Partial Discharges in Insulation Systems Subjected to Multilevel Converters

Marek Florkowski, Paweł Błaszczyk, Paweł Klimczak

ABB Corporate Research, ul. Starowiślna 13A, 31-038 Kraków, Poland

ABSTRACT

The ubiquitous presence of power electronics devices in power conversion applications across various voltage levels creates new challenges for the designers of insulation systems. The stresses applied to insulation systems by power electronics devices require new approaches for evaluating the intensity and frequency content of working electric field strength and degradation processes. Typically these parameters are assessed through the analysis of partial discharges. Increasingly, due to the advantages they offer for example in efficiency, harmonic distortion and filtering strategies, multilevel converters are implemented in industrial applications. This paper presents an analysis of partial discharges in an electrical insulation system subjected to high voltage waveforms obtained from a multilevel converter. A comparison between the number of levels and modulation frequency on partial discharge inception and intensity are presented.

Index Terms — Partial discharges, multilevel converters.

1 INTRODUCTION

The widespread involvement of power electronics devices in power conversion applications across various voltage levels creates new challenges for designers of insulation systems. Fast switching processes produce complex stresses and high frequency phenomena interplaying with charge behavior in dielectric insulating materials. The most widely accepted control technique typically utilized in converters and inverters are based on pulse width modulation. These kinds of control schemes impart stresses on insulation systems that require new approaches for evaluating the intensity and frequency content of working electric field strength and degradation processes. Typically these parameters are assessed through analysis of partial discharges. However, most research studies devoted so far to electrical insulation aspects, have been based on two-level converters. Increasingly, multilevel converters are implemented in industrial applications, due to their advantages for example in efficiency, harmonic distortion and filtering strategies. This paper presents an analysis of partial discharges in electrical insulation systems subjected to a high voltage waveform from a multilevel converter. The experiments have been performed on specially prepared model samples. A programmable voltage source modular multilevel converter was used in the tests. The topology of the power electronics building blocks and control approach is described. The flexible configuration allows for adjustment of the number of voltage levels and switching frequency of the modulated subperiods. Partial discharges (PD) were detected by a high frequency transformer, galvanically separated from the power path. A comparison of the partial discharge inception and intensity for various number of converter levels and modulation frequencies are presented. The partial discharges were acquired in the form of phase-resolved patterns and correlated with multilevel voltage waveforms on the slopes and constant voltage parts. In addition partial discharges on individual levels in the multilevel sequence were evaluated.

2 MEASUREMENT SETUP AND SPECIMEN

Multilevel converters can be realized in a number of ways, with various forms of topologies and a variety of control algorithms being possible [e.g. 1, 2]. Modular Multilevel Converters (MMC) have gained high attention mainly due to their scalability and the fact that they may be comprised of subcomponents with lower ratings. There are different conversion applications such as AC-DC, AC-AC, DC-DC, DC-AC including direct or indirect realizations [e.g. 3, 4]. Measurements were performed using the setup presented in Figure 1a. The inverter stage consists of 4 full bridge (FB) power electronics building blocks (PEBB). The single cell topology is shown in Figure 1b. Depending on the switch control sequence the output voltage from the PEBB can be zero, direct or inverted voltage of capacitor C_B (C_B=4.2mF). The resistor R_D (R_D=200 kW) is responsible for proper discharging of the cell. The supply voltage chain is composed of single phase autotransformer (0-230VAC), a boosting transformer (230 – 690 VAC) and a bridge rectifier, with DC link voltage rating up to 1kV. The transformer stage provides the galvanic separation between network side and also between different sections of the multilevel converter. The converter yields a peak-to-peak output AC voltage equal to 8kV, which can be broken down by up to 9 levels. The basic frequency of the AC output voltage is 10-100Hz. The modulator pattern was sinusoidal. The modulator switching frequency of a single cell can be adjusted in the range 200Hz-4kHz. The control of the PEBBs is provided by the AC800PEC controller, combi I/O module (with analog and digital I/O’s), and a set of relays and fuses [5]. The test object, represented by capacitance C_s in Figure 1a, is placed with one side terminal grounded. The output stages of the individual PEBBs are protected with limiting resistors R_L (R_L=40kΩ). Voltage measurements were obtained by means of resistive voltage divider.

Table 1. Parameters of the multilevel converter

Output voltage peak-to-peak	8 kV
Number of levels	up to 9
Switching frequency	200Hz-4kHz
Basic frequency	10-100Hz

A wideband method was used to detect partial discharges. The PD signal was picked up by a wideband current transformer (WCT), recorded by a phase-resolved PD acquisition unit (PRPDA in Fig. 1a) and visualized on a host computer. The programming of the converter control unit was also conducted from the host computer level. For PD measurement synchronization, the SYNC signal, representing the basic frequency, was taken from the control unit.

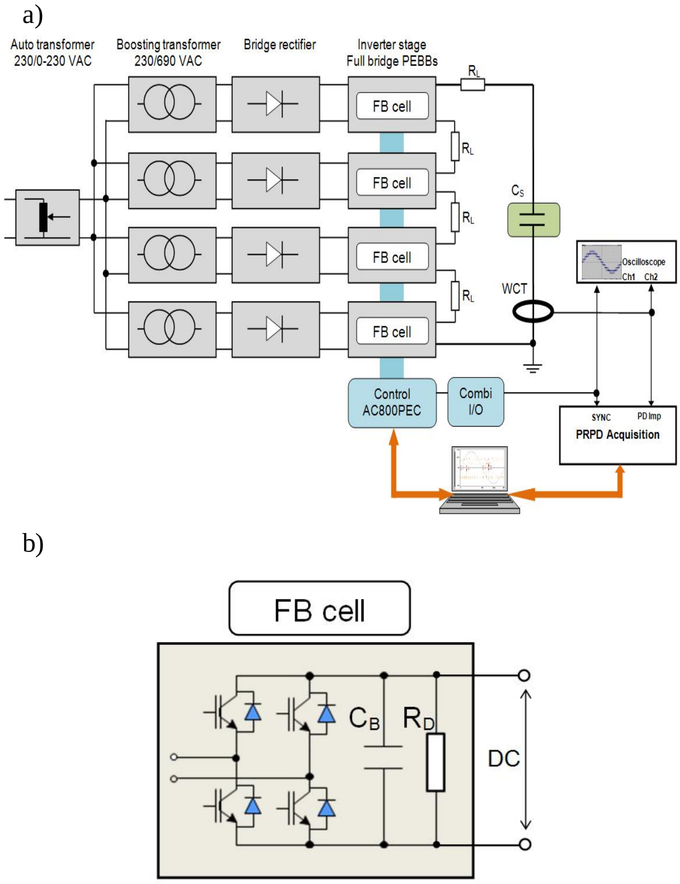

Figure 1. PD measurement setup and modular multilevel converter topology consisting of 4 full bridge (FB) power electronics building blocks (a), and internal structure of full bridge cell (b), C_B- cell capacitor, R_D – discharging resistor.

Various insulation system model samples were tested. In this paper investigations of PD on magnet wire twisted-pair samples (TP), exposed to multilevel voltage stresses are presented. Twisted-pair samples simulate the turn-to-turn insulation of the low voltage stator winding of motors [6]. The twisted pair samples were composed of two enameled coated copper round wires, outer diameter 1.5 mm with polyamide-imide insulation thickness 40 ㎛. The PD sinusoidal inception voltage for the twisted pair specimen was 0.9kV. The mechanism of PD dynamics in chopped voltage sequence is described in [7, 8].

3 RESULTS

This paper presents an analysis of partial discharges in the electrical insulation system of twisted-pair model specimens, subjected to high voltage waveforms obtained from a multilevel converter. A comparison of partial discharge inception and intensity for differing numbers of levels and modulation frequencies are presented. The partial discharges were acquired in the form of phase-resolved patterns and correlated with multilevel voltage waveforms on the slopes and constant voltage parts. In addition partial discharges on individual levels in the multilevel sequence were evaluated.

The inverter voltage waveforms at 1 kV_{pk} (PWM modulation index=85%, output frequency 2 kHz) for 3, 5 and 9 levels and corresponding PD patterns are presented in Figure 2.

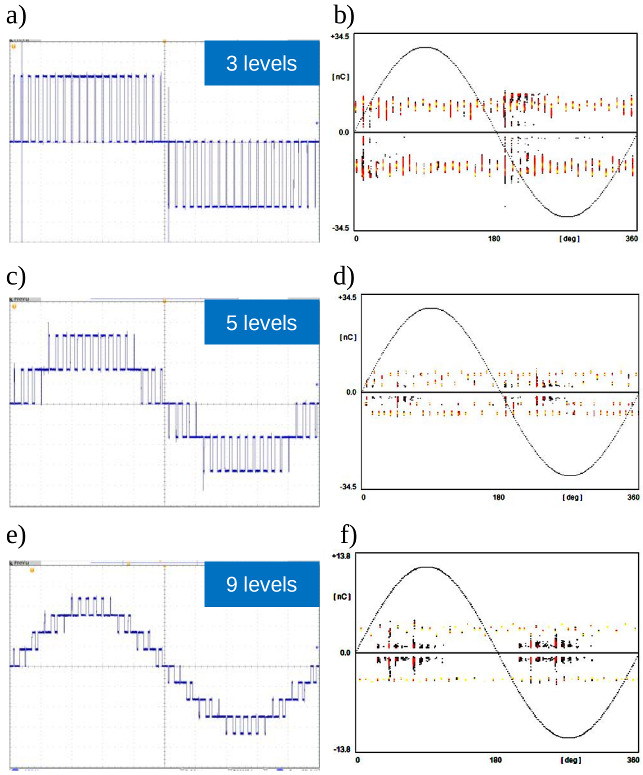

Figure 2. Inverter voltage waveforms at 1 kV_{pk} (PWM=85%, frequency 2 kHz) and corresponding partial discharge patterns (b, d, f) for different number of levels: a) 3 levels, c) 5 levels, e) 9 levels.

The PD patterns contain both the switching pulses (regularly spaced) and embedded discharges. From the comparisons presented, a few observations can be drawn:

- the higher the number of levels (smaller step voltage), the smaller PD magnitude, notice different full scale range in Figure 2f comparing to 2b,d,
- the shift of PD inception phase angle with increasing number of levels.

Comparing the magnitude of the partial discharges with respect to the number of converter levels (Table 1), one can observe the reduction from 11.3nC at 3 levels to 3.1nC at 9 levels.

Table 1. PD magnitude versus number of inverter levels

Number of levels	PD magnitude [nC]
3	11.3
5	5.1
9	3.1

A comparison of number of levels and modulation frequency on partial discharge inception and intensity is presented in Figure 3.

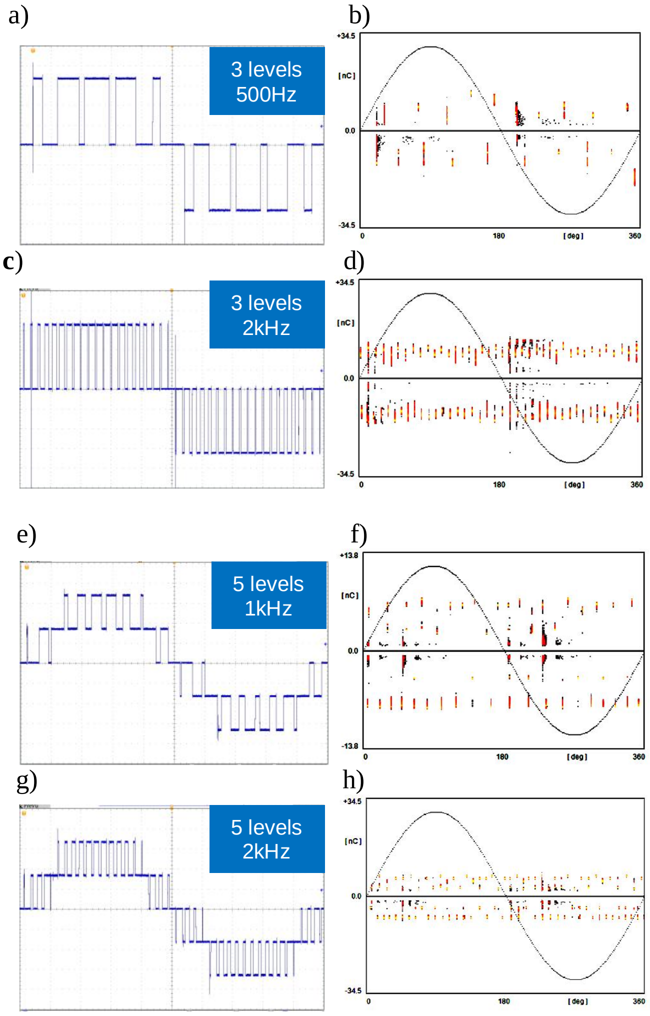

Figure 3. Inverter voltage waveforms at 1 kV_{pk} (PWM=85%) obtained at different switching frequency and corresponding partial discharge patterns (b, d, f, h) for different number of levels: a) 3 levels, 500Hz, c) 3 levels, 2kHz, e) 5 levels, 1kHz, g) 5 levels, 2kHz.

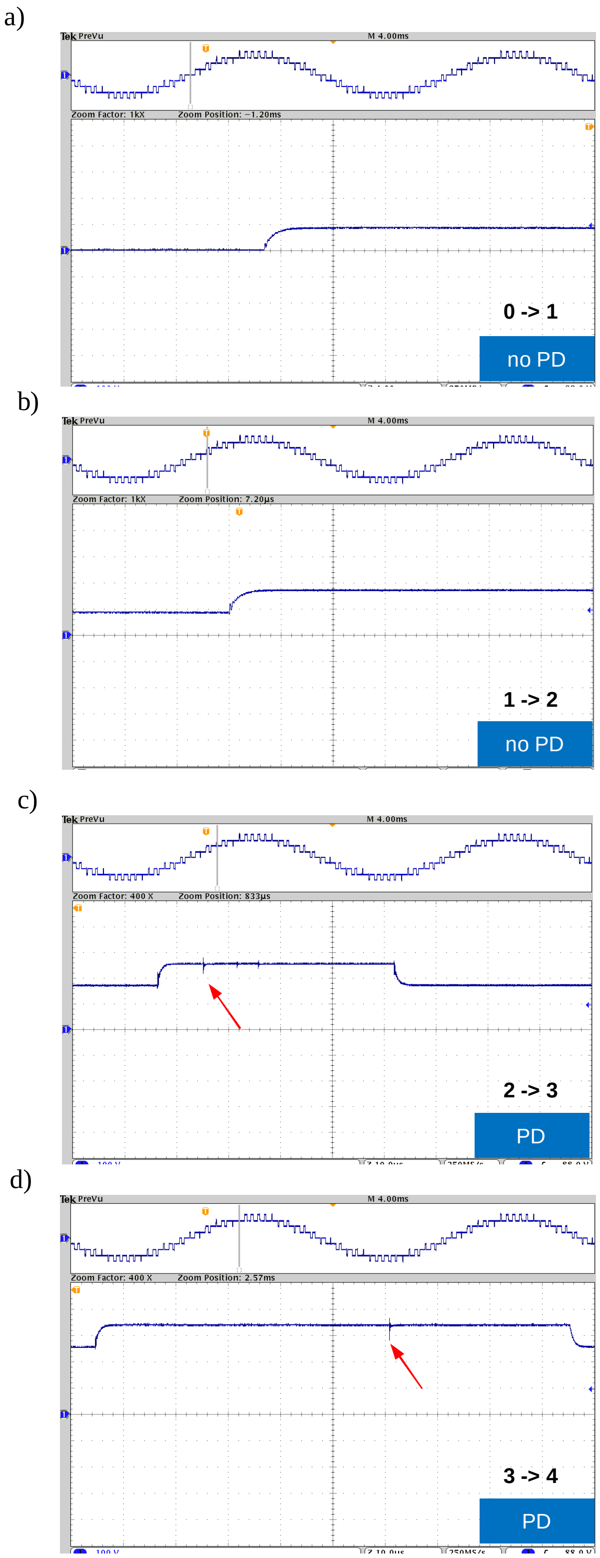

Figure 4. Individual PD pulses recorded at different voltage pulse levels 1 kV (PWM=85%, frequency 2 kHz).

a) 9 levels, transition level form 0-> 1 positive polarity
b) 9 levels, transition level form 1-> 2 positive polarity
c) 9 levels, transition level form 2-> 3 positive polarity
d) 9 levels, transition level form 3-> 4 positive polarity

Figure 3 shows the inverter voltage waveforms at 1 kV (PWM=85%) obtained for different switching frequency (500Hz, 1kHz, 2kHz) alongside corresponding partial discharge patterns for both 3 and 5 converter levels. It may be observed both at 3 and 5 levels that higher switching frequency promotes a higher PD magnitude. This is consistent with the observation in [9], related to the increase of the switching frequency. However, the predominant impact is most visible through the pulse rise time. The PD patterns also visualize the shift of inception phase with increasing number of levels. At lower switching frequency e.g. 500Hz, more intensive discharges occur also on the pulse plateau of the modulating voltage.

In order to observe the PD inception, a time domain recording for individual levels was performed by means of a wideband current transformer. The 9 level converter waveform at voltage $1kV_{pk}$ and modulator frequency 2kHz is presented in Figure 4. The PD presence may be observed on the individual 4 transition levels at positive polarity, thus: 0-> 1, 1-> 2, 2-> 3 and 3-> 4. At the first 2 levels there are no partial discharge pulses recorded (Fig.4a, b), as the voltage level is below the inception threshold. The first PD occurs at the transition from level 2 to 3 (Fig. 4c) and is followed by subsequent pulses. The charge q transported by the individual PD is proportional to capacitance C and voltage drop, being the difference between the inception U_{PD_i} and extinction voltage U_e:

$$q = C\cdot DU=C\cdot(U_{PD\_i}-U_e) \qquad (1)$$

Multilevel converters approximate the sinusoidal waveform; the more levels in the sequence, the more exact the approximation. Thus, at low numbers of levels the step voltage change is of high magnitude, resulting in a higher electric field in the discharge space, therefore promoting the discharge inception and reducing the time lag. A certain criterion for comparison between sinusoidal and multilevel cases, might be a product P of voltage and time exposition above the PD inception threshold, defined in (2-4), which can also be a time varying function $U_{PD\_i}(t)$. The integration time was assumed from zero to quarter of a base waveform period T/4. The X_P yields a ratio of the above mentioned products. Denoting the sinusoidal and multilevel voltage waveforms respectively as $U_{SIN}(t)$ and $U_{ML}(t)$ one can obtain P_{SIN} and P_{ML}:

$$P_{SIN} = \int_{\arcsin(U_{PD0})}^{T/4} U_{SIN}(t) - U_{PD\_i}(t)dt \qquad (2)$$

$$P_{ML} = \begin{cases} \int_0^{T/4} U_{ML}(t) - U_{PD\_i}(t)dt & for\ U_{ML} \geq U_{PD\_i} \\ 0 & for\ U_{ML} < U_{PD\_i} \end{cases} \qquad (3)$$

$$X_P = \frac{P_{ML}}{P_{SIN}} \qquad (4)$$

Assuming for example the PD inception level as 70% and 90% of sinusoidal and multilevel voltage magnitude at 1kV, one can obtain the products and ratios for 3 and 5 levels waveforms with respect to the partial discharge inception voltage (Table 2).

Table 2. PD product P and ratio X_P for 3 and 5 level converters at $U=1kV_{pk}$.

	U_{PD_i}=0.7U	U_{PD_i}=0.9U
P_{SIN} [V·s]	1.15	0.57
P_{ML} 3 levels [V·s]	0.52	0.18
P_{ML} 5 levels [V·s]	0.28	0.09
X_{P3}	0.46	0.31
X_{P5}	0.24	0.16

Comparing the multilevel and sinusoidal case, the discharge activity and intensity should be thus proportional to the above defined product P, reflecting the exposition of the discharge space to the electric field above the inception level.

4 CONCLUSION

This paper presents an analysis of partial discharges in electrical insulation systems subjected to high voltage waveforms obtained from a multilevel converter. A comparison of the impact of number of levels and modulation frequency on partial discharges are presented. The measurement results lead to the observation that the higher the number of levels (smaller step voltage), the smaller PD magnitude. A shift of PD inception phase angle, as the inception level is reached was also observed for different numbers of converter levels. These investigations of partial discharges at multilevel voltage stresses highlight a new class of stress imposed on the electrical insulation systems, formed as a combination of AC, DC and chopped waveforms and related PD mechanisms.

REFERENCES

[1] J.Rodríguez, J.Lai, F.Peng„ A Multilevel Inverters: A Survey of Topologies, Controls, and Applications, IEEE Trans. Industrial Electronics, Vol. 49, No. 4, pp.724-738, 2002.

[2] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L.G. Franquelo, B. Wu, J. Rodriguez, M. Perez, J.I. Leon „Recent Advances and Industrial Applications of Multilevel Converters" IEEE Transaction on Industrial Electronics, Vol. 57, No. 8, pp. 2553-2580, 2010.

[3] P. Klimczak, P. Blaszczyk, R. Jez, K. Koska, "Double Wye Modular Multilevel Converter - Direct DC-DC Topology", 8th IET Intern. Conf. on Power Electronics, Machines and Drives, Glasgow, UK, 2016.

[4] A.J. Korn, M. Winkelnkemper, P. Steimer, J.W. Kolar, Capacitor Voltage Balancing in Modular Multilevel Converters, Proc. of the 6th IET Inter. Conf. on Power Electronics, Machines and Drives (PEMD 2012), UK, 2012.

[5] M. Steurer, F. Bogdan, M. Bosworth, O. Faruque, J. Hauer, K. Schoder, M. Sloderbeck, D. Soto, K. Sun, M. Winkelnkemper, L. Schwager and P. Blaszczyk, "Multifunctional Megawatt Scale Medium Voltage DC Test Bed based on Modular Multi Cell (MMC) Converter Technology", 3rd Intern. Conf. on electrical systems for aircraft, railway, ship propulsion and road vehicles, Aachen, Germany, 2015.

[6] B. Florkowska, M. Florkowski, J.Furgał, J. Roehrich, and P. Zydron, "Impact of Fast Transient Phenomena on Electrical Insulation Systems", Publishing House AGH, Kraków, Poland, 2012.

[7] M. Florkowski, B. Florkowska, P. Zydron, "Chopped Partial Discharge Sequence", IEEE Trans. Dielectr. Electr. Insul., Vol. 22, No. 6, pp. 3451-3458, 2015.

[8] M. Florkowski, B. Florkowska, P. Zydron, "Partial Discharge Echo Obtained by Chopped Sequence", IEEE Trans. Dielectr. Electr. Insul., Vol. 23, No. 3, 2016.

[9] B.Florkowska, M.Florkowski, J.Roehrich, P.Zydron, Measurement and Analysis of Surface Partial Discharges at Semi-square Voltage Waveforms, IEEE Trans. Diel. Electrical Insulation, Vol. 18, No. 4, pp. 990-996, 2011.