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New Clustering Techniques based on Current Peak Value, Charge and Energy Calculations for Separation of Partial Discharge Sources

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ABSTRACT

Clustering techniques are of main interest for separation of partial discharge (PD) sources. The separation is achieved if it is possible to extract from the PD pulses specific information related to the source. In this sense, this paper explores the capability of fundamental quantities derived from PD current pulses such as the peak amplitude I_{peak}, the apparent charge Q, and the energy E as parameters intended for source separation. For this purpose, an unconventional PD measuring circuit is used to acquire PD pulses from several laboratory test objects. Once the pulses are digitized and stored, the values of I_{peak}, Q, and E are computed according to the proposed methods in time and frequency domain. A theoretical analysis is presented to illustrate how values of I_{peak}, Q and E can be related to the pulse shape so that they can be used as source separation parameters. Then, the I_{peak}QE clusters are computed for laboratory measurements. The results showed that these parameters are suitable for separation of sources provided that the pulse shapes are different. This cluster technique was also proved to be independent of the change of the acquisition parameters that are relevant for unconventional measuring systems. In addition, the easiness of the quantities computation makes the clustering technique introduced in this paper feasible for practical applications.

Index Terms —**Partial discharges, clustering techniques, charge, energy, frequency domain, time domain, pulse shapes.**

1 INTRODUCTION

Partial Discharge (PD) measurements for the diagnosis of high-voltage equipment have been exhaustively researched over the years because of their accuracy to detect and quantify defects and damages in the dielectric insulation. One of the main challenges with the analysis of PD measurements is the separation of PD sources. Once a PD source has been separated by a certain means, then the recognition of the source can be done, e.g. by means of phase resolved PD patters (PRPD)[1, 2].

The separation of PD sources entails a proper measuring circuit and a technique of feature extraction that is suitable for the recognition. A requirement for the measuring circuit is a bandwidth wide enough so that the shape of the PD pulse can be resolved in time. For this purpose, the detection and measuring circuits have to be unconventional systems as far as the limits for the bandwidth described in [3] is concerned. Some examples of the bandwidth used for unconventional PD measurements are reported in [4, 5]. On the nanosecond scale of the duration of a PD pulse, the acquired waveforms are determined by the interaction of the physical phenomena of a PD pulse, the object under test and the detection/measuring circuit. Under such an interaction, a bandwidth in the range of MHz might be enough to resolve the shape of the PD pulse that arrives to the measuring sensor.

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The collection of digitally-stored PD pulses are then available for extraction of features. Proper features allow PD source separation based on the assumption that PD pulses from the same source will have homogeneous features [6–8]. The homogeneity of the pulses from the same source is seized to generate clusters by means of which it is possible to separate multiple PD sources from any interfering noise. Moreover, to be effective, the clustering technique should extract information about the PD pulse shape while it is resistant to factors such as noise, external interferences and pulse acquisition parameters [9].

In the search for a suitable clustering technique, this paper evaluates the performance of the values of charge Q, energy E and peak amplitude I_{peak} of the PD pulses as source separation parameters. Although, it is possible that different PD sources give rise to similar values of charge, energy or peak values, the results in this paper show that these parameters and the ratios between them, e.g. E/I_{peak}, E/Q, I_{peak}/Q and E/Q, can still withdraw information about the pulse shape.

The paper proposes a new algorithm for the computation of the charge and energy of PD pulses and then discusses the possibilities for those parameters to be similar depending on the pulse shapes. An experimental part is also considered for the acquisition of PD signals from corona, internal, free moving particle, surface and floating electrode type sources. The signals were produced and acquired by means of a testing platform developed by TU Delft and reported in [10]. The characteristic of the measuring circuit and test samples gave rise to PD pulses having particular shapes for each source which was convenient for this analysis. The data were processed by the software tool to estimate the charge in time domain [11], the energy in frequency domain, build the PRPD patterns and apply clustering techniques. Finally, the effect of changing the acquisition parameters on the proposed clusters is tested and compared with the effect on other clusters reported in literature.

2 SET-UP DESCRIPTION

Measurements were conducted by means of an unconventional PD system comprised of a high frequency current transformer (HFCT) type sensor having a bandwidth from 34.4 kHz to 60 MHz, and an acquisition unit based on a high performance oscilloscope Tektronix DPO7354C with 8 bits of vertical resolution and maximum sampling frequency of 40 GS/s.

The 'Fast Frame Acquisition Mode' feature of the oscilloscope was employed to allow acquisitions with a trigger rearming time below 1 µs, which avoids to miss much PD pulses that arrive narrowly spaced.

This characteristic is useful to record PD pulses of high repetition rate such as those coming from the corona source.

The synchronization signal and each PD pulse acquisition were then stored and processed by means of a software tool developed by TU Delft for the purposes of the test platform reported in [10].

3 COMPUTATION METHODS FOR PD QUANTITIES

The main three quantities that are significant for the clustering techniques in this paper are the current peak value I_{peak}, the charge Q computed in the time domain, and the energy E computed in the frequency domain, of the PD signal sampled at the output of the measuring sensor.

3.1 PEAK VALUE I_{PEAK}

The output of the HFCT is sampled by the acquisition system and stored for post-processing. This voltage output v_k is then affected by the HFCT gain to calculate the current of the PD pulse y_k flowing through the measuring loop. The peak value I_{peak} is computed as the maximum value of the stored vector y_k.

3.2 APPARENT CHARGE Q

The apparent charge Q from a PD pulse can be calculated both in time and frequency domain [11]. For the objectives of this paper only the method in time domain according to the flow chart in Figure 1 will be considered.

In time domain, the charge Q is defined as the integral over the time of duration of the sampled current PD pulse y_k. For the straightforward case of a positive PD pulse such a corona discharge pulse, the charge is the area under the curve of y_k. However, for the specific response of the measuring circuit used in this paper, PD pulses can show oscillations that affect the charge estimation, e.g. the pulses from internal discharges. In order to smooth the effect of oscillations, the signal y_k is first filtered by a second order Butterworth low-pass filter with a cut-off frequency of 10 MHz. Removing the high frequency content of the signal reduces the oscillation as can be seen in Figure 2, which reduces the calculation error.

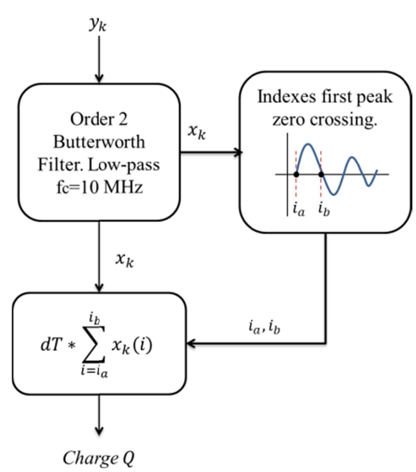

Figure 1. Flow chart to compute the apparent charge Q of a PD pulse.

From the output of the filter x_k, the indexes i_a and i_b representing the first zero-crossing points to the left and to the right of the main peak are computed. In the discrete domain, the charge is then calculated as an approximation of the integral of the first peak of x_k between i_a and i_b via the trapezoidal method with a spacing dT = 1/Fs (Fs=sampling rate) [11].

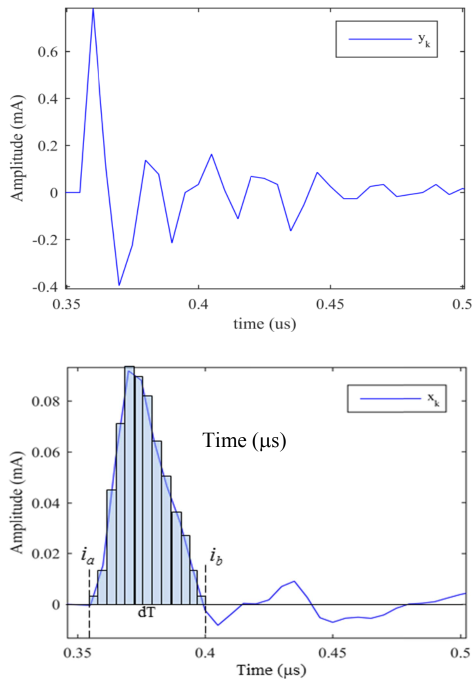

Figure 2. Current input pulse y_k (top). Output of the filter x_k (bottom).

3.3 ENERGY E

Given the voltage signal v_k, the power of the signal is defined as in equation (1) and the energy as in equation (2).

$$P_k = \frac{(v_k)^2}{R} \tag{1}$$

$$E_k = \frac{dT}{R} \cdot \sum_{1}^{N} (v_k)^2 = \frac{dT}{R \cdot N} \cdot \sum_{1}^{N} \left| fft(v_k) \right|^2 \tag{2}$$

where R is the input resistance of the acquisition system, N is the number of samples, and fft is the Fast Fourier Transform.

The equality in equation (2) refers to the Parseval's theorem, stating that the energy of a signal can be computed from time and frequency domain.

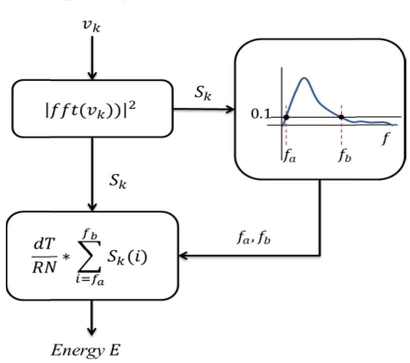

Figure 3. Flow chart to compute the energy E of a PD pulse.

As can be seen in the flow chart of Figure 3, the frequency spectrum S_k is directly computed from the voltage signal v_k. Following a similar procedure as in the charge estimation, the frequency spectrum is truncated by only considering frequency components larger than the 10 % of the maximum peak of the spectrum, i.e. the frequency spectrum within f_a and f_b. This is done as a method to avoid or smooth noise contribution on energy calculation.

4 PD SOURCES CHARACTERIZATION

Laboratory measurements were performed on six distinct PD sources, having acquisition settings as listed in Table 1. The interaction of the test object capacitance and the measuring circuit brought about different PD pulses for each source whose characteristic pulse shapes are shown in Figure 4 to Figure 9 along with the corresponding PRPD pattern. Particularly, for positive and negative corona discharges the pulse shapes had an exponentially damped waveform without any oscillation, whereas the other PD sources were characterized by a sinusoidal damped waveform with multiple oscillations.

Table 1. Acquisition parameters for the different PD tests.

Name	PD source	VR (mV)	Fs (GS/s)	T (μs)
Test A	Floating particle	78.12	0.2	1
Test B	Free moving particle	1.95	0.2	1
Test C	Internal	11.72	0.2	1
Test D	Negative Corona	0.39	0.2	1
Test E	Positive Corona	0.39	0.2	1
Test F	Surface	117.8	0.2	1

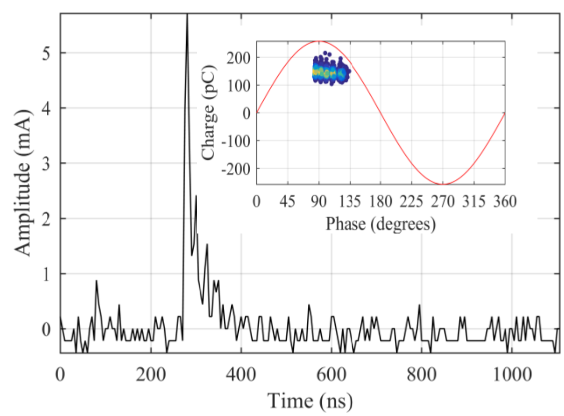

Figure 4. PRPD pattern and pulse shape for a negative corona discharge.

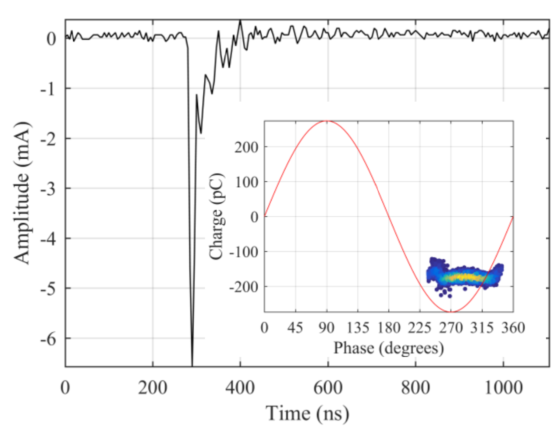

Figure 5. PRPD pattern and pulse shape for a positive corona discharge.

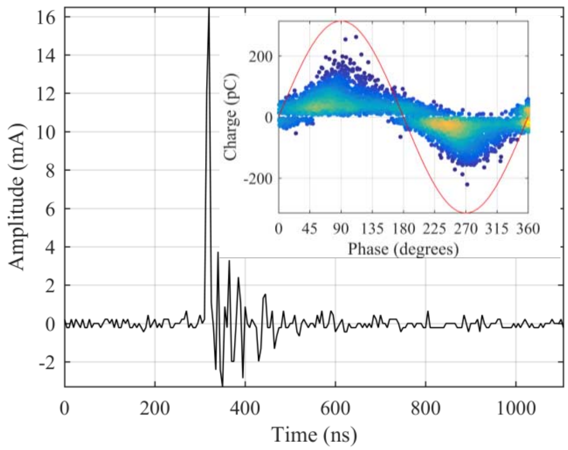

Figure 6. PRPD pattern and pulse shape for a free moving particle discharge.

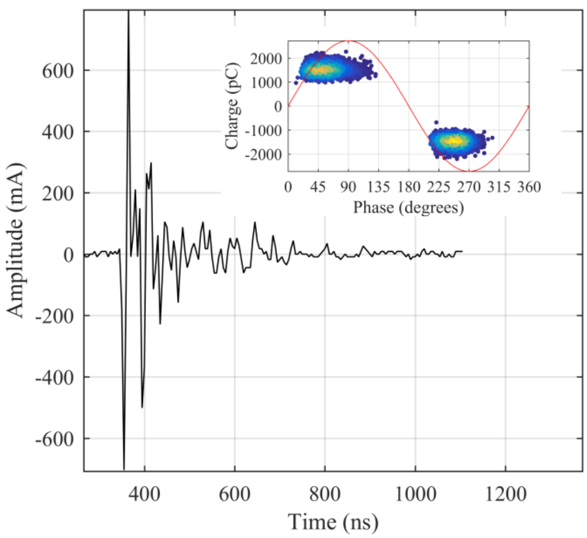

Figure 7. PRPD pattern and pulse shape for a floating electrode discharge.

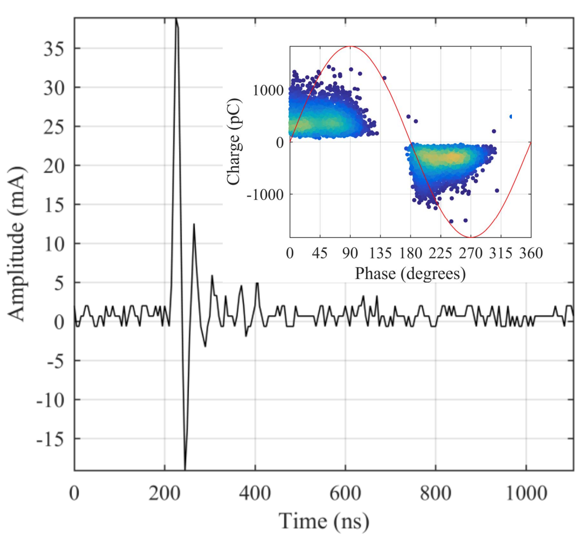

Figure 8. PRPD pattern and pulse shape for an internal discharge.

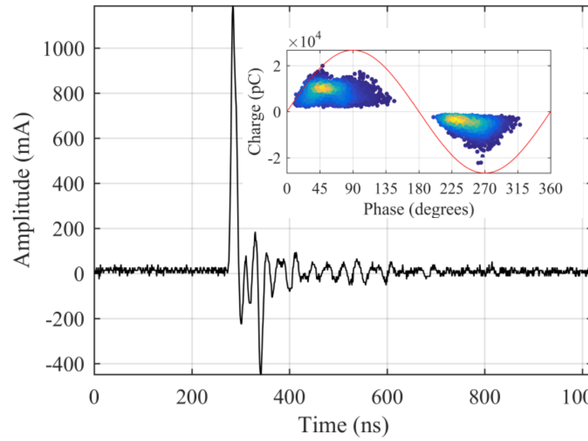

Figure 9. PRPD pattern and pulse shape for a surface discharge.

The similarities in time domain seen for positive and negative corona discharges are confirmed by Figure 10, where the frequency spectrum for both types of discharges is also comparable. However, this is not the case for the oscillatory PD pulse shapes. The frequency spectra in Figure 11 show particular differences for the oscillation of each PD source.

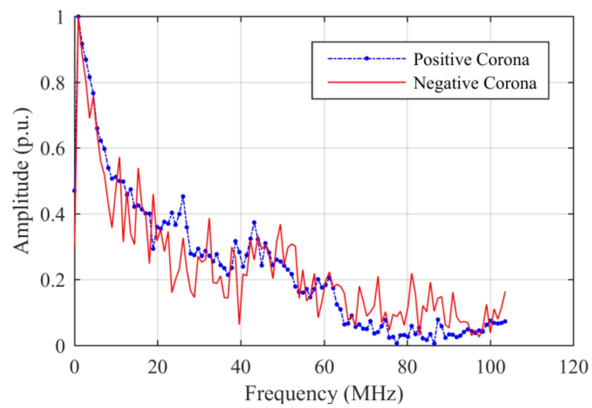

Figure 10. Frequency spectrum for a positive and negative corona discharge.

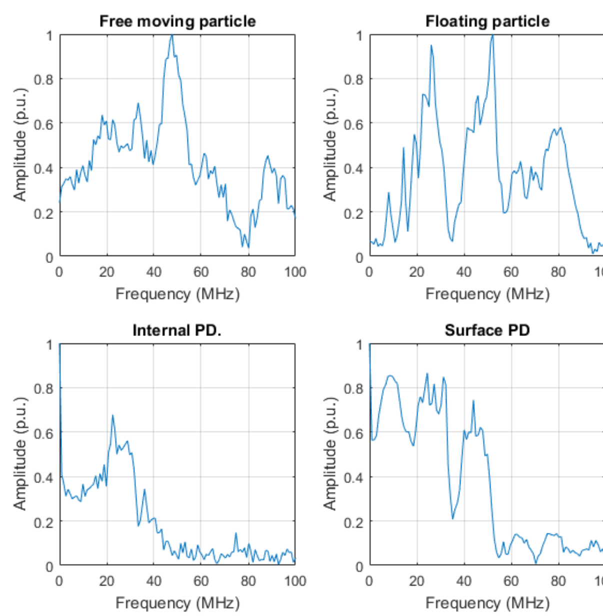

Figure 11. Frequency spectrum for discharges with an oscillatory waveform.

5 PD SOURCE SEPARATION BY I_{peak}QE CLUSTERS

5.1 THEORETICAL ANALYSIS

To separate PD sources, in this paper the set of parameters peak value I_{peak}, charge Q and energy E were analysed.

The ability of these set of parameters to separate PD sources depends on the assumption that the pulse shape is significantly different from one source to another. In this sense, two different sources might have similar values of any two of the parameters I_{peak}, Q and E, but if the waveforms are different then there is a low likelihood that all the three parameters become similar. Several scenarios as those shown in Figure 12 to Figure 14 are proposed to illustrate how different theoretical pulses can share one or two parameters, whereas it is still possible that a third parameter remains independent.

The first case, in Figure 12, shows two square pulses having the same values of charge but different amplitudes and energy values.

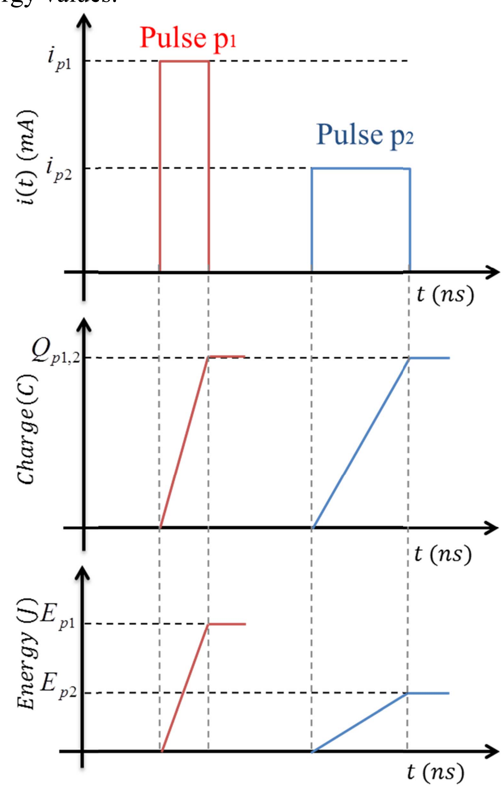

Figure 12. Two square pulses having the same charge but different energy and amplitude.

The second case in Figure 13 shows oscillatory pulses with the same amplitude. It is interesting to note that the area of positive peaks cancels out the area of negative peaks, as in the case of pulse p_4, leading to the same values of charge. However, on account of the square operand for the computation of the energy, this cancelation would not be possible, and the values of energy will be different for each type of pulse.

The opposite effect is illustrated in Figure 14, where the energy and amplitude are the same for both oscillatory pulses, but the charge of pulse p_6 doubles the charge of pulse p_5

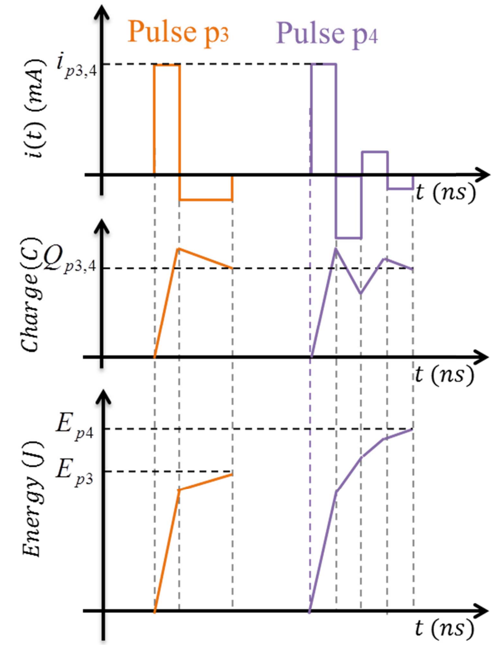

Figure 13. Two oscillatory pulses having the same charge and amplitude but different energy.

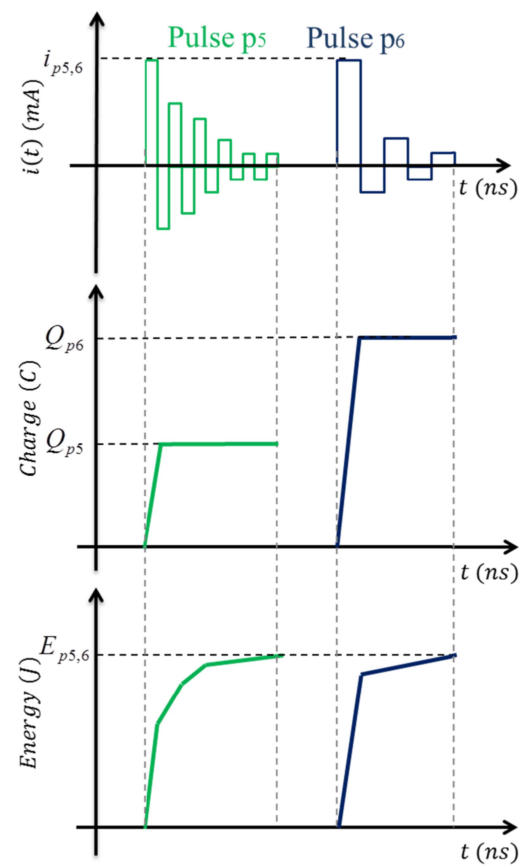

Figure 14. Two oscillatory pulses having the same amplitude and energy but different charge.

Laboratory measurements on PD electrodes were conducted to prove the limits of the former hypothesis. The performance of the values of peak amplitude I_{peak}, charge Q and energy E as well as the relations E/I_{peak}, E/Q, I_{peak}/Q and E/Q were tested as parameters for source separation. The experimental results are analyzed in the next section.

5.2 EXPERIMENTAL RESULTS FOR SINGLE SOURCES

For each single PD source test listed in Table 1, 20.000 PD pulses were acquired. The computation of the peak value I_{peak}, charge Q and energy E by the methods described in section 3 led to the I_{peak}QE cluster plots.

Figure 15 to Figure 17 correspond to the cluster plots when only two parameters are considered. As expected, some PD sources share some features, which can be seen as an overlapping of clusters with common features. Since not all the three parameters are similar for two PD sources, they can be overlapped in one cluster, but separated in any other.

This is for example the case for the pulses from test F and A; in Figure 16 both clusters appear very close as they have similar values of amplitude and energy, however, in Figure 15 both clusters are clearly separated on account of different values of charge.

Comparison between corona and free moving particle is interesting because despite the pulse shapes from test E and D differ from the pulse shape from test B, their values of amplitude and energy came out comparable, leading to an overlapping as shown in Figure 16. Alternatively, different values of charge make it possible a separation as can be seen in Figure 15 and Figure 17.

Particularly for test E and D, the clusters always were overlapped regardless of the parameters used, which is explained mainly by the similarity in pulse shapes of corona discharge pulses, see Figure 4 and Figure 5.

Moreover, the case of test C and B is a good example of the role of the statistical distribution of results in the separation of sources. Note that both sources can be slightly overlapped in any cluster of Figure 15 to Figure 17, but since the values of the parameters spread over a wide range, it is still possible to separate one source from the other.

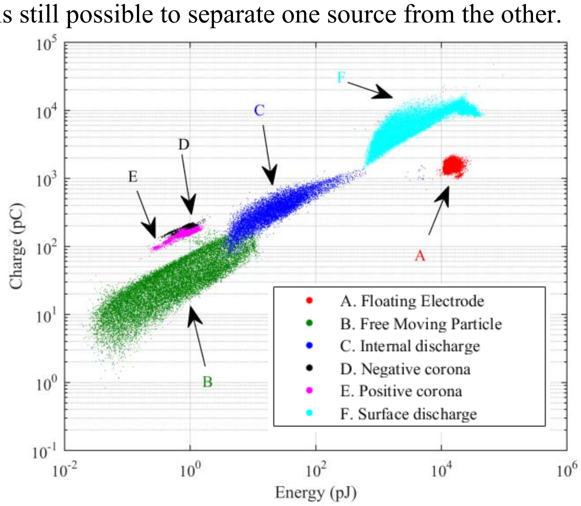

Figure 15. Cluster Q vs E.

As it was highlighted, a characteristic required for the best performance of a clustering technique is that the parameters used can bring about separated clusters as much as possible, avoiding overlapping areas. Accordingly, an improvement in the separation of the clusters is achieved by considering the relations E/I_{peak}, I_{peak}/Q and E/Q as clustering parameters.

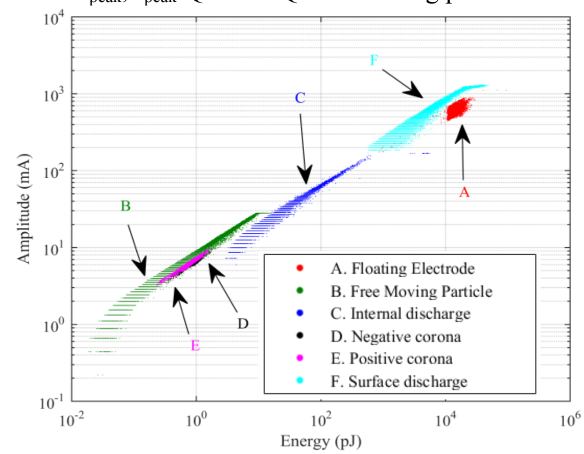

Figure 16. Cluster I_{peak} vs E.

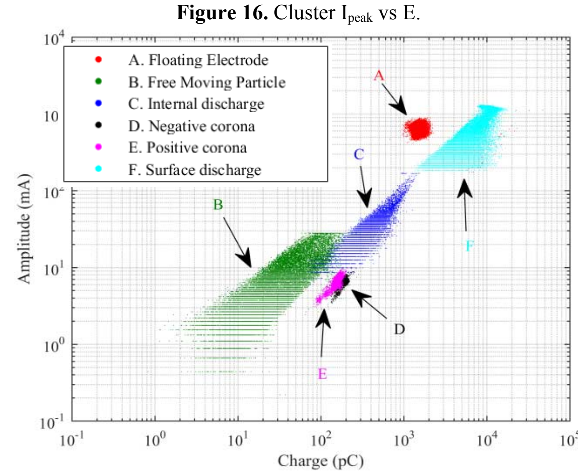

Figure 17. Cluster I_{peak} vs Q.

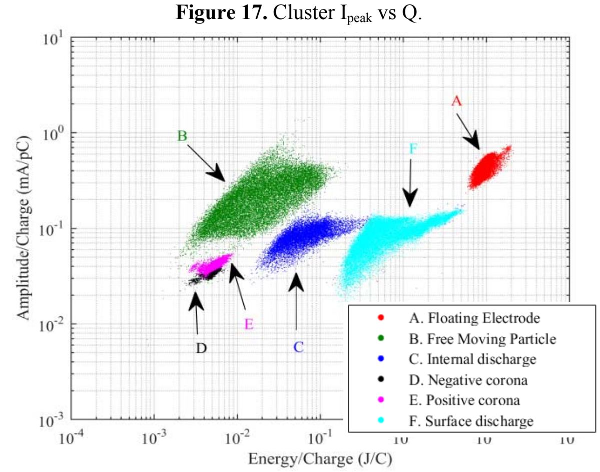

Figure 18. Cluster I_{peak}/Q vs E/Q.

The resulting cluster plots with these relation parameters are shown in Figure 18 and Figure 19. Each PD source now appears separated from each other without any overlapping, except for the case of test D and E corresponding to the corona discharges. These experiments show the performance of the I_{peak}QE cluster technique.

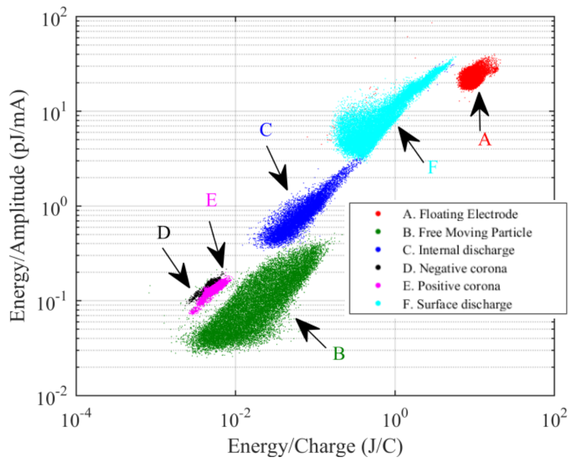

Figure 19. Cluster E/I_{peak} vs E/Q.

5.3 EXPERIMENTAL RESULTS FOR MULTIPLE SOURCES

An extra set of measurements were carried out on an arrangement having corona and free moving particle discharges. The PRPD pattern for this case of multiple PD sources is shown in Figure 20.

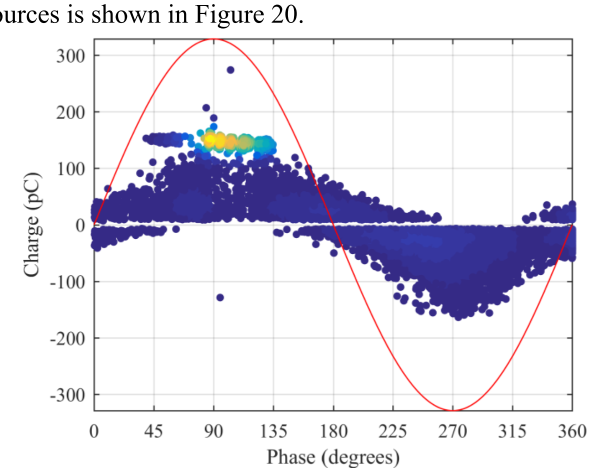

Figure 20. PRPD pattern for corona and free moving particle discharges.

Figure 21 shows that based on the parameters I_{peak} and E it is not feasible to separate the cluster of the corona discharge pulses from those of the free moving particle discharges. Both parameters are common for both sources and therefore they appear as merged clusters.

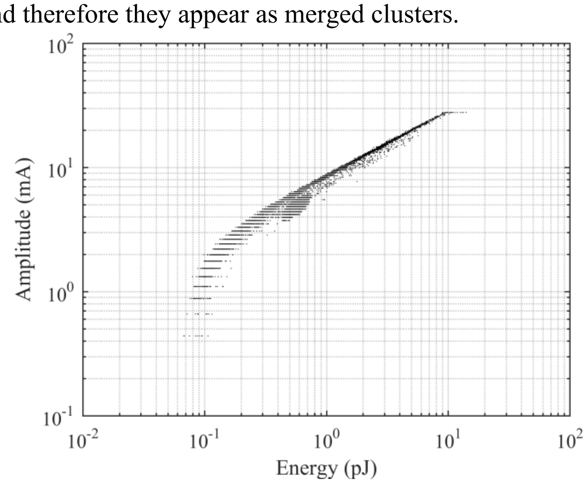

Figure 21. Cluster I_{peak} vs E for the case of corona and free moving particle discharges.

If the parameter I_{peak} is now replaced by the charge Q, even when the PRPD pattern shows values of charge in the same order of magnitude, the cluster Q vs E in Figure 22 clearly allows to distinguish the two different PD sources. Likewise, the separation of the sources is also possible if the relations E/I_{peak} vs E/Q are employed as depicted in Figure 23.

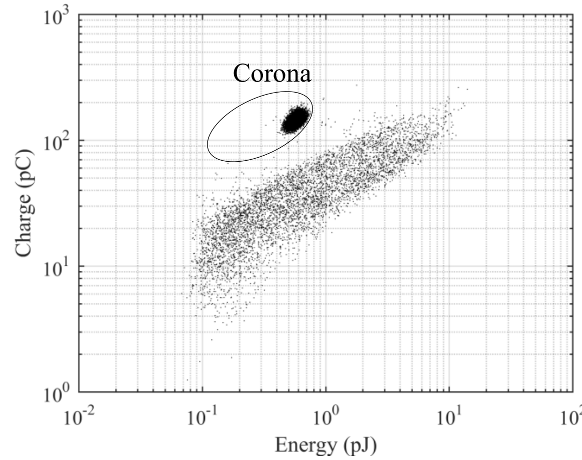

Figure 22. Cluster Q vs E for the case of corona and free moving particle discharges.

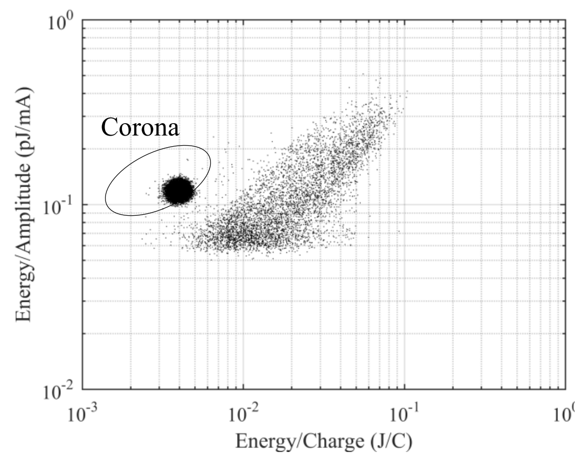

Figure 23. Cluster E/I_{peak} vs E/Q for the case of corona and free moving particle discharges.

6 EFFECT OF ACQUISITION PARAMETERS ON CLUSTERS

In [9] it was discussed the effect of the acquisition parameters that are relevant for unconventional PD measuring systems on the results of clustering parameters.

Particularly, the well-known and extensively used classification map reported in [12], that is based on the computation of the equivalent time T_{eq} and frequency bandwidth W_{eq}, was proved to be affected by settings such as sampling frequency, acquisition time, number of samples and vertical resolution of the acquisition.

To test the effect of these settings on the clusters based on I_{peak}, Q and E, a number of tests as described in Table 2 were carried out with different acquisition parameters.

For this analysis, the positive corona discharge source was chosen because of its stability. By using corona discharge pulses is possible to record pulses having fairly homogeneous shapes and a high repetition rate.

Table 2. Acquisition parameters for the measurements of positive corona.

Name	VR (mV)	Fs (GS/s)	T (μs)
Test G1	0.39	0.2	1
Test G2	0.39	2.5	5
Test G3	0.39	5	2
Test G4	0.39	1	10
Test G5	0.39	1	1
Test G6	1.56	1	1

Likewise, the repeatability of the measurements is high so that the experiments can be easily duplicated elsewhere.

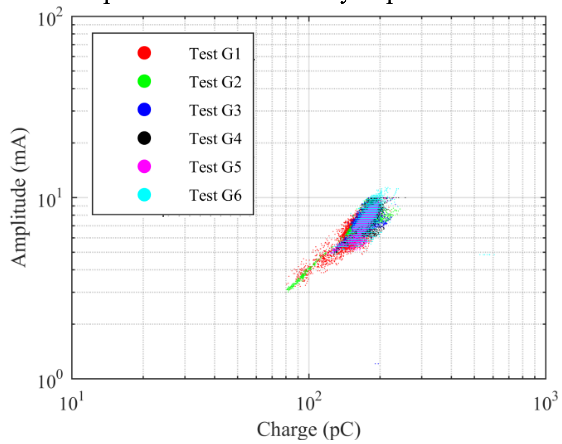

Figure 24. Cluster I_{peak} vs Q for the case of positive corona discharges with varied acquisition parameters.

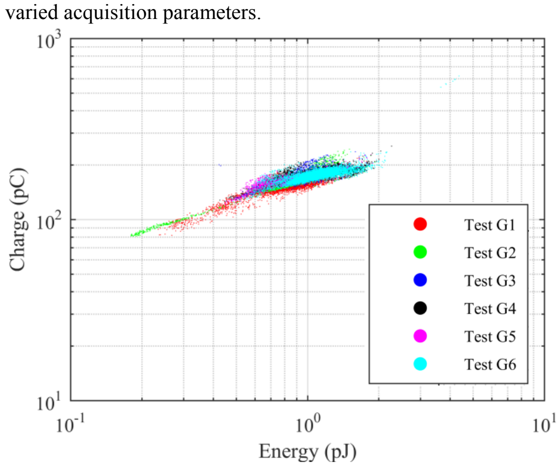

Figure 25. Cluster Q vs E for the case of positive corona discharges with varied acquisition parameters.

When comparing the clusters based on I_{peak}, Q and E (Figure 24 and Figure 25) with the clusters from the classification map (Figure 26), it can be claimed that no critical differences arose from the change in the acquisition parameters in the case of clusters based on I_{peak}, Q and E. Conversely, in the case of the classification map, each setting gave rise to a different cluster for the same PD source with different magnitude and shape.

These results suggest that the acquisition parameters are not critical parameters for the construction of clusters based on I_{peak}, Q and E which entails an advantage. Less requirements on the acquisition parameters also suggests that the proposed clustering technique is achievable by a wide range of instruments that can easily be implemented for laboratory measurements.

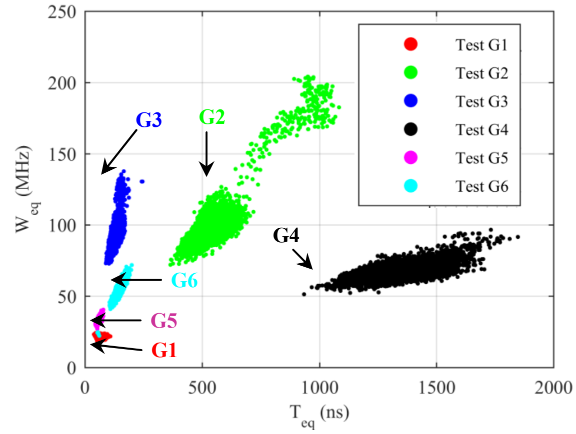

Figure 26. Cluster W_{eq} vs T_{eq} (classification map) for the case of positive corona discharges with varied acquisition parameters.

7 CONCLUSION

A new clustering technique based on the parameters I_{peak}, Q and E was evaluated for the purpose of separation of PD sources. The results showed that the use of these parameters succeeds in the source separation provided that the pulse shapes are significantly different from one source to another. For the measurements in laboratory test objects, it was found that different sources can have similar values of any two of the parameters I_{peak}, Q and E but if the waveforms are clearly different then there is a low likelihood that all the three parameters become similar. This fact enabled the source separation by the selection of the proper combination of parameters. The relations E/I_{peak}, I_{peak}/Q and E/Q also proved to contribute to enlarge subtle differences between source waveforms, showing that the I_{peak}QE clusters are a powerful tool for PD source clustering.

Correspondingly, the values of I_{peak}, Q and E were similar for PD sources with similar pulse shapes. This was the case of positive and negative corona where the set of clusters always were overlapped regardless of the parameters. On the other hand, the algorithms hereby implemented were able to distinguish the polarity of the pulses which in the case of corona discharges would allow the separation of positive from negative corona discharges.

The stochastic behaviour of the PD phenomena brings about a statistical distribution of the results. However, if there exist significant differences between the values of I_{peak}, Q and E for distinct PD sources, the effect of the statistical distribution will be less.

With unconventional PD measuring systems the acquisition parameters play an important role in clustering techniques because as reported in Figure 26 the parameters such as sampling frequency, period, number of samples and vertical resolution of the acquisition affect the magnitude and shape of the clusters based on the equivalent time and frequency bandwidth. On the other hand, the clusters based on I_{peak}, Q and E were proved to be more independent on such acquisition parameters which makes it suitable for practical application.

Another advantage of a cluster based on I_{peak}, Q and E is its versatility. A combination of two parameters might be unable to separate sources, but it is possible that any other combination does succeed.

In field measurements, PD sources are likely to have different pulse shapes on account on the physics of the discharge and the propagation path. Therefore, the I_{peak}QE clustering technique introduced in this paper is a feasible tool for practical applications.

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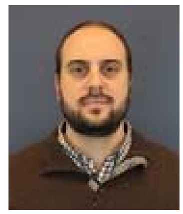

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