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Analysis and Classification of Different Types of Partial Discharges by Harmonic Orders

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***Abstract*—The genesis of this research work was constituted for the issue of classifying the characteristics of harmonics caused by partial discharge (PD). This work was undertaken based on the hypothesis that the characteristics of the harmonic orders caused by different types of Partial Discharge (PD) can be classified. Experimental work was initially performed and the data obtained from it was validated. This work was then followed by an analysis of the data in order to extract the characteristics of harmonics order and to distinguish information of the harmonics distortion. The findings show that different types of PD produce distinctive harmonics characteristics and distinguishable Total Harmonic Distortion (THD) levels. The outcome of this study show that the hypothesis was precise in stating that different PD types can cause different levels and characteristics of harmonic distortions where in all data obtained were able to be classified. The classification criteria were then tested for accuracy and precision. The results obtained from the classification based on harmonics order characteristics show that 100 % of the PD data tested were identified successfully.**

Index Terms–Partial discharge (PD), harmonics, total harmonics distortion (THD) and classification.

I. INTRODUCTION

Harmonics are currents or voltages with frequencies that are a multiple of the fundamental power frequency which commonly originates from electrical device or equipment that draws current not proportionally to voltage [1]–[3]. Harmonic sources include power electronic devices, arcing devices, transformers and rotating machines [4]. Harmonics can also possibly be caused by the occurrence of partial discharge (PD).

PD can be described as an electrical discharge that does not completely bridge the insulation between conductors, which may or may not occur adjacent to a conductor [5]. PD occurs when an insulation material of an electrical equipment gradually deteriorate after a long period of time [6]–[8]. PD data provide useful information about the typology and the extent of insulation degradation and is useful in the prevention of the complete failure of insulation [6], [7].

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PD occurrence is associated with a burst of energy (although small in magnitude) as described in the following section. Harmonics is associated with this burst of energy. The released energy will produce effects where changes ensued in the chemical, physical and structural emit electromagnetic signals [9], [10]. It can also cause disturbance to the power source and can lead to electrical equipment failure. When the measurement of the power quality is taken, the results can potentially show increase of harmonics and distortion of supply voltage. Generally, current harmonics do not affect equipment that is connected to the electrical system, but causes issues with distribution equipment from the utility transformer [2], [3].

In contrary, when current harmonics generate sags in the voltage supply, the voltage harmonics increase and sensitive equipment connected to the electrical systems can be affected [2], [3]. In this work, the hypothesis is made based on the suggestion that the PD has distinct harmonics content and its characteristics can also be distinguishable. Thus, the characteristic of harmonics for different PD types are further investigated and analysed.

The PD types that are involved in this work are corona, internal and surface discharge. Current harmonics became the main research attention because voltage harmonics is typically low. Albeit the unawareness of voltage harmonics, most problems involving sensitive equipment are usually caused by voltage harmonics [2], [3].

The significant implication of this work demonstrate the evidence on harmonics present during the occurrence of difference types of PD and have distinct and this distinction can be detected. Another important contribution is the analysis on Total Harmonic Distortion (THD) level distinction that is caused by the different types of PD. This work on harmonics and PD could be used to provide expedient comprehension for elucidation outcome on harmonics problem caused by PD and potentially could be able to deliver preliminary inclusive analysis on issues related to power quality.

A review has been made on the latest related works and it was found that there was lack of existing research on harmonics caused by PD. Most publications focussed on distorted PD images caused by harmonics [11], [12] but to the best of the authors' knowledge there has been no works on characterization of harmonic for the purpose of PD classification. In the previous works that have been reviewed no classifications have been made on the PD types of the distorted PD images since the studies mostly focused on electrical treeing PD which involves analysis of insulation material.

Other researchers conducted were focused on transmission lines which experience a fairly different PD phenomenon compared to equipment [13]. Only corona discharge was mentioned to be detected in transmission lines.

II. Recurrence of Discharges

The discharges occurring due to PD disrupts the voltage output and are potentially linked to recurrence of discharges. The recurrence discharges phenomena can be briefly defined as capacity of cavity that is represented by capacitance which is shunt by breakdown path [14]. When AC voltage is applied the discharge occurs, the capacitance is charged and reaches the cavity's voltage breakdown and it is then recharged, repetitively. The recurrence of discharges can be described pictorially as shown in Fig. 1, where V_a is the high voltage across the dielectric, V_c is the high voltage across the cavity, ΔV is the voltage drop limit, U is the breakdown voltage and t represents time.

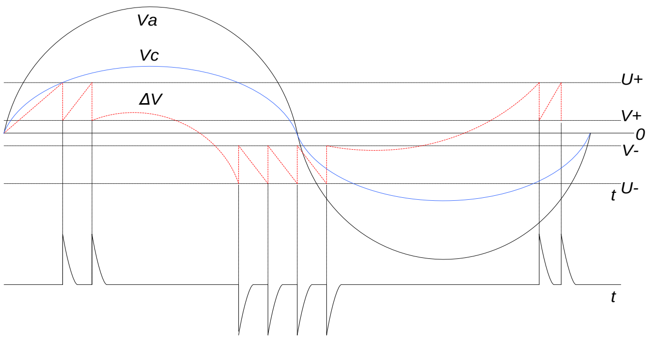


Fig. 1. The recurrence of discharges.

The terminology of recurrence discharges can clarify the phenomena of the discharges that interrupt the voltage output when PD occurred. The voltage output that is distorted may potentially cause THD to increase. When the high voltage across V_c reached the voltage breakdown U^+, a discharge occur in the cavity. The voltage then drops to V^+ where the discharge is extinguished. The voltage drop may be considered as a step function. The voltage over the cavity increase again after the discharge is extinguished. The new discharges occurs when the void reach U^+. The discharges occur several times when V_a over the samples decreases and V_c drops to U^- before new discharges occur. The discharges in the cavity cause impulses and these impulses concentrate in the region where the voltage applied to the sample increase or decrease. The charges that are transferred across the void in the cavity are referred to as transfer charge (q_1). The charge transferred can be described as (1) where b and c are the capacitance of the cavities

$$q_1 \sim (b+c)\Delta V. \tag{1}$$

The discharges of the wasted energy can be measured and they are directly related to the deterioration of the dielectric. The discharge energy (p) dissipated can be described as (2) when the V_c drops from U^+ to V^+ (or from U^- to V^-)

$$p_2 \sim \tfrac{1}{2}c \times \Delta V \times \left(U+V\right). \tag{2}$$

The energy of the discharge is related to the apparent charge that crosses the cavity. When ΔV is nearly zero, and hence can be neglected, the discharge energy will become 10 % lower.

The discharge magnitude (q) is practically a decent measure for p at the discharge. The q can be related to the size of the discharge area (A) in a cavity. The thickness of the discharge gap is minor compared to insulation thickness (d) and the electric field is taken consequently as

$$q \sim \varepsilon_0 \times \varepsilon \times A \times \Delta V \times \left(1/d\right), \tag{3}$$

where ε is the dielectric constant of the insulation used, A is the area of the discharge, ΔV is the ignition voltage and d is insulation thickness. The increment of ΔV and A will lead to the increment of q which increase with the discharges site thickness and the volume of discharges.

The correlation of the discharge to the released discharge energy which occur in the voltage output cause the fundamental power frequency to be disrupted and potentially cause the harmonic components to increase. From the recurrence of discharges occur on the voltage due to PD, further analysis of the harmonic characteristic is performed. The analysis finding is expected to discover the distinct characteristic of harmonic profile due to the recurrence of discharge that can be used to differentiate the PD types.

III. Experimental Work Setup

Measuring and classifying the PD have become one of the vital techniques for preventing equipment failure [7]. PD can occur at weaker insulation areas such as inside material cavities, bubbles in liquid insulation, sharp edges and between insulation layers which can produce different types of PD [7]. To determine the different types of PD, experimental work was conducted in a high voltage laboratory and using existing standards [5], [9], [15]–[18] and other publications as guidelines [4], [6]–[8], [10], [19], [20]–[23].

A. *Arrangement setup*

The HV transformer output voltage is tested in order to ascertain the voltage output and the measured waveform are similar. The measurement for the AC power supply voltage is initially taken, without the presence of PD.

The waveforms of the voltage are measured directly from the HV transformer using the capacitor divider. For the arrangement with the presence of PD, the devices for the experimental work were setup as shown in Fig. 2(a). The HV transformer is connected to PD source and the capacitor divider is connected to the PD source to obtain the voltage waveform.

B. *PD generation setup*

The PD source, shown in Fig. 2 is generated using custom made devices to produce the desired PDs. The PD source is then connected to the HV transformer. In this work, three types of PD are tested, namely Corona discharge, internal discharge and surface discharge. The generation of these PD are described in the following subsections:

1) Corona discharge

Corona discharge was produced by using brass needle and brass plate as shown in Fig. 3(a). The brass needle, injected with voltage is pointed towards a grounded brass plate. The corona occurring at the tip of the brass needle is shown enlarged in Fig. 3(b).

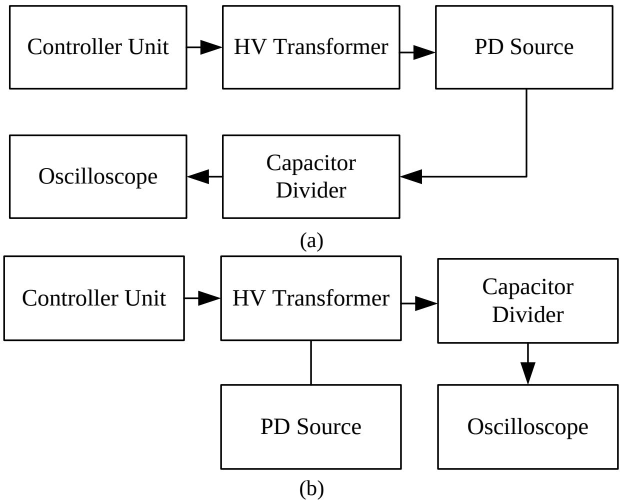


Fig. 2. The different setup (a) and arrangements (b) for the experimental work.

2) Internal discharge

Electrodes of the same size and perspex placed in between were used for producing internal discharge as shown in Fig. 3(c). The purpose is to avoid the occurrence of surface discharge. A vessel with the capability of withstanding high voltage is preferred. The internal discharge that occurs is shown enlarged in Fig. 3(d).

3) Surface discharge

To produce surface discharge, the size of the top electrode is made comparatively smaller than the bottom electrode as shown in Fig. 3(e). Perspex is firmly placed as the insulation material between the electrodes. The top electrode is injected with high voltage and the bottom electrode is grounded. The surface discharge that occurs on the surface of the perspex is shown enlarged in Fig. 3(f).

C. *Procedure*

The voltage output of the transformer is connected to the capacitor divider before being measured using the oscilloscope. The voltage is increased until the PD occurs. In this work, corona discharge occurred up until 7 kV before the air completely broke down. For surface and internal discharges, the voltage was up until 13 kV.

To ensure that the harmonics, recorded, using power quality analyser in the measurement, are genuinely due to PD and not originating from the mains or equipment, a test was conducted using the arrangement shown in Fig. 2(b). The harmonics in the HV transformer voltage outputs for the two arrangements were compared for similarity. Fig. 4 shows the obtained waveforms from the experimental work performed.

Both arrangements show similar results in terms of the waveform and the spike that occur in the waveform. This results show that either of the setup can be used to obtain the measured voltage while PD occurred. The THD level measured from the main supply were in the range of 1.7 % to 1.8 % which is very similar to the measurement taken from the HV transformer.

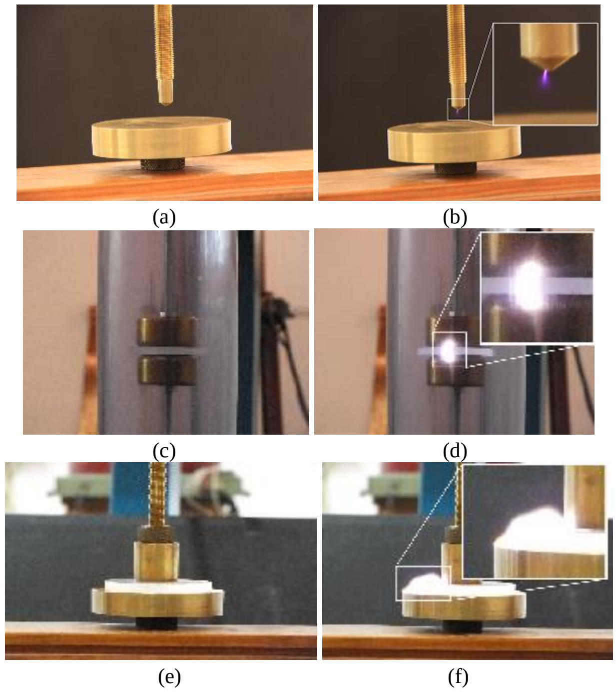


Fig. 3. The high voltage vessel (a); the internal discharge occurrence (b); the apparatus arrangement to produce corona discharge (c); the corona discharge occurrence (d); the apparatus arrangement to produce surface discharge (e); the surface discharge occurrence (f).

From the test performed, the THD level measured from the supply and the HV transformer is identical and within the acceptable THD standard limits in accordance to the IEEE standard which is under 5 % [6].

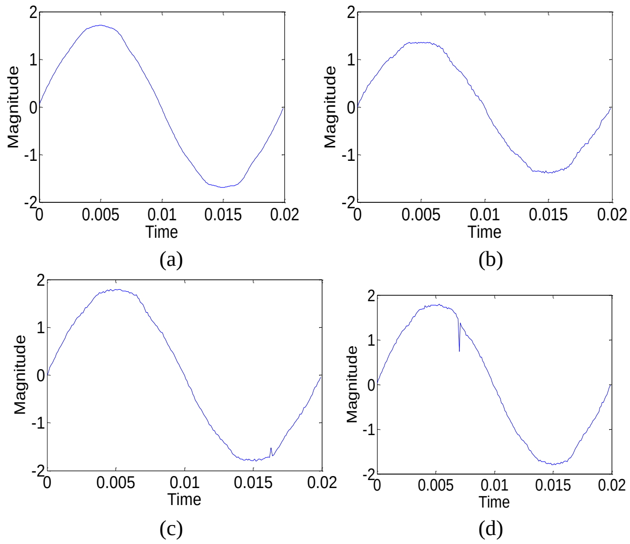


Fig. 4. The voltage waveform that was measured from the HV transformer: (a) the waveform taken without PD occurrence; (b) during corona discharge occurrence; (c) during internal discharge occurrence and (d) during surface discharge occurrence.

Thus, the experimental data from the HV transformer obtained have been verified as valid to be used in the following. The data measurement conducted on the PDs using various PD source setup as mentioned earlier were recorded and then analysed. The results of the analysis are discussed in the following section.

IV. CHARACTERISTICS OF THE MEASURED DATA

The measured data of Fig. 4 was analysed in order to find its characteristic and to identify the characteristic corresponding to the correct types of the PD. An observation made on the corona discharge signal found ripples occurring throughout most of the waveform. In this work corona discharge breakdown occurred at nearly 7 kV compared to internal and surface discharge, where it occurs at close to 13 kV.

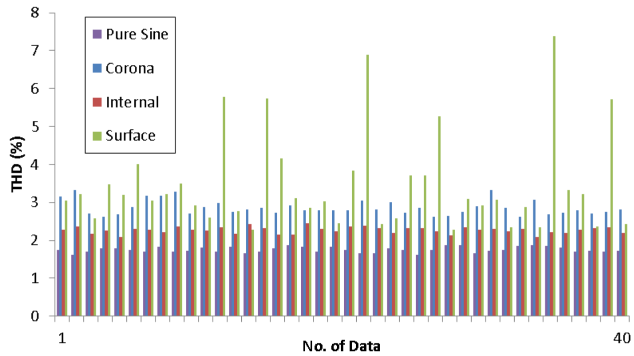


Fig. 5. The randomly selected data of THD values comprises forty sets of data.

Observation was also made on the spikes that appear on the waveform due to PD. It was also observed that the occurrence of spikes was random in nature for all types of PD. The intermission period between spikes on all PD types were different. For internal discharge, spike appearance was less frequent compared to surface discharge, based on observation and other data obtained during the experiments.

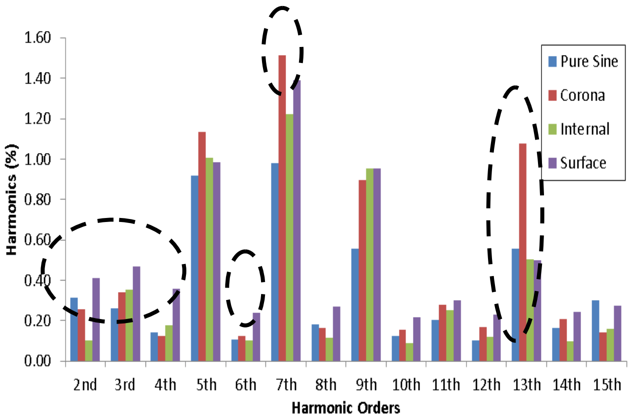


Fig. 6. The average of the harmonic orders for all PD types. The dotted circle in the figure shows the significant difference in even and odd harmonic order of the PD types.

Despite experiencing similar breakdown voltage of less than 13 kV and producing identical PD output voltage, the THD values of internal discharge and surface discharge are not similar. This phenomenon indicates that the harmonic distortion is diverse by different types of PD. Furthermore, the measurement likewise shows that the harmonic level of the measured voltage is not affected by the level of voltage.

This statement is proven when the validation process preformed on the measured voltage waveform without PD occurrence at 7 kV and 13 kV, which produce similar THD level. A randomly selected THD data percentage for all PD types is shown in Fig. 5. The comparison shows that internal discharge produce less THD compared to surface and corona discharge. Corona discharges generate higher THD levels compared to internal discharge albeit using lower voltage.

Using the randomly selected THD data of Fig. 5 gathered from the experimental work, it is observed that there are more than 6 data, which have THD values exceed the 5 % standard limit. If the complete data is considered, there will be more than 6 data producing THD values exceeding the 5 % standard limit. Apart from THD, the even and odd harmonic patterns are also taken into consideration in order to classify the type of PD. The average of the harmonic order for the corona, internal and surface discharges are shown in Fig. 6. The 1st harmonic order which shows the fundamental value of the harmonic has been omitted.

The analysis of the harmonic orders is taken from 2nd up to 15th order. The differences observed as shown by the dotted circle in Fig. 6 including 2nd, 4th, 6th, 7th and the 13th order are significant enough to be used to classify the characteristic of PD. MATLAB FFT software was used to analyse the THD level from the validated data obtained.

V. CLASSIFICATION OF THE HARMONIC DATA CHARACTERISTIC

Observation has been made on the experimental work conducted. The hypotheses made that the pattern of the even and odd harmonic orders can be used to classify the distinct PD types were proven to be certain. To prove this statement and elaborate on the findings, this work proceeds with the classification process. The classification process begins with selecting 10 sets of randomly chosen data and the data are calculated into average. The average value is used so that it can provide more consistency in the THD values though not affecting much to the original values. The characteristic of the harmonics order observed from the results obtained are classified as followed:

A. Corona discharge: condition 1

The average value of the 13th order from a minimum 10 sets of data is almost equal or greater than the average values of 5th and 9th order. The 5th order has around 10 % higher than the 9th order. Fig. 7(a) shows the average of 10 data of harmonic orders obtained from the corona discharge.

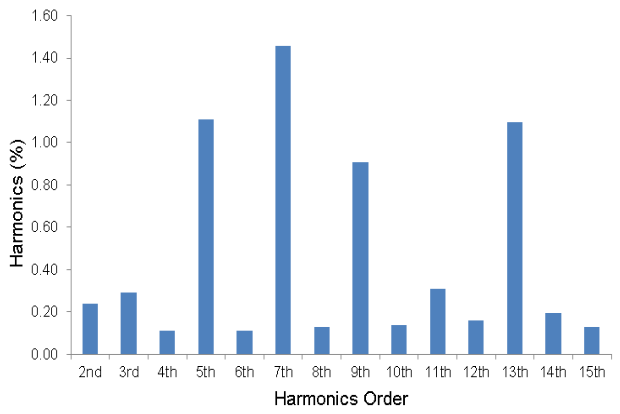
B. Internal discharge: condition 2

The average of the 7th order from a minimum 10 sets of data is higher in the range 20 % to 25 % from the average of 5th and 9th order values. The 5th and 9th order have almost similar values. The 13th order is lower than the 9th order. Since the range of the odd harmonic order is very close and unable to provide the distinct pattern, the even harmonic order is taken into account. The value of the 2nd order is much lower than the 3rd and the 4th order. Fig. 7(b) shows the average of 10 data of harmonic orders obtained from the internal discharge occurred.

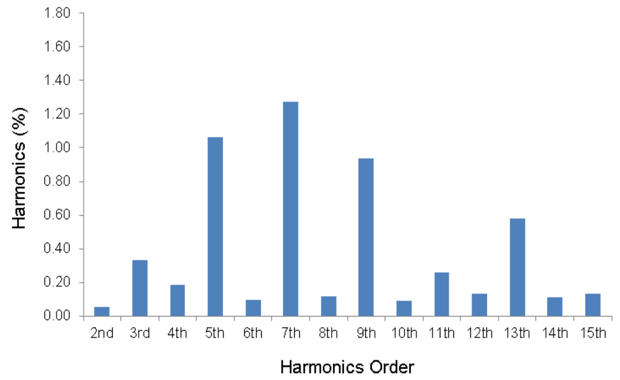
C. Surface discharge: condition 3

The average of a minimum 10 sets of data for the, 13th order is lower in the range of 40 % than the 5th and 9th order.

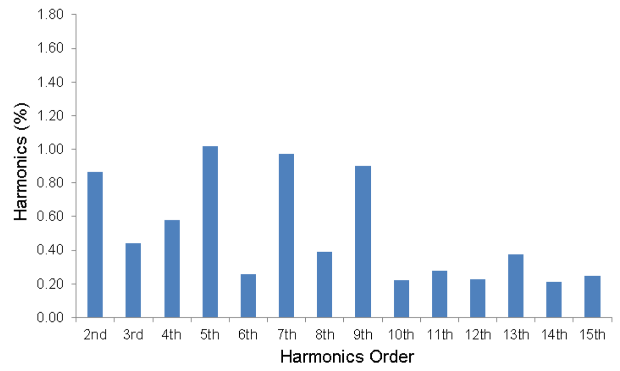
The value of even harmonic order can be concluded as 2nd order is the highest followed by 4th order and 6th order, respectively. Fig. 7(c) shows the average of 10 data of harmonic orders obtained from the surface discharge occurred.



(a)



(b)



(c)

Fig. 7. The average data of harmonic order based on the observation made on the different PD occurred. The harmonic order of (a) corona discharge, (b) internal discharge and (c) surface discharge.

VI. RESULTS AND ANALYSIS

The classifications proposed have been tested using the validated experimental data and the results obtained are presented in Fig. 9–Fig. 10. 10 sets of data have been randomly selected and the harmonic orders of the datasets are extracted. MATLAB software was used to develop an identification system in order to perform the identification process of the data.

The flow diagram of the developed system is shown in Fig. 8. The conditions of each of the PD have been described in the previous section where Condition 1, 2 and 3 representing corona, internal and surface, respectively as stipulated in previous section.

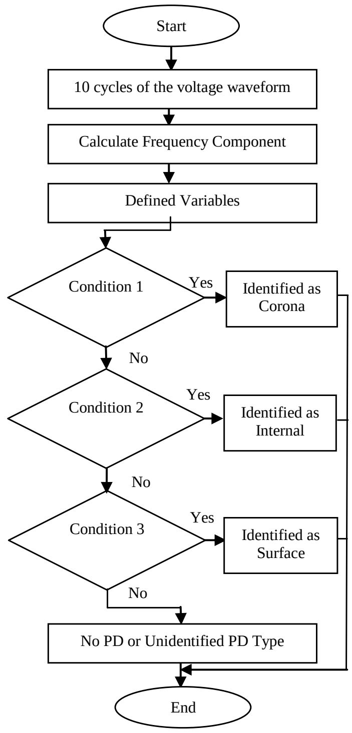


Fig. 8. The flowchart diagram for the new proposed algorithm of conditional method system.

The system criteria selection was developed based on the gathered information of the characteristic of the harmonic order. The average sets calculated earlier will be used as training sets. The purpose of the training set is that the tested data can be matched or refer to the training set for the reference of the classification Fig. 9 shows twenty randomly selected data comprises all types of discharges. Table I show the results obtained in the classification of data from Fig. 9. Twenty data were randomly selected and the identification was based on the classification proposed using the harmonic order. The condition column indicates the type of discharges according to the classification.

TABLE I. THE FIRST SET OF CLASSIFICATION RESULTS USING RANDOMLY SELECTED DATA.

No.	Data	Condition			Results	Remark
		1	2	3		
1.	Data 1	1			Identified	Corona
2.	Data 2	0	0	1	Identified	Surface
3.	Data 3	1			Identified	Corona
4.	Data 4	0	0	1	Identified	Surface
5.	Data 5	0	1		Identified	Internal
6.	Data 6	1			Identified	Corona
7.	Data 7	1			Identified	Corona
8.	Data 8	0	1		Identified	Internal
9.	Data 9	0	0	1	Identified	Surface
10.	Data 10	0	0	1	Identified	Surface
11.	Data 11	0	1		Identified	Internal
12.	Data 12	0	1		Identified	Internal
13.	Data 13	1			Identified	Corona
14.	Data 14	0	0	1	Identified	Surface
15.	Data 15	1			Identified	Corona
16.	Data 16	0	1		Identified	Internal
17.	Data 17	0	0	1	Identified	Surface
18.	Data 18	1			Identified	Corona
19.	Data 19	0	1		Identified	Internal
20.	Data 20	0	1		Identified	Internal

The results column indicates whether the data was successfully identified or not. The remark column indicates the original classification of the data. In order to fully ascertain the classification method proposed, another test was carried out using another set of randomly selected data. Fig. 10 shows another set of randomly selected data comprising of all types of discharges.

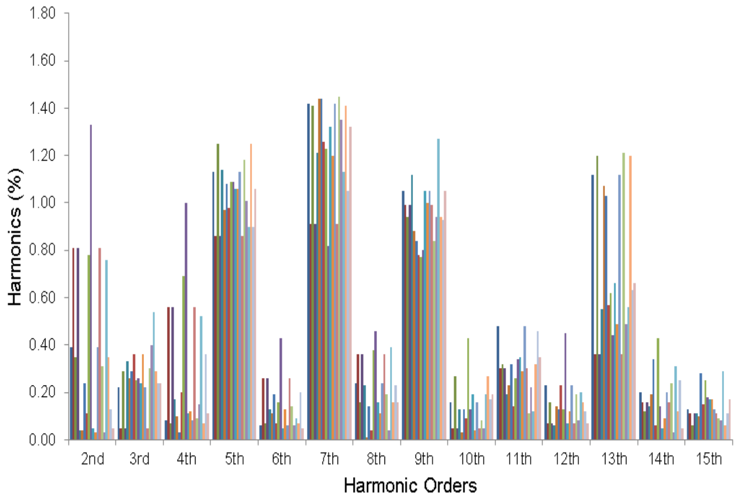


Fig. 9. The twenty randomly selected data.

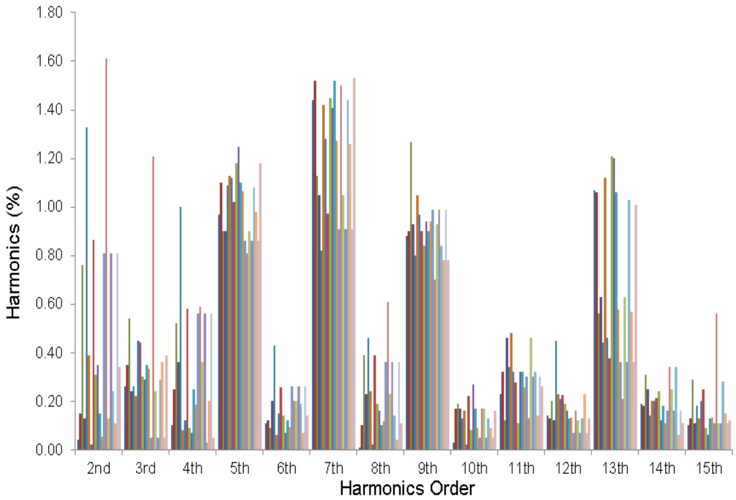


Fig. 10. Another set of 20 randomly selected data to be tested.

Table II shows the results obtained from Fig. 10. The classification based on the proposed algorithm produced identical results to the original classification, showing that data were successfully identified. Results presented in Table I and Table II indicate that all randomly selected data were able to be identified. Obviously the proposed classifications were able to give 100 % of accuracy to identify the precise PD types.

TABLE II. THE SECOND SET OF CLASSIFICATION RESULTS USING RANDOMLY SELECTED DATA.

No.	Data	Condition			Results	Remark
		1	2	3		
1.	Data 21	0	1		Identified	Corona
2.	Data 22	0	1		Identified	Corona
3.	Data 23	1			Identified	Surface
4.	Data 24	0	0	1	Identified	Internal
5.	Data 25	1			Identified	Surface
6.	Data 26	0	1		Identified	Corona
7.	Data 27	0	0	1	Identified	Internal
8.	Data 28	1			Identified	Surface
9.	Data 29	0	1		Identified	Corona
10.	Data 30	0	1		Identified	Corona
11.	Data 31	1			Identified	Corona
12.	Data 32	0	1		Identified	Internal
13.	Data 33	0	0	1	Identified	Surface
14.	Data 34	0	0	1	Identified	Surface
15.	Data 35	0	1		Identified	Internal
16.	Data 36	0	0	1	Identified	Surface
17.	Data 37	1			Identified	Corona
18.	Data 38	0	1		Identified	Internal
19.	Data 39	0	0	1	Identified	Surface
20.	Data 40	1			Identified	Corona

VII. CONCLUSIONS

This work focused on investigating the distinction of harmonics present during the occurrence of PD. The distinction between harmonics characteristics caused by different PD types can be used to classify types of PD. The results of the THD values and harmonics order from 2^{nd} to 15^{th} order were presented. This work has proven that the harmonic characteristic is feasible to be used for classifying the PD type. The experimental result shows a precision of 100 % of the tested data were successfully identified based on the classification using the harmonic order characteristic. There is a high potential for it to be applied in the realm of practical high voltage applications. In real practice, it might be necessary for parameters and settings of the proposed technique to be modified or amended to take into account the condition in the field as opposed to the condition existing in a laboratory setting.

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