Effect of Harmonics on Pulse Sequence Analysis Plots from Electrical Trees

N.H. Aziz[1], V.M. Catterson[1], S. M. Rowland[2] and S. Bahadoorsingh[3]
[1]Institute for Energy and Environment, University of Strathclyde, Glasgow G1 1XW, United Kingdom
[2] School of Electronic and Electrical Engineering, The University of Manchester, Manchester M13 9PL, United Kingdom
[3]Department of Electrical and Computer Engineering, The University of the West Indies, St Augustine, Trinidad and Tobago

***Abstract*- This paper investigates the effect of harmonic pollution on the Pulse Sequence Analysis (PSA) pattern. Partial discharge data was captured from electrical trees growing in epoxy resin in the presence of different harmonic regimes. These regimes included 50Hz waveforms polluted with 3rd, 5th, 7th, 11th, 13th, 23rd and 25th order harmonics, at varying levels of Total Harmonic Distortion (THD) and waveshape factor (K_S). In this paper, the data has been analyzed using PSA by plotting the external voltage of consecutive PD pulses (u_n vs u_{n-1}). Under pure 50 Hz conditions, four clusters of data points can be identified in the plot and the formation of the clusters is discussed. Further investigation was performed by running the samples to breakdown. The results show that even in the presence of harmonics, an increase of PD occurrence and phase distribution translates into the expected PSA pattern, where clusters of data points merge to form a 45° straight line. Therefore, PSA is relatively immune to the effects of harmonic distortion when considering it only as an indicator of breakdown.**

I. Introduction

Partial discharge (PD) is a well-accepted indicator of the degradation of electrical insulation, permitting early detection of insulation faults. A common method of analyzing PD data is to use phase-resolved partial discharge (PRPD) patterns. In order to minimize statistical scatter, this method usually examines accumulated data sets by extracting some statistical parameters from distributions of specific discharge quantities. However, in last two decades, pulse sequence analysis (PSA) has been introduced to give a different interpretation of the real physical phenomena involved in partial discharge activity during the degradation process [1]. The main idea behind this method is the strong correlation between consecutive pulses: specifically that previous discharges influence the initiation and development of subsequent pulses.

Harmonic pollution on power networks is an issue of growing interest, due to increasing numbers of polluting loads such as switched mode power supplies and power electronics [2]. Harmonics have been shown to affect the PRPD pattern in ways that may lead to an over-estimation of PD severity, depending on the type of defect and harmonic orders present [3]. Previously, the effect of harmonics on PD activity [4], electrical tree growth [5] and insulation breakdown time [6] have been discussed using electrical treeing experimental data from epoxy resin samples. In this paper, the effect of harmonics on electrical tree growth is again discussed, but using the PSA approach.

II. Experimental Methodology

The experimental approach employed here has previously been described in [6]. Electrical trees were induced in LY/HY5052 epoxy resin samples using a point-plane setup of 3 μm radius hypodermic needles with a 2 mm insulation gap. Seven composite waveforms, defined in Table I and shown in Fig. 1, containing the 50Hz fundamental and various controlled magnitudes of harmonic components [6] were applied to separate samples. The peak signal voltage was held constant in each test at 14.4 kV.

In this study, total harmonic distortion (THD) was set at values up to 40%. In Table 1, ϕ is defined as the phase difference between the harmonic components and the fundamental. K_s, formulated by Montanari et al [7], is defined as a proportional measure of the RMS derivative of the composite waveform. Thus, K_s is an indication of the waveform steepness and can be described as a measure per unit time of change in the electrical field of the dielectric (relative to a non-distorted sinusoidal waveform).

III. Pulse Sequence Analysis

Pulse sequence analysis (PSA) treats PD pulses as events within a sequence. The rationale behind this approach is that the history and condition of a sample, including recent discharge events, influence the ignition and nature of the next discharge pulse. In particular, key governing parameters of

TABLE I
Properties of Seven Test Waveforms

Wave	*Composition + 50Hz*				*THD %*
	Harmonic Order	% of Each Harmonic	ϕ	K_s	
1	3	40.0	0	1.56	40.00
7	1	100.0	0	1.00	0.00
8	5	5.0	0	1.03	5.00
9	7	5.0	0	1.06	5.00
11	7	17.8	0	1.60	17.8
12	5,7,11,13,23,25	3.2	0	1.60	7.85
13	5,7,11,13,23,25	2.0	0	1.27	5.00

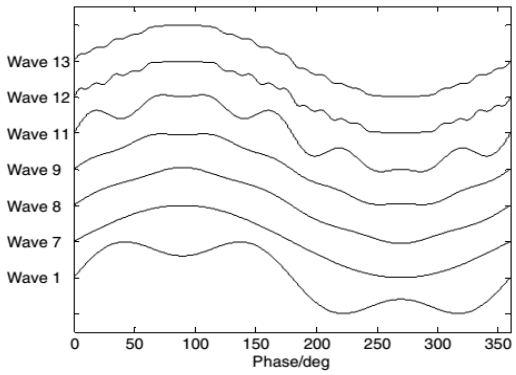


Fig. 1. Illustration of the seven test waveform defined in Table 1

each discharge are the local electric field and its change from the last pulse, which are both dependent on the voltage difference between consecutive pulses. The voltage differences do not occur at random but in specific sequences characterizing the discharge processes in the defect, at least in part due to the build-up of space charges [8].

In this paper, the sequence of the voltage difference between pulses, ΔU, is identified as a key parameter (shown in Fig. 2a). This is calculated by first examining the instantaneous voltage, $u(t)$, of every PD pulse using one of equations (1) to (7), which define the test waveforms in Table 1 and Fig. 1. ΔU is then determined using (8).

$$u_1(t) = 10.25\sqrt{2}(\sin\theta + 0.4\sin 3\theta) \quad (1)$$

$$u_7(t) = 10.18\sqrt{2}(\sin\theta) \quad (2)$$

$$u_8(t) = 9.7\sqrt{2}(\sin\theta + 0.05\sin 5\theta) \quad (3)$$

$$u_9(t) = 10.4\sqrt{2}(\sin\theta + 0.05\sin 7\theta) \quad (4)$$

$$u_{11}(t) = 9.35\sqrt{2}(\sin\theta + 0.178\sin 7\theta) \quad (5)$$

$$u_{12}(t) = 10.15\sqrt{2}(\sin\theta + 0.032(\sin 5\theta + \sin 11\theta \sin 13\theta + \sin 23\theta + \sin 25\theta)) \quad (6)$$

$$u_{13}(t) = 10.18\sqrt{2}(\sin\theta + 0.02(\sin 5\theta + \sin 11\theta \sin 13\theta + \sin 23\theta + \sin 25\theta)) \quad (7)$$

$$\Delta U_i = u(t_i) - u(t_{i-1}) \quad (8)$$

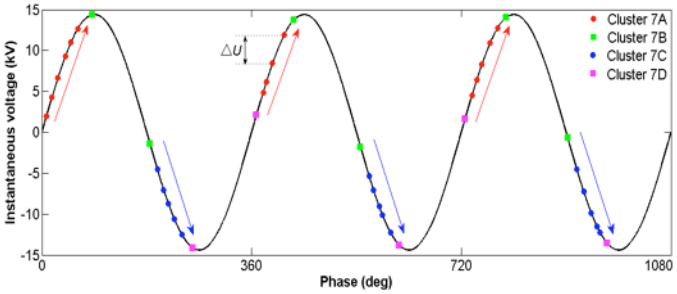
Fig. 2 shows three voltage cycles of instantaneous voltage for a sample tested under Wave 7 (fundamental) at early tree growth (Fig. 2a) and immediately before breakdown (Fig. 2b). The breakdown time of the sample is 130 minutes. The Figure shows two groupings of PD, which have been labeled as four clusters:

- All PD pulses in the 1st quadrant form Cluster 7A.
- The last pulse of the 1st quadrant and the first pulse of the 3rd quadrant form the Cluster 7B.
- All PD pulses in 3rd quadrant form Cluster 7C.
- The last pulse of the 3rd quadrant and the first pulse of the 1st quadrant form Cluster 7D.

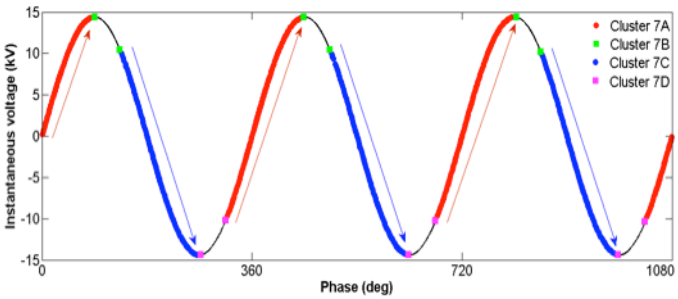
These clusters can be observed more clearly in the u_n vs u_{n-1} plot, shown in Fig. 3. Clusters B and D arise from the relatively large ΔU around the peak voltage, since PD stops occurring when ΔU changes from positive to negative or vice versa. Clusters A and C contain the majority of the PD pulses which occur after a relatively small voltage change.

Prior to breakdown, three distinct features can be observed which can be treated as indicators when estimating the insulation breakdown time:

- The number of PD pulses per voltage cycle increases
- The voltage difference, ΔU, decreases
- The phase distribution expands.

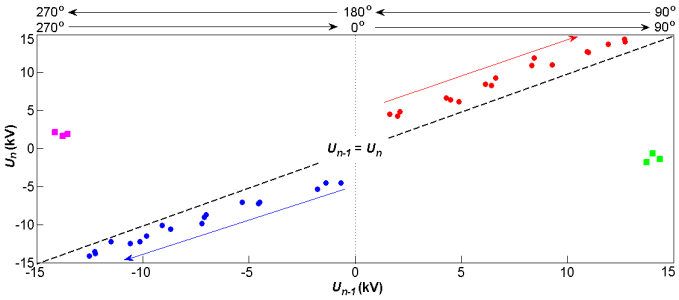


(a) 20 minutes

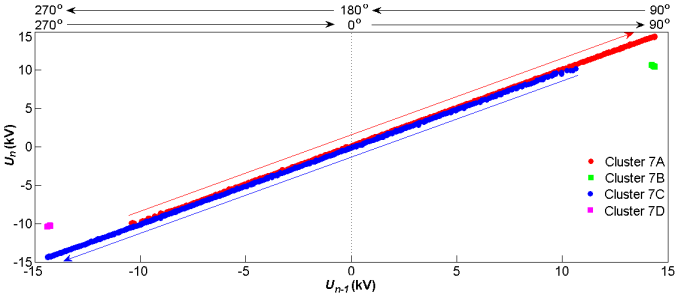


(b) 110 minutes

Fig. 2. The instantaneous voltage, $u(t)$, of PD occurrence overlaid on Wave 7

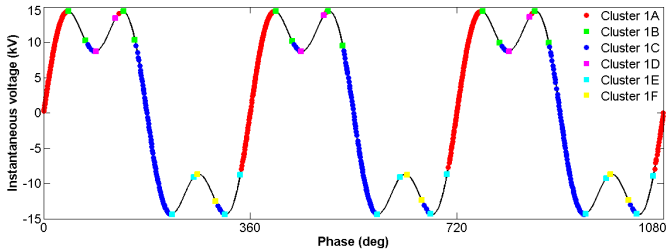


(a) 20 minutes

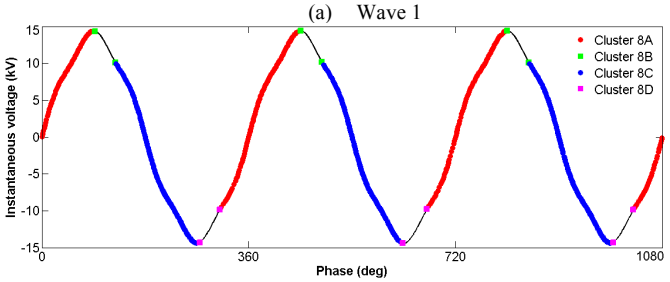


(b) 110 minutes

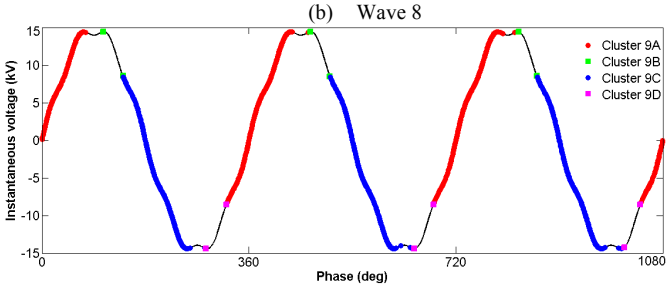
Fig. 3. The consecutive voltage plot, u_n vs u_{n-1}, of PD from a sample tested



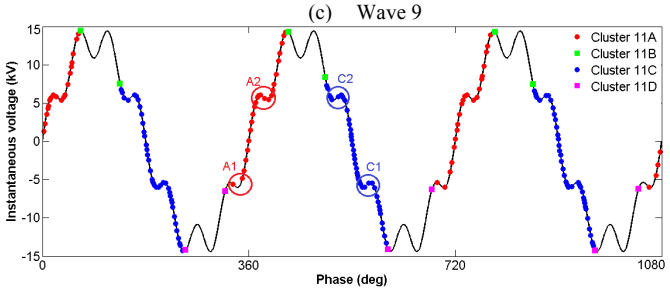
(a) Wave 1



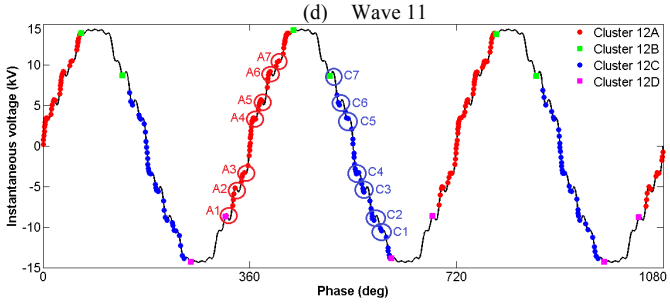
(b) Wave 8



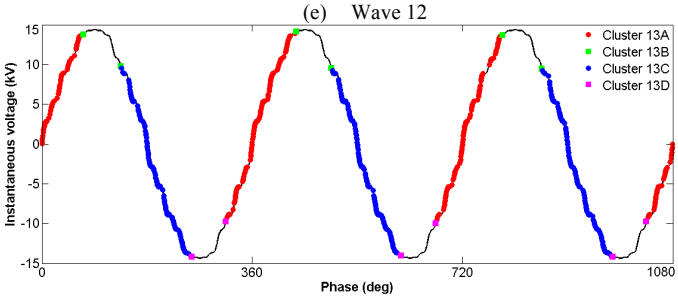
(c) Wave 9



(d) Wave 11

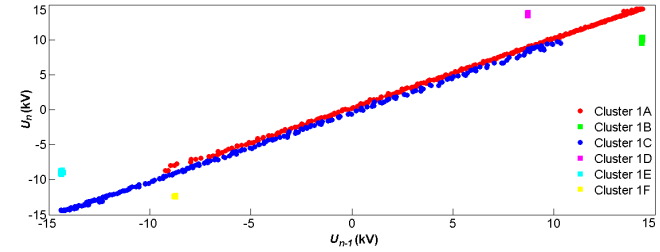


(e) Wave 12

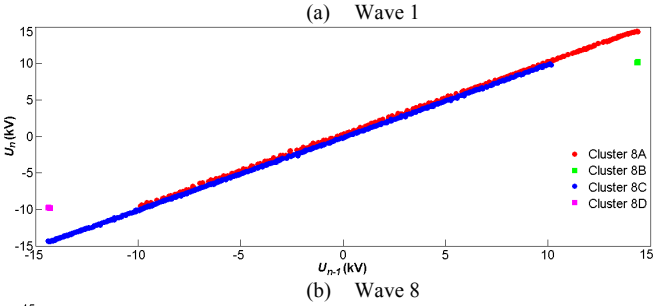


(f) Wave 13

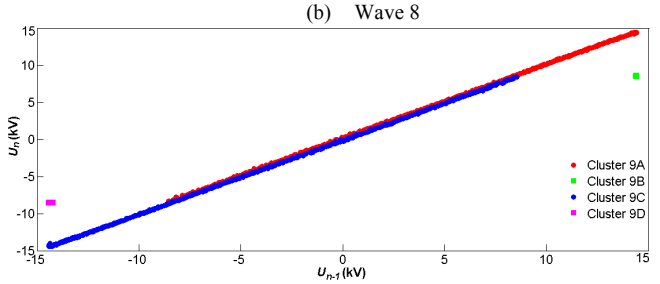
Fig. 4. The instantaneous voltage, $u(t)$, plot of samples tested



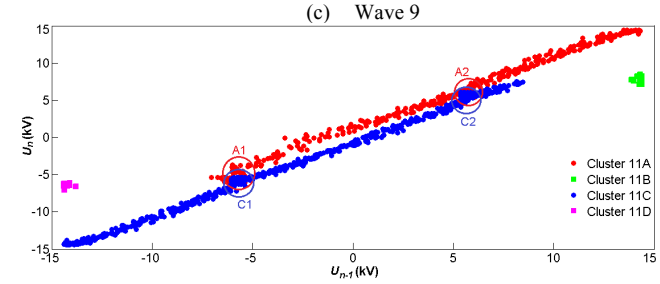
(a) Wave 1



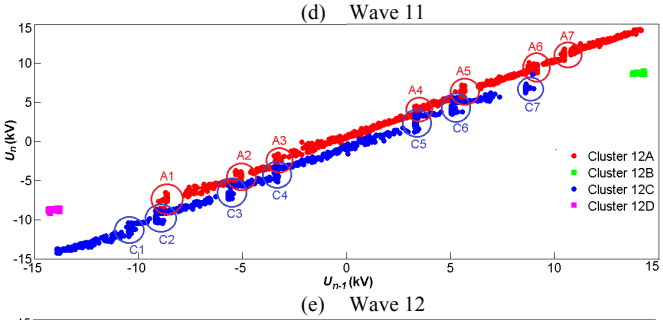
(b) Wave 8



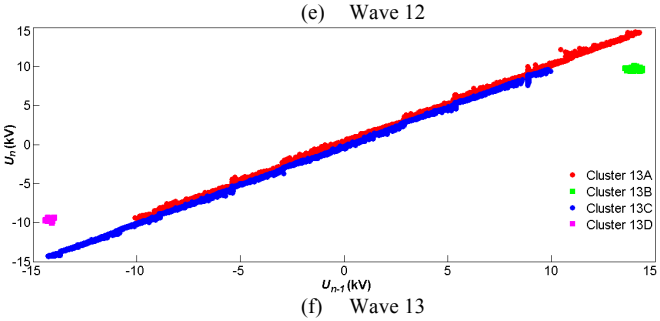
(c) Wave 9



(d) Wave 11



(e) Wave 12



(f) Wave 13

Fig. 5. The consecutive voltage plot, u_n vs u_{n-1}, of samples tested

It is expected that PD pulses fill almost the entire phase range immediately before breakdown occurs, resulting in very small voltage change, i.e, $u_{n-1} \approx u_n$. Thus, the u_n vs u_{n-1} plot for breakdown will form a 45° line. Throughout the tree growth, the four clusters in Fig. 3a merge to form the dominant diagonal line in Fig. 3b.

IV. Effect of Harmonics

The instantaneous voltage and u_n vs u_{n-1} plots of test waveforms 1, 8, 9, 11, 12 and 13 are shown in Fig. 4 and 5 respectively. Among the six non-sinusoidal test waveforms, the sample tested with Wave 1 shows a great difference, having six clusters compared to the four clusters of all others. This is because Wave 1 has an extra two peaks per voltage cycle compared to Wave 7. Although Wave 9 and 11 also have 4 peaks, their THD values are smaller than Wave 1, thus giving a smaller range of ΔU values between the two peaks in either the positive or negative half cycle. These contribute to Clusters 9A and 9C respectively (see Fig. 4c) rather than forming new clusters.

Since Wave 8 has the smallest THD and K_s compared to the other harmonic waveforms, the u_n vs u_{n-1} plot looks very similar to the fundamental Wave 7. Wave 9 also shows the same characteristics as Wave 7 and 8, having also only a 5% THD.

Wave 11 contains the 7^{th} harmonic like Wave 9, but with greater THD and K_s. Thus, it has extra features in the u_n vs u_{n-1} plot as shown in Fig. 4d and 5d. It can be seen that around ±5kV of Cluster 11A and 11C, the ΔU changes polarity from positive to negative (Cluster 11A) and vice versa (Cluster 11C). Those changes however do not generate a new cluster of points, but instead form an extra feature marked by circles in Fig. 5d.

The samples tested with Waves 12 and 13 show similar characteristics to Wave 11 but at different voltages, depending on the voltage at which the polarity of ΔU changes. As we can see in Fig. 4e and 5e, the changes occur at seven spots in Cluster 12A and seven spots of Cluster 12C. The same applies to Wave 13, but is not clearly shown in Fig. 4f and 5f because the changes are very small due to smaller THD and K_s.

V. Conclusion

This paper investigates the effect of harmonics on the PSA plot of PD generated by electrical trees. Some of the test harmonic waveforms produce special features in the u_n vs u_{n-1} plot, notably Waves 11, 12, and 13, due to THD being high enough for the extra voltage peaks to temporarily cease PD activity. In the case of Wave 1, the THD is so severe that the extra peak generates separate clusters in the PSA plot. However, when the waveshape factor is low enough, the PSA plot is almost indistinguishable from that generated by the fundamental.

Despite these properties, as all samples near breakdown the data points merge to form the PSA's characteristic 45° straight line. For this reason, the PSA plot can be considered an indicator of breakdown which is relatively immune to the effects of harmonics.

Acknowledgment

The first author wishes to acknowledge the Universiti Teknikal Malaysia Melaka and Malaysian Government, for giving her the opportunity to pursue her PhD study and for her financial support.

VMC and SMR gratefully acknowledge the EPRSC for the financial support of this work through the Supergen HubNet project EP/I013636/1.

References

[1] M. Hoof and R. Patsch, "Analyzing partial discharge pulse sequences—A new approach to investigate degradation phenomena," in *IEEE Int. Symp. Electrical Insulation*, 1994, pp. 327–331.

[2] A. Kusko and M. T. Thomson, "Power quality in electrical systems," McGraw-Hill, 2007.

[3] B. Florkowski, M. Florkowski and P. Zydron, "The Role of Harmonic Components on Partial Discharge MEchanism and Degradation Processes in Epoxy Resin Insulation," *Int. Conf. Solid Dielectrics*, 2007.

[4] S. Bahadoorsingh and S. Rowland, "An investigation of the harmonic impact on electrical treeing partial discharge activity," in *IEEE Int. Symp. Electrical Insulation (ISEI)*, 2010.

[5] S. Bahadoorsingh and S. M. Rowland, "An investigation of the harmonic impact on electrical tree growth," *IEEE Int. Symp. Electrical Insulation (ISEI)*, 2010.

[6] S. Bahadoorsingh and S. Rowland, "Investigating the impact of harmonics on the breakdown of epoxy resin through electrical tree growth," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 17, no. 5, pp. 1576–1584, 2010.

[7] G. Montanari and D. Fabiani, "The effect of nonsinusoidal voltage on intrinsic aging of cable and capacitor insulating materials," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 6, no. 6, pp. 798–802, 1999.

[8] R. Patsch and F. Berton, "Pulse Sequence Analysis—a diagnostic tool based on the physics behind partial discharges," *Journal of Physics D: Applied Physics*, vol. 35, no. 1, p. 25, 2002.