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Analysis of Partial Discharge Behaviour under Staircase-based Sinusoidal Voltage Waveforms

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Abstract- This paper presents a comparison in Partial Discharge (PD) behaviour when an air corona setup is subjected to different waveforms, namely an idealized 50 Hz sinusoidal and staircase-based sinusoidal waveforms near inception voltage and at a higher voltage. In this study, it has been observed that the PD repetition rate and the Phase-Resolved PD (PRPD) pattern with the staircase waveform better resemble that of a pure sinusoidal waveform if the number of voltage levels of the staircase waveform is sufficiently increased. When observed more closely at the PRPD pattern near inception voltage, PDs tend to occur near the slope of the staircase waveform, even when the step voltage is small.

Keywords- Partial Discharges, Air corona, Staircase waveforms, MMC-based HV test source

I. INTRODUCTION

High Voltage (HV) equipment in the electrical power system are experiencing new electrical stresses due to the rise of renewable energy integration with power electronics [1,2]. For this reason, HV equipment must be designed and tested for such new electrical stresses to ensure their reliable operation. To emulate these new electrical stresses, a Power Electronics (PE)-based programmable HV test source is being developed using a Modular Multilevel Converter (MMC) for KEMA laboratories. Such a PE-based test source generates HV test waveforms in the form of a staircase waveform when Nearest Level Control (NLC) methodology is used [3]. When a sinusoidal and other periodic waveforms are generated from such a test source, it is possible to eliminate these harmonics using a low pass filter. However, the idea is to generate complex wave shapes with a wide frequency spectrum where the addition of passive filtering is not straightforward. That is why it is important to study the effect of steep fronts (with high dV/dt) and introduced harmonics of the staircase waveform on the HV testing.

The evaluation of insulation stresses in grid assets can be conducted by examining Partial Discharges (PD), dielectric losses, breakdown strength, and electric field distribution. Since there is extensive knowledge about PD behaviour in 50 Hz sinusoidal waveform, this is selected as a benchmarking case to study the effect of the staircase waveform. Hence, this paper compares PD behaviour under pure sinusoidal and staircase waveform made of different voltage levels. It is important to point out that the maximum number of levels generated from an MMC is a design constraint which strongly affects the cost and complexity of the system. Thus, to identify the minimum number of levels and suitable step response of the generated voltage waveform that produces acceptable performance closer to the desired (ideal) reference is of paramount importance for the optimal design of the test source.

Ref. [4,5] studied the effect of a 2 level Pulse Width Modulated (PWM) waveform on the HV insulation system of electrical machines. It was found that the features of the PWM waveform, i.e. switching frequency, duty ratio, and voltage magnitude have a deep impact on the PD magnitude, repetition rate, phase and time-resolved pattern. Ref. [6,7] suggested that the higher the number of levels in the PWM waveform, the lesser is the PD magnitude and inception voltage. Also, it is concluded in [6] that the multilevel PWM applies a new type of stress, which is a combination of AC, DC, and chopped waveforms.

For a better understanding of different wave shapes mentioned above, the typical voltages generated by power electronic systems operating with 3-, and 9-levels are shown in Fig. 1. Note that the graphs in pink and blue are generated by voltage source converters operated with PWM modulation logics, while the voltage generated in green and brown are created by a multilevel converter operated with NLC. 3-levels PWM waveforms are quite critical with respect to both magnitude and frequency of dV/dt application when compared to the staircase waveform. Multilevel PWM waveforms are mainly critical with respect to frequency of dV/dt application when compared to the staircase waveform with the same number of levels. This paper offers a comparison in PD behaviour when an air corona setup is subjected to a pure 50 Hz sinusoidal and staircase waveform with a different number of voltage levels and different step responses for each voltage level.

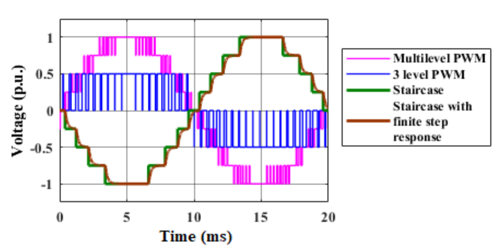

Fig. 1. Different wave shapes as the output of the PE converters

The remainder of the paper is divided into four sections. Section II describes the experimental setup and test

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methodology. Section III and IV show and discuss the obtained results, respectively. Section V concludes the article and gives future research recommendations.

II. Experimental setup

Since the MMC-based HV test source is not yet ready in our laboratory, an arbitrary waveform generator and a Trek 30/20A HV amplifier setup are used to generate the desired staircase waveform with different number of levels. The test object is a traditional air corona with a needle length of 3.2 cm with a diameter of 0.3 mm. PD measurements are performed using two identical High-Frequency Current Transformers (HFCTs), along with a high-end oscilloscope, Tektronix DPO 7354C. Each HFCT has a gain of 9.1 mV/mA and bandwidth of 40 kHz to 130 MHz. A coupling capacitor is used to provide a low impedance and high-frequency path for the PD signal. In addition, a blocking inductor is installed to limit the noise from the amplifier. The schematic and the actual PD measurement setup are shown in Fig. 2. After the HFCTs, band-pass filters (1.37 MHz – 90 MHz) are installed to filter the capacitive current present when the staircase waveform is applied.

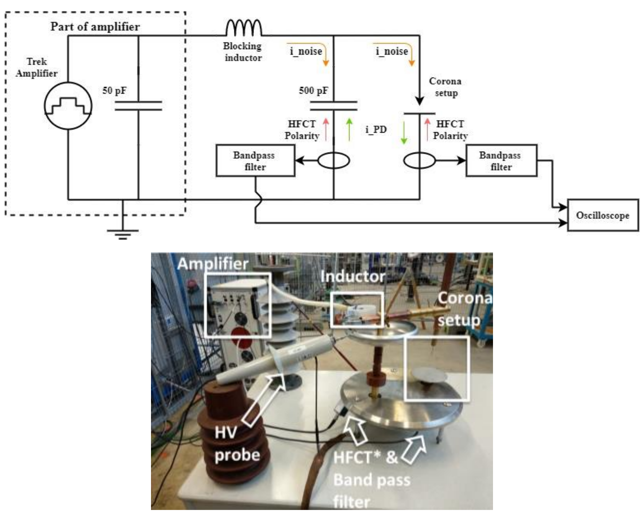


Fig. 2. Schematic and actual PD measurement setup

The polarities of the two installed HFCTs are in the same direction so that it is possible to check if the measured signals are PDs or electrical disturbances by comparing the polarity of signals obtained from both HFCTs. Before the actual PD measurement, the setup is checked to be PD free by measuring PDs without the corona needle. After preparing the setup, PDs are captured using a single HFCT, which is below the test object to showcase the results. The methodology used is as listed in the following:

- Apply different wave shapes such as sinusoidal and staircase waveforms with 3-, 5-, 7-, 13-, and 41-levels to observe the trend. Also, the step response in staircase waveforms has finite delay as defined by the slew rate of the HV amplifier and the impedance of the circuit. This delay is made longer by adding a resistor and the performance of sinusoidal and staircase waveforms with 41-, and 68-levels are compared with and without the resistor.
- Due to the presence of an overshoot in the staircase waveforms, the inception voltage changes slightly for different staircase waveforms as a function of the overshoot. To avoid this effect, the performance of different waveforms is compared at a voltage slightly higher than the inception voltage i.e. 5.6 kV and a voltage of 8 kV, some 40% higher than the 5.6 kV.
- Fixed number of PD events (1000) are captured for each measurement, and the repetition rate is calculated based on the timestamp of the last PD. Each wave shape is not tested repetitively. Hence, the showcased results don't analyze the pseudo-stochastic behaviour of PD.

III. Results

This section presents the obtained experimental results in four subsections, each showing the effect of the staircase waveform with a different number of voltage levels and with the different step response, on repetition rate, and Phase-Resolved PD (PRPD) pattern.

A. Effect of the staircase waveform with a different number of voltage levels on the PD repetition rate

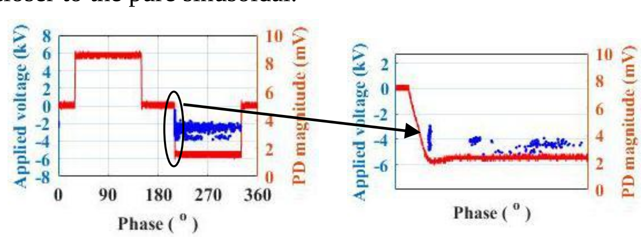
The average repetition rate for sinusoidal and staircase waveforms with different voltage levels are summarized in table I at the peak voltage of 5.6 kV and 8 kV. The voltage at which the first PD occurs at the higher voltage is also represented along with the repetition rate in table I.

TABLE I
TREND IN THE PD REPETITION RATE WITH SINUSOIDAL AND STAIRCASE WAVEFORM WITH A DIFFERENT NUMBER OF VOLTAGE LEVELS

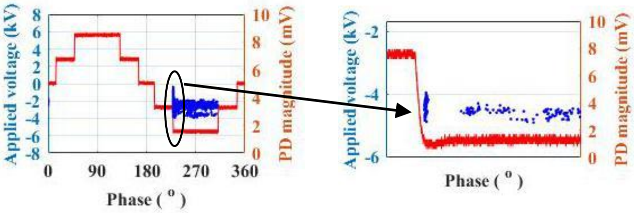
No of levels	$V_{p, applied}$ = 5.6 kV	$V_{p, applied}$ = 8 kV	
	Average repetition rate (PD k.pulses/s)	Average repetition rate (PD k.pulses/s)	Voltage at which first PD observed (kV)
3 levels	0.4	6.2	-5.5
5 levels	0.3	4.1	-5.4
7 levels	0.2	3.8	-5.3
13 levels	0.2	3.1	-5.2
41 levels	0.1	2.9	-5.0
Pure Sine	0.1	2.7	-5.0

B. Effect of the staircase waveform with a different number of voltage levels on the PRPD pattern

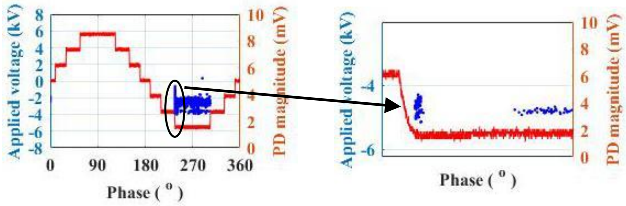
The PRPD patterns of sinusoidal and staircase waveforms with a different number of voltage levels are shown in Fig. 3 at peak voltage of 5.6 kV. The PRPD pattern at higher voltage of 8 kV is shown for the pure sinusoidal and staircase waveform with 41 levels in Fig. 5 since this gives a response closer to the pure sinusoidal.



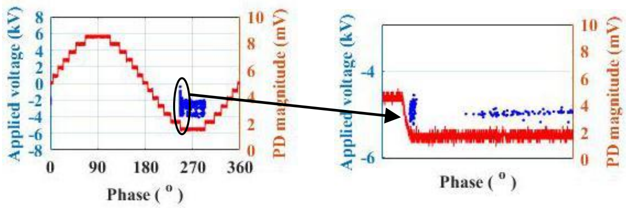
(a) Staircase waveform with 3 levels



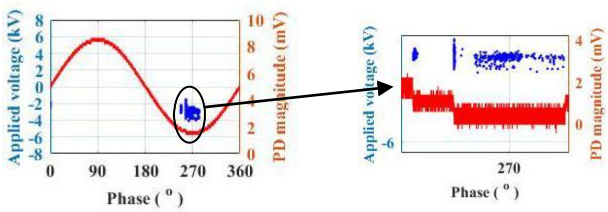
(b) Staircase waveform with 5 levels



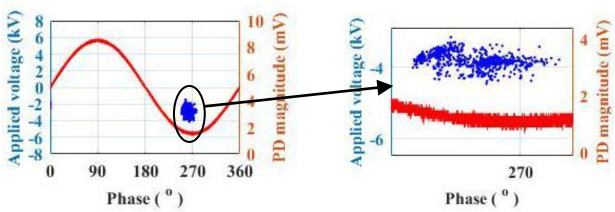
(c) Staircase waveform with 7 levels



(d) Staircase waveform with 13 levels



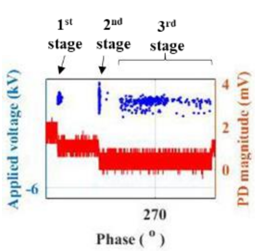
(e) Staircase waveform with 41 levels



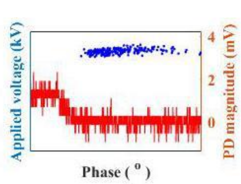
(f) Pure sinusoidal

Fig. 3. Comparison of sinusoidal and staircase waveform with a different number of voltage levels on the PRPD pattern at V_p = 5.6 kV

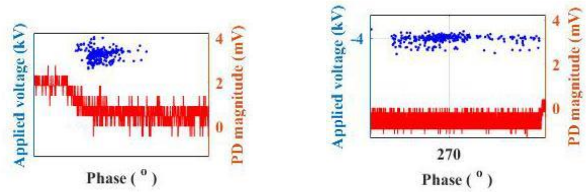
When further zoomed into Fig. 3(e), three different stages of PD patterns are observed as shown in Fig. 4. In *stage I*, PDs occurs just after the slope. In *stage II*, PDs occur on the slope. *Stage III* shows random behaviour of PDs as seen in DC. In this case, the magnitude of voltage step is 280 V.



(a) Zoomed version



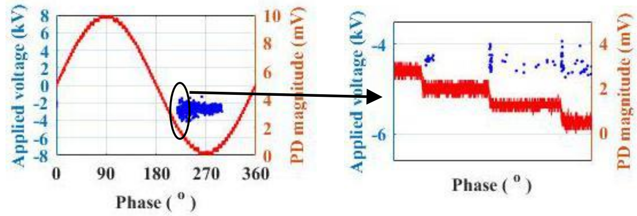
(b) Stage I



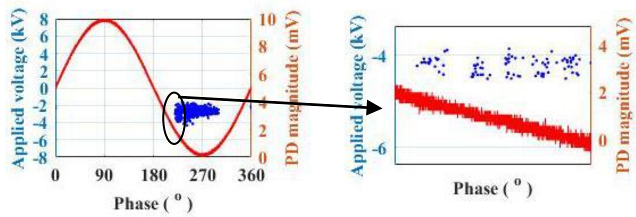
(c) Stage II (d) Stage III

Fig. 4. PRPD pattern for staircase waveform with 41 level at V_p = 5.6 kV

Fig. 5 shows the PRPD pattern for 41 level staircase waveform and sinusoidal waveform with a zoomed picture. In this case, the magnitude of voltage step is 400 V.



(a) Staircase waveform with 41 levels



(b) Pure sinusoidal

Fig. 5. Comparison of sinusoidal and staircase waveform with 41 levels on the PRPD pattern at V_p = 8 kV

C. Effect of the staircase waveform with a different step response on the PD repetition rate

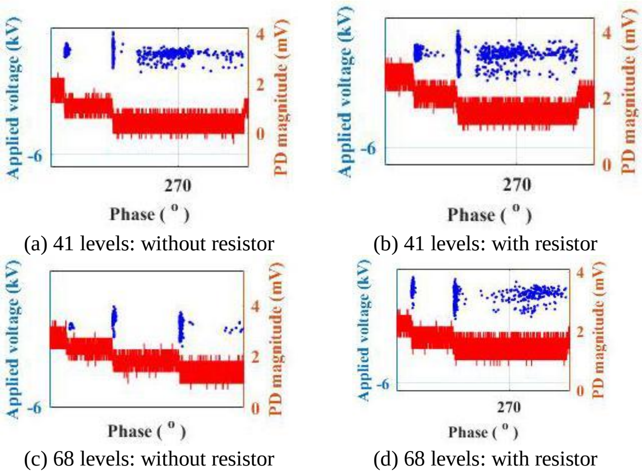
The step response of the staircase waveform is changed by adding a resistor of 100 kΩ in series with the blocking inductor. By adding such a resistor, the step response is changed from 10 µs to 50 µs. The obtained results are compared for 41 levels, 68 levels, and pure sinusoidal in table II.

TABLE II
TREND IN THE PD REPETITION RATE WITH SINUSOIDAL AND STAIRCASE WAVEFORM WITH A DIFFERENT STEP RESPONSE

No of levels	$V_{p, applied}$ = 5.6 kV		$V_{p, applied}$ = 8 kV	
	Average repetition rate (PD k.pulses/s)		Average repetition rate (PD k.pulses/s)	
	Without resistor	With resistor	Without resistor	With resistor
41 levels	0.2	0.2	2.6	2.6
68 levels	0.2	0.2	2.5	2.6
Pure Sine	0.1	0.1	2.6	2.6

D. Effect of the staircase waveform with a different step response on the PRPD pattern

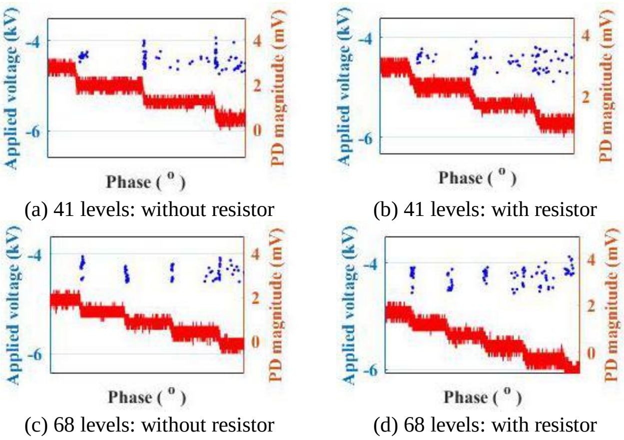
The effect of different step response of the staircase waveform is shown in Fig. 6 and Fig. 7 with zoomed pictures since the full cycle PRPD pattern is not changing drastically.



(a) 41 levels: without resistor (b) 41 levels: with resistor

(c) 68 levels: without resistor (d) 68 levels: with resistor

Fig. 6. PRPD pattern at V_p = 5.6 kV



(a) 41 levels: without resistor (b) 41 levels: with resistor

(c) 68 levels: without resistor (d) 68 levels: with resistor

Fig. 7. PRPD pattern at V_p = 8 kV

IV. Discussion of Results

The observations made from the obtained results are summarized below:

- The average PD repetition rate of the staircase waveform at Vp = 5.6 kV and Vp = 8 kV resembles one of the pure sinusoidal as the number of levels is increased, as shown in table I.
- At Vp = 8 kV with the staircase waveforms, the voltage at which the first PD observed changes due to involved voltage steps. As the magnitude of the voltage step is reduced in the staircase waveform, the voltage at which the first PD observed becomes the same as pure sinusoidal.
- PRPD pattern of staircase waveform changes near inception voltage when compared to the sinusoidal case. There are bulk of PDs occurring near the slope even though the magnitude of the voltage step is relatively small (~ 230 – 400 V).
- When zoomed into the performance of 41 levels near inception voltage in Fig. 4, three stages are observed as described below:
  - *Stage I* – PDs occur just after the slope, as shown in Fig. 4(b)
  - *Stage II* – PDs occur on the slope in Fig. 4(c)
  - *Stage III* – PDs occur randomly, as shown in Fig. 4(d). There is a gap between PD occurring on the slope and the subsequent constant (DC) part.

  This behaviour suggests that the electric stress applied is a combination of AC, DC, and transient.
- The average PD repetition rate of staircase waveforms with different step responses is almost the same, as shown in table II.
- For the staircase waveform with a slower step response, the concentrated bulk of PDs move to the subsequent constant (DC) part in the case of a staircase waveform with 41 levels near inception and higher voltage. However, this is not distinctly visible for the staircase waveform with 68 levels with the PRPD pattern shown in Fig. 6 and Fig. 7.

V. Conclusion and Further Recommendations

For the corona discharges in air, the PD performance of the staircase waveform resembles the pure sinusoidal as the number of voltage levels is increased. However, a significant difference has been observed with the PRPD pattern near inception voltage with the staircase waveform. A staircase waveform with a slower step response did not conclusively shift the bulk of PDs away from the voltage steps near inception voltage. Primary analysis suggests that the applied electric stress with the staircase waveform is a combination of AC, DC, and transient. Nevertheless, further investigations and measurements are needed to find out why the PRPD pattern changes near the inception and how the step response affects it. In summary, the change in PRPD pattern near inception voltage with staircase waveforms indicates different electrical stress compared to pure sinusoidal, and therefore the MMC based HV test source should generate output voltage waveform with at least 68 levels with a rather slow step response.

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