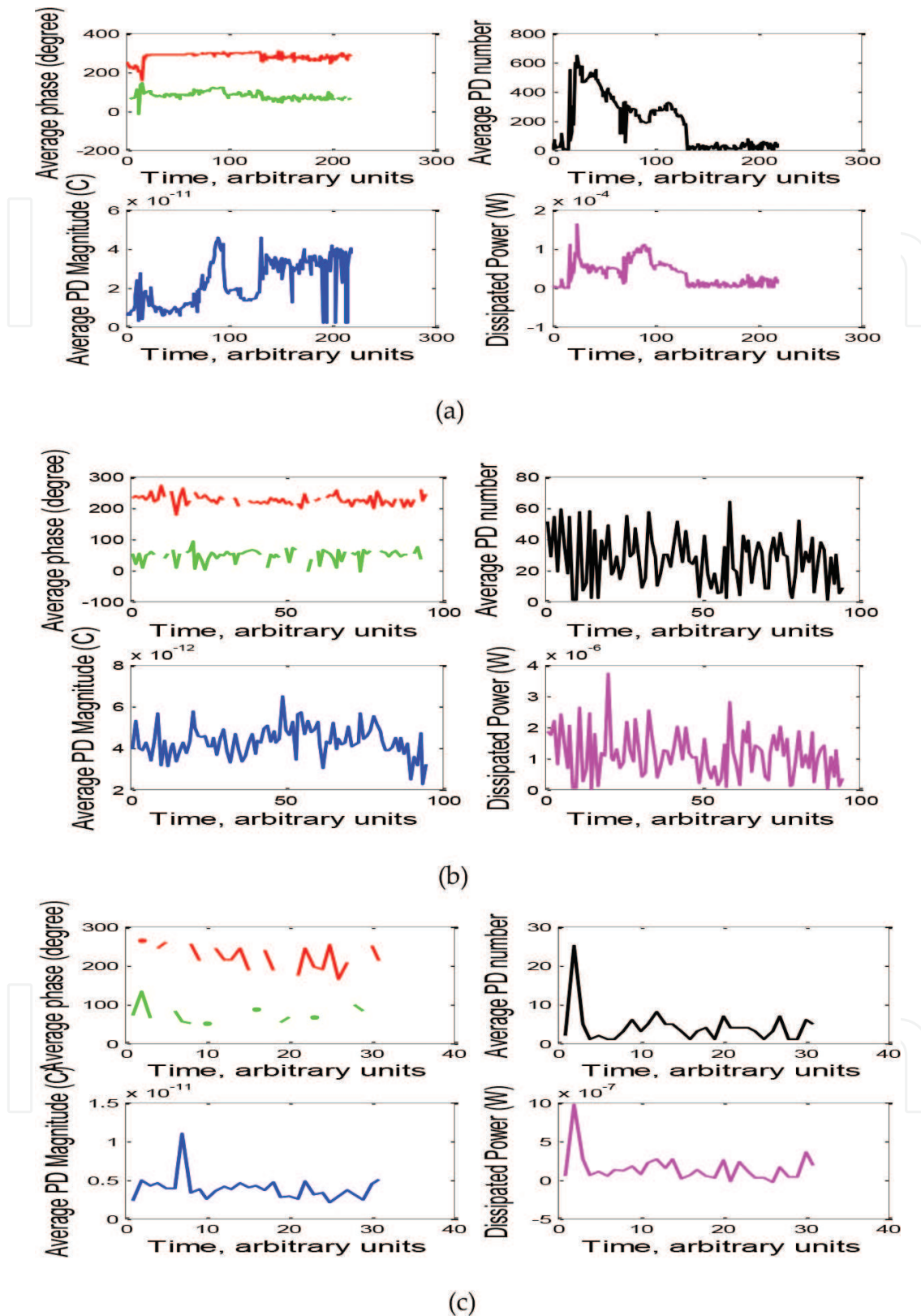


(c)

**Figure 19.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD magnitudes,  $H_n(q)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (3 wt%) at (a) 20°, (b) 40°, and (c) 60°C. Green solid line = positive PD and red solid line = negative PD. Dashed lines indicate sporadic PDs.



**Figure 20.** Mean, standard deviation, skewness, and kurtosis of positive and negative PD phase distributions,  $H_n(\phi)$ , as a function of time obtained from PDs during tree growth in silicone rubber-based nanocomposite (3 wt%) at (a) 20°C, (b) 40°C, and (c) 60°C. Green solid line = positive PD and red solid line = negative PD. Dashed lines indicate sporadic PDs.



**Figure 21.** Average phases of occurrence of positive and negative PDs, average number of PDs, average PDs magnitude, and dissipated power as a function of time obtained from PDs activity during tree growth in silicone rubber based nanocomposite (3 wt%) at (a) 20°C, (b) 40°C, and (c) 60°C. Green solid line = positive PD and red solid line = negative PD. Dashed lines indicate sporadic PDs.

3. Discussion

As discussed by Champion et al. [20] and Champion and Dodd [19], PD events in neat epoxy resin (CY1311) exhibited burst-type behavior. During the burst period, the number of discharges increases significantly, which indicate faster growth of electrical tree, and the discharges were found to be reproducible due to electrical tree length elongation. In addition, it was found that the phase of occurrences shifted to lower values during the burst periods, suggesting the enhancement and fluctuation of local electric field during the half-cycle that leads to the occurrence of PD at lower angle [21].

The processing results of the PD data are shown in **Table 1**. This presents a summary of the recorded PD data. In the case of neat SiR, the average PD magnitude was found to increase with increasing temperature, while the average number of PDs per second was found to decrease with increasing temperature. Also, a significant shift in the average phase of PD occurrence of both the positive and negative discharge distributions was taking place simultaneously. The average phase of occurrence of the positive PDs increased from 37° at 20°C to 55° at 60°C. A similar dependence on temperature of the PD phases was found in the case of the electrical trees growth in a flexible epoxy resin. This phase shift is attributed to an increase in the electrical conductivity of the epoxy resin with increasing temperature leading to decreased accumulation of space charge surrounding the tree structure.

Type of sample	PD characteristics	20°C			40°C			60°C		
		Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Neat SiR	Discharge magnitude (pC)	83	218	160	57	387	280	70	610	332
	Number of PDs (s <sup>-1</sup> )	687	1244	952	117	7571	199	65	649	197
	Phase of occurrence of positive PDs (°)	34	41	37	36	60	44	44	93	55
	Phase of occurrence of negative PDs (°)	215	220	218	218	244	226	223	247	239
	Dissipated power (mW)	0.87	1.40	1.24	0.35	3.4	0.54	0.05	0.997	0.668
SiR/1 wt% nanoclay	Discharge magnitude (pC)	31	641	450	5	492	294	137	478	257
	Number of PDs (s <sup>-1</sup> )	249	1831	495	1	581	338	416	831	580
	Phase of occurrence of positive PDs (°)	33	86	44	36	61	47	34	44	38
	Phase of occurrence of negative PDs (°)	209	275	223	209	274	217	212	225	217
	Dissipated power (mW)	0.22	3.50	1.91	0.061	1.5	0.94	0.75	2.00	1.395
SiR/3 wt% nanoclay	Discharge magnitude (pC)	2	45	22	2	6	4	2	11	4
	Number of PDs (s <sup>-1</sup> )	1	643	181	1	64	27	1	25	4
	Phase of occurrence of positive PDs (°)	17	142	80	5	94	46	52	133	75
	Phase of occurrence of negative PDs (°)	154	306	280	177	272	226	164	265	222
	Dissipated power (μW)	0.34	163	35.7	0.002	3.7	1.13	0.03	0.98	0.15

Min is minimum value, Max is maximum value, and Ave is average value.

**Table 1.** Summary of partial discharge statistical parameters.

However, the reverse circumstances on PD numbers and PD magnitudes have been exhibited in epoxy resin sample since the PD numbers increased while PD magnitudes decreased with the increasing of temperature from 20°C to 70°C [21]. This dissimilarity between epoxy resin and silicone rubber is probably due to the increase of vulcanization/cross-link numbers in silicone rubber matrices with increase of temperature which was discussed thoroughly by Du et al. [22].

In the case of 1 wt% nanoclay nanocomposite, the average PD magnitude has been found to decrease with increasing temperature from 450 pC at 20°C to 257 pC at 60°C. However, the other three PD physical parameters remained relatively insensitive to the changes in temperature. The decrease in PD magnitude when the temperature increased in silicone rubber-based nanocomposites (1 wt%) is because the addition of nanoparticles contributes to trapping of space charges in which the electrons injected from the electrode move toward the opposite electrode and get trapped at the nanoparticle surfaces and inside the nanoparticles. When the applied field is sufficiently high, it can cause ionization of nanoparticle within the polymer. Heterocharges will occur due to discharge (bulk material transport charges more easily than they are extracted by the polymer/metal interface). Thus, internal field will be created to oppose the direction of applied field, making the net field inside the nanoparticle more than the discharge inception field thereby extinguishing the discharge. This would reduce the PD magnitude. If the applied field is high enough and exceeds the internal field, the discharge will occur again. However, the particles tend to agglomerate thereby resulting in less interfacial area leading to lesser charge carriers getting trapped around the particle surfaces (localized states). Due to repetition and sufficiently high electric field, the trap sites provided by microparticles for electron localizations are not enough thereby leading to drift of electron (detrapping). This would cause charge movements (mobility) that give more PD repetition rate.

The addition of 3 wt% nanoclay nanoparticles in silicone rubber had caused an effective electrical tree inhibition. Electrical trees have not been observed during the 4 hours of the experiment. Only localized light emission was detected at the needle tip using the CCD camera, which is recognized as electroluminescence. It appears that the silicone rubber matrices were reinforced by an addition of 3 wt% of nanoclay nanofillers to an extent that prevented the formation of an initial void with the sufficient dimension required for PD generation and subsequent electrical tree initiation. The PD magnitudes and PD numbers were obtained, and they decrease with the increase in temperature from 20°C to 60°C: the PD magnitudes decreased from 22 to 4 pC. However, the phase of positive PDs was found to be insensitive to temperature changes, whereas the phase of negative PDs shifted to the lower values with the increase in temperature.

Moreover, the small discharges detected in that nanocomposite material was probably a swarming partial micro-discharges (SPMD) which is related to the existence of microvoids at polymer/electrode interface due to imperfect bonding between the tungsten needle and the silicone rubber. Tanaka [23] reported that small PD of less than 1 pC was detected in the void prior to tree initiation. Swarming partial micro-discharge phenomena can be found in [23–26]. Thus, the detection of PD prior to the tree initiation may be caused by the microvoid at the needle tip due to charge carriers recombination. The holes and electrons are injected into the polymer during the positive and negative half-cycle of AC voltage, and they are trapped in

the recombination centers. Light is emitted when the electron-hole recombination occurs at the luminescent center [27]. However, the electric field intensity was insufficient to initiate the electrical treeing due to low energy. In addition, it appeared that the silicone rubber matrices were reinforced by the addition of 3 wt% of nanoclay nanofiller to an extent that prevented the formation of a void with sufficient dimensions required for PD generation and electrical tree initiation.

In polymer nanocomposites, the nanoparticles act as charge carrier traps with high barrier potentials. These trapped carriers need more energy to get extracted from one trap to another trap; therefore, this would slow down the growth of electrical treeing. With the addition of 1 wt% of nanoclay nanofillers, the tree inception time and propagation time were enhanced distinctly. However, PD magnitudes and PD numbers of silicone rubber-based nanocomposite (1 wt%) became insensitive with the increase in temperature as the PD magnitudes seem to be higher than neat silicone rubber at 20°C and 40°C, whereas the PD numbers of silicone rubber-based nanocomposite (1 wt%) were greater than neat silicone rubber at 40°C and 60°C. The reason of the increase in PD magnitudes and PD numbers is attributable to agglomeration of nanofiller in silicone rubber matrix. The tactoids represent the weak points that could enhance the PD repetition inside the polymer. However, the agglomerated nanoparticles bigger than 100 nm are considered as a microparticle. The microparticle has also contributed to the suppression of an electrical tree as reported in reference [17, 28] that reacted as a physical barrier to the growth of tree channel resulting in the tree forming more side branches when it collides with the microparticle.

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