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Analysis of Phase Resolved Partial Discharge Patterns using Statistical Techniques

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Abstract: ***Partial discharges (PDs) in high-voltage (HV) insulating systems originate from various local defects, which further results in degradation of insulation and reduction in life span of equipment. One of the most widely used representations is phase-resolved PD (PRPD) patterns. For reliable operation of HV equipment, it is important to observe statistical characteristics of PDs and identify the properties of defect to ultimately determine the type of the defect. In this work, we have obtained and analysed combined use of PRPD patterns (φ-q), (φ-n) and (n-q) using statistical parameters such as skewness and kurtosis for (φ-q) and (φ-n),and mean, standard deviation, variance, skewness and kurtosis for (n-q).***

Keywords: Kurtosis, Partial Discharge, Phase- Resolved, Skewness and Statistical Techniques

1. Introduction

PD is an incomplete electrical discharge that occurs between insulation or insulation and a conductor. Partial discharges occur wherever the electrical field is higher than the breakdown field of an insulating medium. There are two necessary conditions for a partial discharge to occur in a cavity:(1) presence of a starting electron to initiate an avalanche

(2) The electrical field must be higher than the ionization inception field of the insulating medium [1]. In general, PDs are concerned with dielectric materials used, and partially bridging the electrodes between which the voltage is applied. The insulation may consist of solid, liquid, or gaseous materials, or any combination of them. PD is the main reason for the electrical ageing and insulation breakdown of high voltage electrical apparatus. Different sources of PD give different effect on insulation performance. The occurrence of sparks, arcs and electrical discharges is a sure indication that insulation problems exist[1]. Therefore, PD classification is important in order to evaluate the harmfulness of the discharge [12].

PD classification aims at the recognition of discharges of unknown origin. For many years, the process was performed by investigating the pattern of the discharge using the well known ellipse on an oscilloscope screen, which was observed crudely by eye. Nowadays, there has been extensive published research to identify PD sources by using intelligent technique like artificial neural networks, fuzzy logic, and acoustic emission [12].

There seems to be an expectation that, with sufficiently sophisticated digital processing techniques, it should be possible not only to gain new insight into the physical and chemical basis of PD phenomena, but also to define PD „patterns" that can be used for identifying the characteristics of the insulation „defects" at which the observed PD occur[2].

Broadly, there are three different categories of PD pulse data patterns gathered from the digital PD detectors during the experiments. They are: phase-resolved data, time-resolved data and data having neither phase nor time information. The phase-resolved data consist of three-dimensional discharge epoch, φ charge transfer, q discharge rate, n patterns (φ~q, q~n and φ~n patterns) at some specific test voltage. The time-resolved data constitute the individual discharge pulse magnitudes over some interval of time, i.e., q~t data pattern. The third category of data consists of variations in discharge pulse magnitudes against the amplitude of the test voltage, V (for both increasing and decreasing levels), i.e., q~V data[3].

There are many types of patterns that can be used for PD source identification. If these differences can be presented in terms of statistical parameters, identification of the defect type from the observed PD pattern may be possible[4]. As each defect has its own particular degradation mechanism, it is important to know the correlation between discharge patterns and the kind of defect. Therefore, progress in the recognition of internal discharge and their correlation with the kind of defect is becoming increasingly important in the quality control in insulating systems[5]. Researches have been carried out in recognition of partial discharge sources using statistical techniques and neural network. In our study, we have tested various internal and external discharges like void, surface and corona using statistical parameters such as skewness and kurtosis for (φ-q) and (φ-n) and mean, standard deviation, variance, skewness and kurtosis for (n-q).

2. Statistical Parameters

The important parameters to characterize PDs are phase angle φ, PD charge magnitude q and PD number of pulses n. PD distribution patterns are composed of these three parameters. Statistical parameters are obtained for phase resolved patterns (φ-q), (φ-n) and (n-q).

2.1. Processing of Data

The data to be processed obtained from generator includes *φ*, *q, n* and voltage *V.* From this data, phase resolved patterns are obtained.

2.1.1. Analysis of Phase-Resolved (φ-q) and (φ-n) using Statistical Techniques

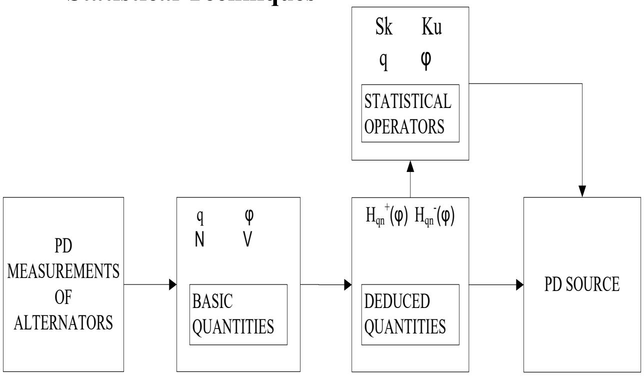

Figure 1(a): Block diagram of discharge analysis for (φ-q)

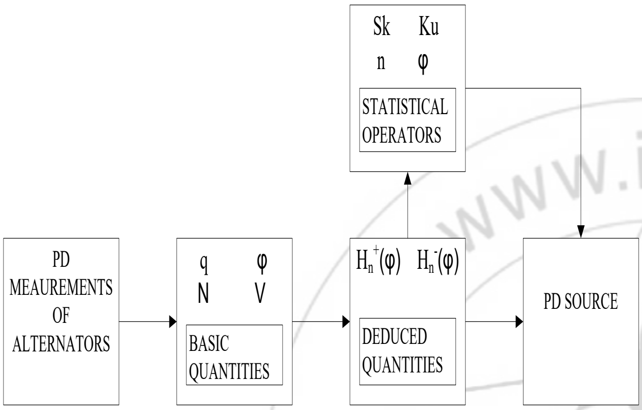

Figure 1(b): Block diagram of discharge analysis for (φ-n)

PD pulses are grouped by their phase angle with respect to the 50 (± 5) Hz sine wave. Consequently, the voltage cycle is divided into phase windows representing the phase angle axis (0 to 360ᵒ). If the observations are made for several voltage cycles, the statistical distribution of individual PD events can be determined in each phase window. The mean values of these statistical distributions results in two dimensional patterns of the observed PD patterns throughout the whole phase angle axis [6]. A two-dimensional (2D) distribution φ-q and φ-n represents PD charge magnitude „q" and PD number of pulses „n" as a function of the phase angle „φ" [3].

The mean pulse height distribution H_{qn} (φ) is the average PD charge magnitude in each window as a function of the phase angle φ. The pulse count distribution H_n (φ) is the number of PD pulses in each window as a function of phase angle φ. These two quantity are further divided into two separate distributions of the negative and positive half cycle resulting in four different distributions to appear: for the positive half of the voltage cycle H_{qn}^{+} (φ) and H_n^{+} (φ) and for the negative half of the voltage cycle H_{qn}^{-} (φ) and H_n^{-} (φ) [5]. For a single defect, PD quantities can be described by the normal distribution. The distribution profiles of H_{qn} (φ) and H_n (φ) have been modeled by the moments of the normal distribution: skewness and kurtosis.

$$\text{Skewness } (S_k) = \frac{\sum_{i=1}^{N}(x_i-\mu)^3 f(x_i)}{\sigma^3 \sum_{i=1}^{N} f(x_i)} \quad \text{.........(1)}$$

$$\text{Kurtosis}: (K_u) = \frac{\sum_{i=1}^{N}(x_i-\mu)^4 f(x_i)}{\sigma^4 \sum_{i=1}^{N} f(x_i)} - 3 \quad \text{.........(2)}$$

where,
f(x) = PD charge magnitude q,
μ = average mean value of q,
σ = variance of q.

Skewness and Kurtosis are evaluated with respect to a reference normal distribution. Skewness is a measure of asymmetry or degree of tilt of the data with respect to normal distribution. If the distribution is symmetric, Sk=0; if it is asymmetric to the left, Sk>0; and if it is asymmetric to the right, Sk<0. Kurtosis is an indicator of sharpness of distribution. If the distribution has the same sharpness as a normal distribution, then Ku=0. If it is sharper than normal, Ku>0, and if it is flatter, Ku<0 [3][7].

2.1.2 Analysis of Phase-Resolved (q-n) using Statistical Techniques

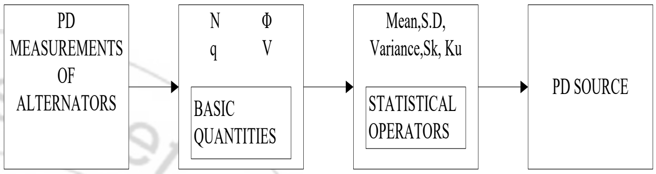

Figure 2: Block diagram of discharge analysis for (n-q)

Where,
S.D = standard deviation
Sk = skewness
Ku = kurtosis

Statistical analysis is applied for the computation of several statistical operators. The definitions of most of these statistical operators are described below. The profile of all these discrete distribution functions can be put in a general function, i.e., $y_i=f(x_i)$. The statistical operators can be computed as follows:

$$\text{Mean Value}: (\mu) = \frac{\sum_{i=1}^{N}(x_i)\, f(x_i)}{\sum_{i=1}^{N} f(x_i)} \quad \text{.........(3)}$$

$$\text{Variance}: (\sigma^2) = \frac{\sum_{i=1}^{N}(x_i-\mu)^2 f(x_i)}{\sum_{i=1}^{N} f(x_i)} \quad \text{.........(4)}$$

$$\text{Standard Deviation} = \sqrt{Variance} \quad \text{.........(5)}$$

where,
x = number of pulses n,
f(x) = PD charge magnitude q,
μ = average mean value of PD charge magnitude q,
σ = variance of PD charge magnitude q
Skewness and Kurtosis are evaluated with respect to a reference normal distribution. Skewness is a measure of asymmetry or degree of tilt of the data with respect to normal distribution. If the distribution is symmetric, Sk=0; if it is asymmetric to the left, Sk>0; and if it is asymmetric to the right, Sk<0. Kurtosis is an indicator of sharpness of distribution. If the distribution has the same sharpness as a normal distribution, then Ku=0. If it is sharper than normal, Ku>0, and if it is flatter, Ku<0 [3][8].

3. Results and Discussions

Analysis involves determining unknown PD patterns by comparing those with known PD patterns such as void, surface and corona. The comparison is done with respect to their statistical parameters[9][10][11].

3.1 Analysis for (φ-q) [9]

The phase resolved patterns are divided into two types: (φ-q) and (φ-n). The phase resolved patterns (φ-q) are obtained for three known PD patterns: void, surface and corona (as discussed in 3.1.1) and three unknown PD patterns: data1, data2 and data3 (as discussed in 3.1.3)

3.1.1. 2D distribution of (φ-q) for known PD patterns

Fig.3 (a), Fig.3 (b) and Fig.3 (c) are the phase φ vs. charge q plot for void, surface and corona discharges respectively.

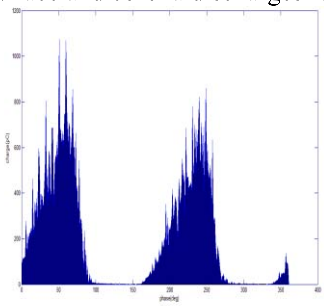

Figure 3(a): Phase plot (φ-q) of void discharge

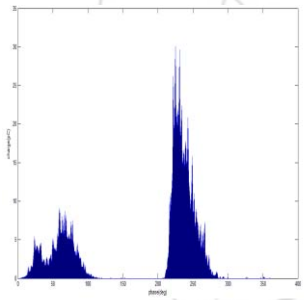

Figure 3(b): Phase plot (φ-q) of surface discharge

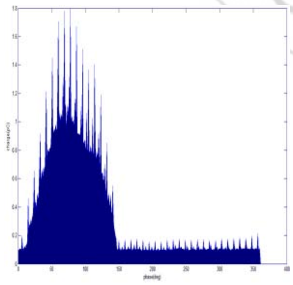

Figure 3(c): Phase plot (φ-q) of corona discharge

3.1.2. Parameters of known PD patterns

Table 1: Parameters of known PD patterns

Parameter	void	surface	corona
Skewness $H_{qn}^{+}(\varphi)$	1.0013	1.2134	0.3555
Skewness $H_{qn}^{-}(\varphi)$	0.9901	1.8219	1.3659
Kurtosis $H_{qn}^{+}(\varphi)$	2.9046	3.6064	2.4354
Kurtosis $H_{qn}^{-}(\varphi)$	2.7872	5.4506	7.5947

3.1.3. 2D distribution of (φ-q) for unknown PD patterns

Fig.4 (a), Fig.4 (b) and Fig.4 (c) are the phase φ vs. charge q plot for data1, data2 and data3 respectively.

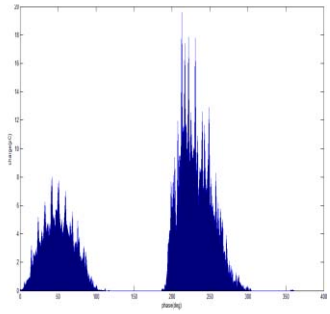

Figure 4(a): Phase plot (φ-q) of data1

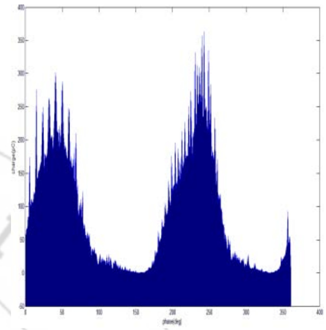

Figure 4 (b): Phase plot (φ-q) of data2

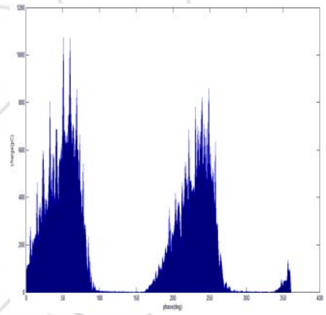

Figure 4(c): Phase plot (φ-q) of data3

From Fig.4 (a), it is seen that the following plot is similar to void and surface discharge. Fig.4 (b), is also similar to void and surface discharge and Fig.4(c), is similar to void discharge.

3.1.4. Parameters of unknown PD Patterns

Table 2: Parameters of unknown PD Patterns

Parameter	data1	data2	data3
Skewness $H_{qn}^{+}(\varphi)$	0.8991	0.7456	1.0013
Skewness $H_{qn}^{-}(\varphi)$	1.1833	0.8509	0.9901
Kurtosis $H_{qn}^{+}(\varphi)$	2.5719	2.1814	2.9046
Kurtosis $H_{qn}^{-}(\varphi)$	3.7467	2.6512	2.7872

3.2. Analysis for (φ-n)[9]

The phase resolved (φ-n) patterns consist of three known PD patterns: void, surface and corona (as discussed in 3.2.1) and three unknown PD patterns: data1, data2 and data3 (as discussed in 3.2.3). The plots are discussed below:

3.2.1 Phase resolved plot (φ-n) of known PD patterns

Fig.5 (a), Fig.5 (b) and Fig.5 (c) are the phase φ vs. number of pulses n for void, surface and corona discharges respectively.

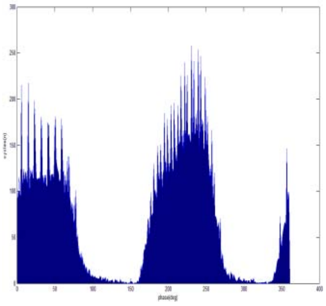

Figure 5(a): Phase plot (φ-n) of void discharge

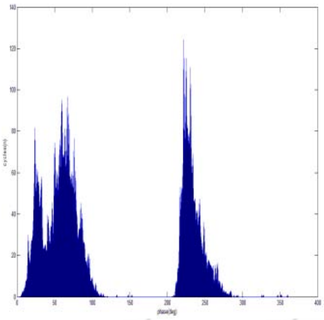

Figure 5(b): Phase plot (φ-n) of surface discharge

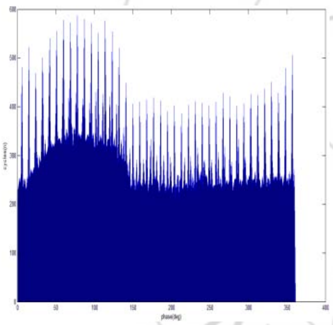

Figure 5 (c): Phase plot (φ-n) of corona discharge

3.2.2. Parameters of unknown PD Patterns

Table III. Parameters of known PD patterns

Parameter	void	surface	corona
Skewness H_n^+ (φ)	0.4954	1.0082	1.3942
Skewness H_n^- (φ)	0.4329	2.3686	1.3798
Kurtosis H_n^+ (φ)	2.0535	2.871	4.8337
Kurtosis H_n^- (φ)	1.9137	8.4788	7.3215

3.2.3. Phase resolved plot (φ-n) of unknown PD patterns

Fig.6 (a), Fig.6 (b) and Fig.6 (c) are the phase φ vs. number of pulses n plot for data1, data2 and data3 respectively.

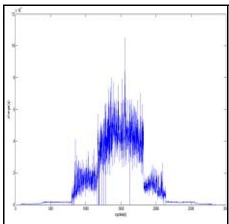

Fig.7(a). Mean plot (n-q) of void discharge

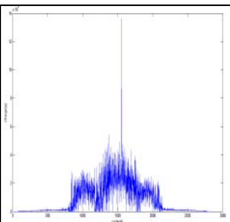

Fig.7(b). Standard deviation plot (n-q) of void discharge

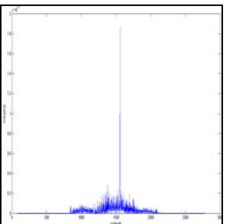

Fig.7(c). Variance plot (n-q) of void discharge

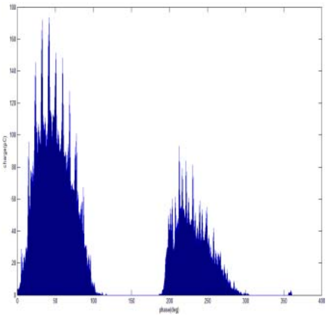

Figure 6 (a): Phase plot (φ-n) of data1

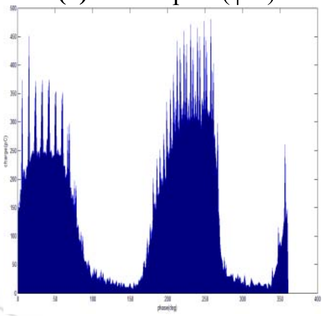

Figure 6 (b): Phase plot (φ-n) of data2

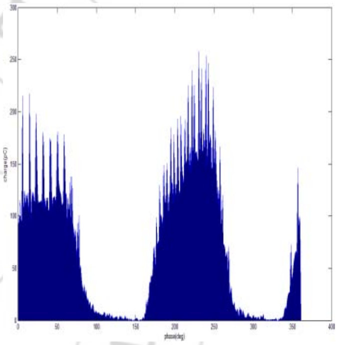

Figure 6 (c): Phase plot (φ-n) of data3

From Fig.6 (a), it is seen that the following plot is similar to void and surface discharge. Fig.6 (b), is similar to void discharge and Fig.6 (c), is also similar to void discharge

3.2.4. Parameters of unknown PD patterns

Table IV. Parameters of unknown PD patterns

Parameter	data1	data2	data3
Skewness H_n^+ (φ)	0.8016	0.574	0.4954
Skewness H_n^- (φ)	1.0169	0.42	0.4329
Kurtosis H_n^+ (φ)	2.3724	2.1091	2.0535
Kurtosis H_n^- (φ)	3.2011	1.8003	1.9137

3.3. Analysis for (n-q)[10]

The phase resolved patterns n-q are obtained for three known PD patterns: void, surface and corona (as discussed in 3.3.1) and three unknown PD patterns: data1, data2 and data3 (as discussed in 3.3.3).

3.3.1. 2D distribution of n-q for known PD patterns

Fig. 7(a), Fig. 7(b), Fig. 7(c), Fig. 7(d) and Fig. 7(e) are the n-q plot of mean, standard deviation, variance, skewness and kurtosis for void discharge respectively.

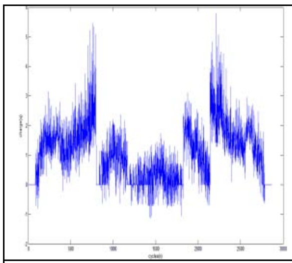
Fig.7(d). Skewness plot (n-q) of void discharge

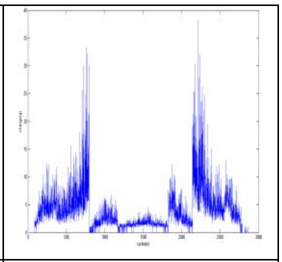
Fig.7(e). Kurtosis plot (n-q) of void discharge

Referring to Fig. 7 (a), Fig. 7 (b) and Fig. 7 (c) of void discharge, it can be seen there is a peak occurring somewhere after 1500 cycle, which is a void discharge and in Fig. 7 (d) and Fig. 7 (e) of skewness and kurtosis, the value decreases at that cycle where peak occurs.

Fig. 8(a), Fig. 8(b), Fig. 8(c), Fig. 8(d) and Fig. 8(e) are the n-q plot of mean, standard deviation, variance, skewness and kurtosis for surface discharge respectively.

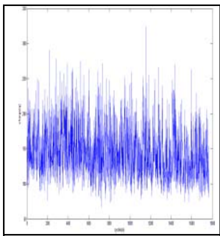
Fig.8(a). Mean plot (n-q) of surface discharge

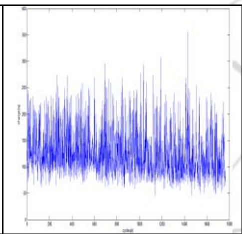
Fig.8(b). Standard deviation plot (n-q) of surface discharge

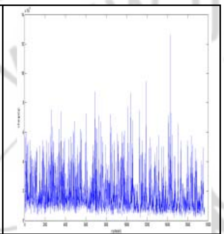
Fig.8(c). Variance plot (n-q) of surface discharge

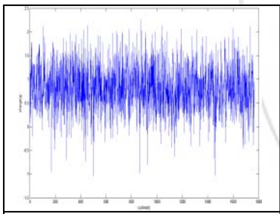
Fig.8(d). Skewness plot (n-q) of surface discharge

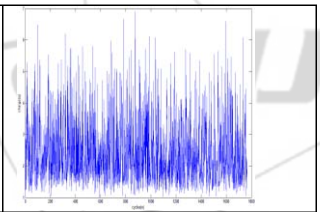
Fig.8(e). Kurtosis plot (n-q) of surface discharge

In surface discharge, charges are distributed uniformly over all cycles for mean, standard deviation, variance, skewness and kurtosis as shown in Fig. 8(a), Fig. 8(b), Fig. 8(c), Fig. 8(d) and Fig. 8(e).

Fig. 9(a), Fig. 9(b), Fig. 9(c), Fig. 9(d) and Fig. 9(e) are the n-q plot of mean, standard deviation, variance, skewness and kurtosis for corona discharge respectively.

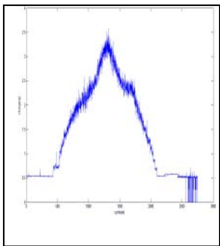
Fig.9(a). Mean plot (n-q) of corona discharge

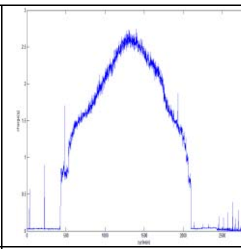
Fig.9(b). Standard deviation (n-q) of corona discharge

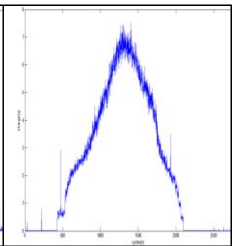
Fig.9(c). Variance plot (n-q) of corona discharge

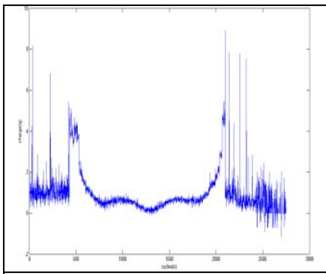
Fig.9(d). Skewness plot (n-q) of corona discharge

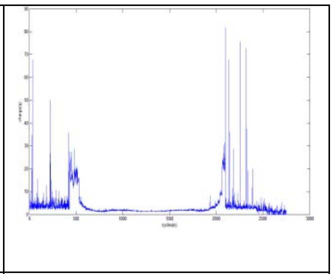
Fig.9(e). Kurtosis plot (n-q) of corona discharge

Referring to Fig. 9(a), Fig. 9(b) and Fig. 9(c) of corona discharge, it can be seen the charges starts occurring after 500 cycle increasing somewhere upto 1200 cycle and then decreasing after 2000 cycle, and in Fig. 9(d) and Fig. 9(e) of skewness and kurtosis, the value decreases from 500 cycle till 2000 cycle.

3.3.2. Parameters of known PD patterns

Table V. Parameters of known PD patterns

Parameters	void	surface	corona
Mean	13320.32	145.706	1.426
Standard deviation	7553.716	126.009	1.139
Variance	$1.64*10^{8}$	17921.01	2.279
Skewness	$3.66*10^{-17}$	0.809	0.26
Kurtosis	0.04878	2.442	0.966

3.3.3. 2D distribution of (n-q) for unknown PD patterns

Fig. 10(a), Fig. 10(b), Fig. 10(c), Fig. 10(d) and Fig. 10(e) are the n-q plot of mean, standard deviation, variance, skewness and kurtosis for data1 respectively.

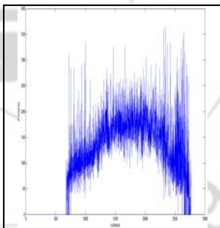
Fig.10(a). Mean plot (n-q) of data1

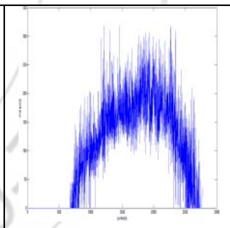
Fig.10(b). Standard deviation plot (n-q) of data1

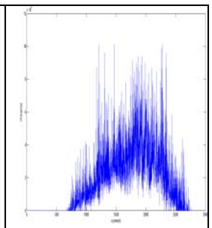
Fig.10(c). Variance plot (n-q) of data1

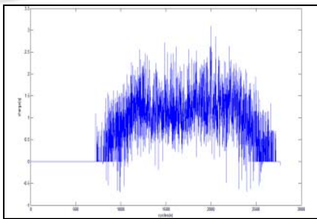
Fig.10(d). Skewness plot (n-q) of data1

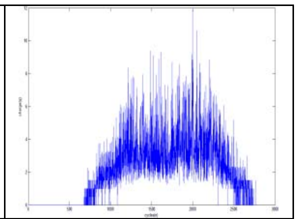
Fig.10(e). Kurtosis plot (n-q) of data1

In Fig. 10(a), Fig. 10(b), Fig. 10(c), Fig. 10(d) and Fig. 10(e), the charges are uniformly distributed similar to surface discharge. Hence, it can be concluded that data1 is having surface discharge.

Fig. 11(a), Fig.11(b), Fig. 11(c), Fig. 11(d) and Fig. 11(e) are the n-q plot of mean, standard deviation, variance, skewness and kurtosis for data2 respectively.

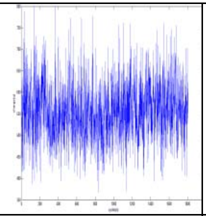
Fig.11(a). Mean plot (n-q) of data2

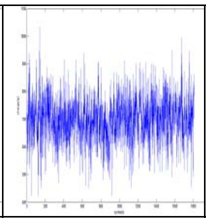
Fig.11(b). Standard deviation plot (n-q) of data2

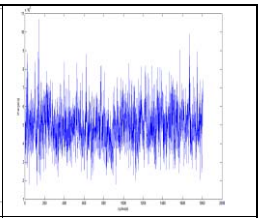
Fig.11(c). Variance plot (n-q) of data2

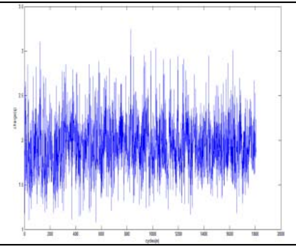
Fig.11(d). Skewness plot (n-q) of data2

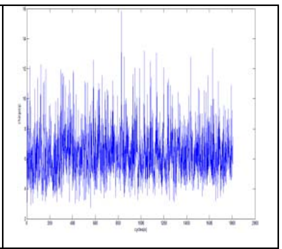
Fig.11(e). Kurtosis plot (n-q) of data2

In Fig. 11(a), Fig. 11(b), Fig. 11(c), Fig. 11(d) and Fig. 11(e), the charges are uniformly distributed similar to surface discharge. Hence, it can be concluded that data2 is having surface discharge.

Fig. 12(a), Fig. 12(b), Fig. 12(c), Fig. 12(d) and Fig. 12(e) are the n-q plot of mean, standard deviation, variance, skewness and kurtosis for data3 respectively

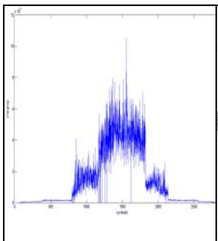
Fig.12(a). Mean plot (n-q) of data3

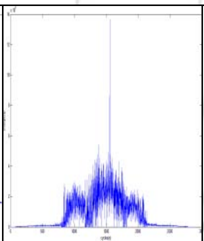
Fig.12(b). Standard deviation plot (n-q) of data3

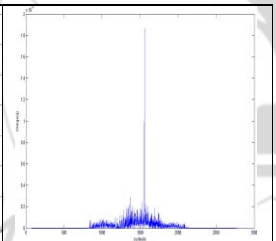
Fig.12(c). Variance plot (n-q) of data3

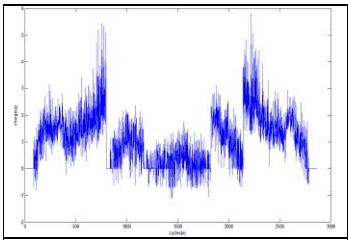
Fig.12(d). Skewness plot (n-q) of data3

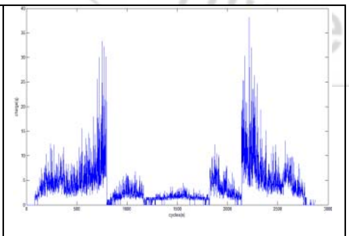
Fig.12(e). Kurtosis plot (n-q) of data3

In Fig. 12(a), Fig. 12(b) and Fig. 12(c), there is a occurrence of peak after 1500 cycle and in Fig. 12(d) and Fig. 12(e), the skewness and kurtosis value decreases at that peak which is similar to void discharge. Hence, it can be concluded that data3 is void discharge.

3.3.4. Parameters of unknown PD patterns

Table VI: Parameters of unknown PD Patterns

Parameters	data1	data2	data3
Mean	105.119	553.93	13320.32
Standard deviation	97.966	698.3	7553.716
Variance	16714.23	$4.94*10^5$	$1.64*10^8$
Skewness	0.692	1.939	$-3.7*10^{-17}$
Kurtosis	2.004	6.31	0.04878

4. Observations

From the above results, following observations are made:[11] Fig. 13(a), Fig. 13(b) and Fig. 13(c) are the characteristics of skewness and kurtosis($H_{qn}^{+}(\varphi)$ and $H_{qn}^{-}(\varphi)$) of data 1, data2 and data3 against void., surface and corona discharges respectively.

d

Fig.13(a). Characteristics of skewness and kurtosis($H_{qn}^{+}(\varphi)$ and $H_{qn}^{-}(\varphi)$) of data1, data2, and data3 against void

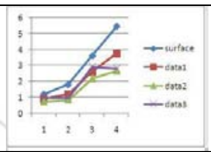

Fig.13(b). Characteristics of skewness and kurtosis($H_{qn}^{+}(\varphi)$ and $H_{qn}^{-}(\varphi)$) of data1, data2, and data3 against surface

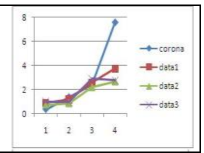

Fig.13(c). Characteristics of skewness and kurtosis($H_{qn}^{+}(\varphi)$ and $H_{qn}^{-}(\varphi)$) of data1, data2, and data3 against corona

From Fig. 13(a), it is observed that data3 characteristics overlaps void discharge characteristics, it can be concluded that data3 is void discharge. Data2 characteristics approximately fits against void, it can be concluded that data2 is also void discharge. From Fig. 13(b), it is observed that data 1 characteristics is similar to surface discharge characteristics, it can be concluded that data 1 is durface discharge. From Fig. 13(c), it is observed that none of the data characteristics is similar to corona discharge characteristics, it can be concluded that none of the data has corona discharge.

Fig. 14(a), Fig. 14(b) and Fig. 14(c) are the characteristics of skewness and kurtosis($H_{n}^{+}(\varphi)$ and $H_{n}^{-}(\varphi)$) of data 1, data2 and data3 against void., surface and corona discharges respectively.

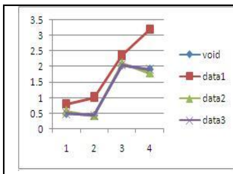

Fig.14(a). Characteristics of skewness and kurtosis($H_{n}^{+}(\varphi)$ and $H_{n}^{-}(\varphi)$) of data1, data2, and data3 against void

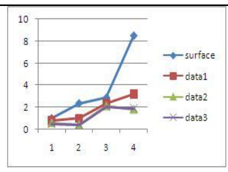

Fig.14(b). Characteristics of skewness and kurtosis($H_{n}^{+}(\varphi)$ and $H_{n}^{-}(\varphi)$) of data1, data2, and data3 against surface

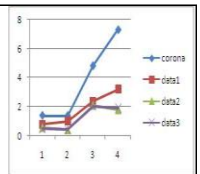

Fig.14(c). Characteristics of skewness and kurtosis($H_{n}^{+}(\varphi)$ and $H_{n}^{-}(\varphi)$) of data1, data2, and data3 against corona

From Fig. 14(a), it is observed that data3 characteristics overlaps void discharge characteristics, it can be concluded that data3 is void discharge. Data2 characteristics approximately fits against void, it can be concluded that data2 is also void discharge

From Fig. 14(b), it is observed that data 1 characteristics is close to surface discharge characteristics, it can be concluded that data 1 is durface discharge.

From Fig. 14(c), it is observed that none of the data characteristics is similar to corona discharge characteristics, it can be concluded that none of the data has corona discharge.

Fig. 15 is the statistical characteristics of mean, standard deviation, variance, skewness and kurtosis of void discharge against data3. Fig. 16(a), Fig. 16(b) are the statistical characteristics of mean, standard deviation, variance, skewness and kurtosis of surface discharge against data1 and data2 respectively.

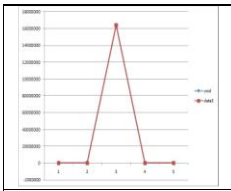	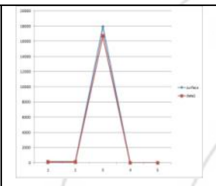	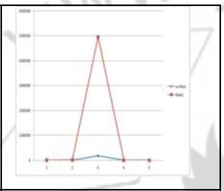
Fig.15. Statistical Characteristics of data3 against void discharge	**Fig.16(a).**Statistical characteristics of data1 against surface discharge	**Fig.16(b).**Statistical characteristics of data2 against surface discharge

Plotting statistical parameters of void discharge against data3 in Fig. 15 shows data3 characteristics overlaps void characteristics, it can be concluded that data3 is void discharge.

Similarly, for surface discharge, data1 and data2 characteristics (Fig. 16(a) and Fig. 16(b)) approximately fits surface discharge characteristics, it can be concluded that data1 and data2 is surface discharge

5. Conclusion

From all the above observations using all the three phase-resolved patterns(φ-q), (φ-n) and (n-q), it can be concluded that, data1 is surface discharge in all the three phase-resolved patterns, data2 is surface discharge in (n-q) pattern and void discharge in (φ-q) and (φ-n), hence data2 is both void and surface discharge and data3 is void discharge in all the three phase-resolved patterns.

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