Electrical and optical partial discharge assessment of dielectric barriers in mineral oil and synthetic ester

Somya Anand, Eric Vagnon, Ayyoub Zouaghi, Martin Guillet, Cyril Buttay, Oussim Agri

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Somya Anand
Power Electronics & Converters/ Ampère Laboratory SuperGrid Institute/ INSA Lyon
69628, Villeurbanne, France
somya.anand@supergrid-institute.com

Eric Vagnon
Univ Lyon, Ecole Centrale de Lyon, INSA Lyon Université Lyon 1, CNRS, Ampère,UMR5005
69130 Ecully, France
eric.vagnon@ec-lyon.fr

Ayyoub Zouaghi
Univ Lyon, Ecole Centrale de Lyon, INSA Lyon Université Lyon 1, CNRS, Ampère,UMR5005
69130 Ecully, France
ayyoub.zouaghi@ec-lyon.fr

Martin Guillet
Power Electronics & Converters SuperGrid Institute
69628, Villeurbanne, France
martin.guillet@supergrid-institute com

Cyril Buttay
Univ Lyon, CNRS, INSA Lyon, Université Lyon 1, Ecole Centrale de Lyon, Ampère,UMR5005
69621 Villeurbanne, France
cyril.buttay@insa-lyon.fr

Oussim Agri
Univ Lyon, Ecole Centrale de Lyon, INSA Lyon Université Lyon 1, CNRS, Ampère,UMR5005
69130 Ecully, France
ouassim.agri@ec-lyon.fr

***Abstract*— In high voltage direct current (HVDC) topology, the transformer insulation system continuously experiences non-sinusoidal voltage waveforms due to its proximity with the power converters. This may cause changes in the discharge mechanisms, and as a consequence, the isolation system might undergo accelerated degradation. This study aims at investigating partial discharge (PD) measurements with different combination of solid/liquid insulation systems along with pressboard/mineral oil which is predominantly used in transformers. In this study, different barriers were tested in mineral oil and synthetic ester liquid. Also, an optical detection technique has been used beside electrical detection to acquire phase resolved partial discharge (PRPD) patterns, as it is a promising detection technique even in the presence of complex electrical waveforms. The optical detection was found to detect PD events during same phase as electrical detection and a correlation was established between two detection techniques. Moreover, the PRPD pattern and partial discharge inception voltage (PDIV) of different solid/liquid combination tested during this work have been presented.**

Keywords—partial discharge, electrical and optical detection, different barriers, synthetic ester, mineral oil

I. Introduction

The power electronic components used in high voltage direct current (HVDC) transmission systems lead to voltage distortion on AC side [1] due to transients produced by switching. Also, recently proposed insulated DC-DC converters for future grids operating in medium frequency range might implement silicon carbide (SiC) devices which offer high speed switching [2]. Due to the close vicinity of transformers with power converters in existing HVDC transmission systems, the isolation system of the transformer is exposed to high harmonic content, with a possible reliability impact.

The insulation system of existing power transformers in AC and HVDC transmission network mainly incorporates mineral oil and pressboard, due to their proven performance, reasonable service lifetime and low cost [3]. However, the porous nature of pressboard and temperature variations can lead to faster degradation of this composite insulation system. Moreover, due to environmental threats posed by mineral oil, alternative biodegradable substitutes such as synthetic ester are being explored. Therefore, in order to address aforementioned constraints, there is an interest to investigate other combination of solid/liquid insulation systems to meet future requirements.

Partial discharge (PD) tests have been widely accepted as defect monitoring tools to estimate the quality of an insulation system. This work focuses on the study of partial discharge inception voltage (PDIV) using electrical and optical detection systems, for different solid barriers in mineral oil and synthetic ester, under AC 50 Hz excitation. Optical PD detection is compared to electrical detection in preparation for future tests with more complex waveforms (such as those encountered in HVDC systems), where electrical detection is more difficult. A needle-barrier-plane configuration was chosen to represent enhanced electric field by sharp points, impurities or gas voids present in dielectric liquid. Unlike mineral oils, synthetic esters are readily biodegradable and possess high flash point which makes it an attractive choice as a dielectric liquid. The experiments were carried out with barrier samples of different materials and thicknesses in mineral oil and synthetic ester. The PRPD patterns obtained from different combination of solid/liquid insulation have been analyzed. Also, a correlation between PDIVs acquired from electrical and optical measurement have been presented.

II. Sample preparation

A. Dielectric liquid and barrier preparation

During this work, the PD tests were performed with Nytro 4000X (mineral oil) and MIDEL 7131 (synthetic ester). Before PD tests, the dielectric liquids were treated. This was followed by moisture content and breakdown voltage (BDV) tests. The results thus obtained from the measurements have been summarized in Table 1. The barriers used during these tests are polyvinyl chloride (PVC), aluminum nitride (AlN) and pressboard (Pb) whose characteristics are provided in Table 2. Barriers were cut in square shapes of same dimension except the pressboard samples impregnated in Nytro 4000X.

Unlike PVC, dry pressboard and AlN are hygroscopic in nature, hence moisture can increase the dielectric constant and affect the discharge inception [3]. Therefore, PVC and AlN barrier samples were cleaned with isopropanol and then dried for 4 hours at 45°C before storing in airtight boxes.

B. Device under test (DUT)

The PD tests were carried out in point-plane configuration with a solid dielectric barrier resting against the grounding electrode (Fig. 1). Tungsten needles with a tip radius of 1 µm and stainless steel plane electrode of 20 mm diameter were used. The needle tip was found to get deformed when placed in contact with the barrier which could influence the electric field. Hence, a constant gap of 0.7 mm was kept between tip and barrier which was achieved using a 0.7 mm thick FR4 spacer. Some studies such as [4] states that slight errors in gap length do not have a major impact on PDIV. In order to verify the effect due to error in gaps on PDIV, some preliminary tests were performed at gaps of 1 mm, 0.7 mm and slightly less than 0.7 mm. The mean PDIVs thus obtained were 6.38 kV, 6.04 kV and 5.62 kV respectively for the same DUT.

TABLE 1: CHARACTERISTICS OF DIELECTRIC LIQUIDS USED

Properties	***Nytro 4000X (Mineral oil)***	***MIDEL 7131 (Synthetic ester)***
Breakdown voltage (kV) (as per IEC60156:1995) *Measured after treatment*	> 70	> 75
Water content (ppm) (Coulometric Karl Fischer measurements) *Measured after treatment*	< 20	<100
Permittivity (typical values from literature)	2.2	3.2
Viscosity (mm²/s) at 40°C from datasheet	< 12	< 35

TABLE 2: SPECIFICATION OF TESTED SOLID BARRIERS

Barrier samples	***Thickness (mm)***	***Sample size (mm × mm)***	***Typical relative permittivity***	***Samples tested with Nytro 4000X***	***Samples tested with MIDEL 7131***
PVC	1	40 × 40	2.24	5	5
	2	40 × 40		5	5
AlN	0.63	40 × 40	8.5	3	3
	1	40 × 40		3	3
Impregnated Pressboard	2	36 × 36	4.4	5	NA

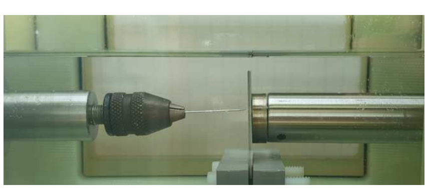

Fig. 1. Device under test with needle-barrier-plane configuration fully immersed in Nytro 4000X

III. EXPERIMENTAL SETUP

The experimental test bench (Fig. 2) under AC 50 Hz excitation consists of two major parts: a high voltage circuit and a PD measurement circuit. The high voltage is generated using a PD free transformer (230 V/ 25 kV) inside the faraday cage which can be controlled from outside the cage. The PD measurement circuit comprises of an OMICRON PD detector for electrical measurement (compliant with IEC60270 standard) and a photomultiplier tube (PMT R943-02 from Hamamatsu) which detects the photons emitted during the discharge processes. The DUT was placed inside a small dark metallic box (within big faraday cage) which improves the capturing capability of the PMT. Two MPD 600 modules from OMICRON were used to allow PD detection using both electrical and optical techniques at the same time. The background noise of the test bench was found to be less than 300 fC up to 16 kV for electrical detection of PDs. Since the PMT counts the photon emitted by the discharge, the PD parameters measured by PMT are reported here using an arbitrary unit (a.u.). The optical detection was found not be impacted at all by the applied voltages and its background noise always remained less than 200 a.u. The voltages quoted here are in root mean square values.

During PD tests, the voltage applied across the DUT was increased in steps of 1 kV with a rising and falling rate of 1 kV/s. A waiting time at high voltage and a resting time at zero voltage of 30s were provided before increasing voltage again until PDIV was achieved as shown in Fig. 3. The electrical measurement was calibrated in accordance with IEC 60270. To verify the reproducibility of PD tests, six tests were performed on each barrier type. After each test, the needle, dielectric liquid and solid barrier samples were replaced by pristine ones.

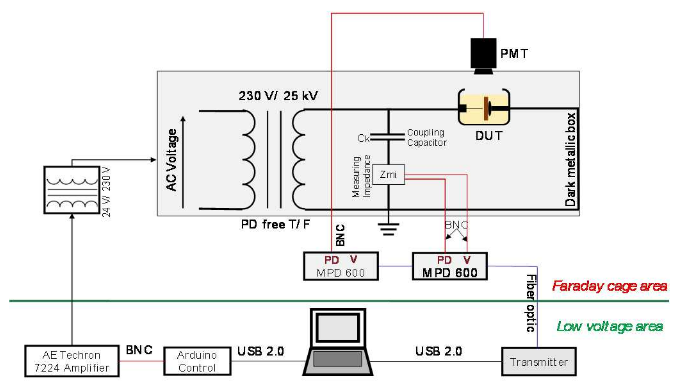

Fig. 2. Experimental set-up

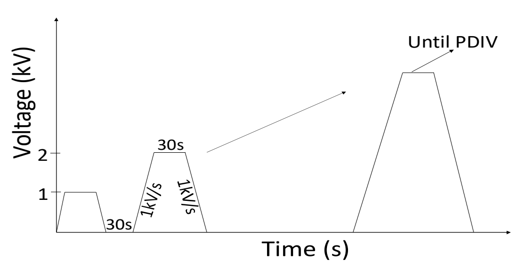

Fig. 3. Voltage profile across DUT

IV. Results and Discussion

A. Correlation between electrical and optical measurements

Fig. 4 shows the PRPD patterns obtained from electrical and optical detection techniques at the same instant for a 2 mm thick pressboard sample in mineral oil. It can be observed that the PMT detected the occurrence of PD events during the same phase as electrical detection. For optical detection, the PD parameters shown in the figure are in a.u. as discussed earlier.

Fig. 5 provides the correlation of PDIV obtained from electrical and optical measurements for different solid barriers in mineral oil. Due to low background noise of set-up, the threshold value of PD detection in electrical measurement can be set at 500 fC. However, it was observed that PDs of low magnitude (a few pC, as detected electrically) were not detected by the PMT during many tests. This could be due to attenuation of optical signals generated from discharges in dielectric liquid [5] which might not have been captured by PMT. Complementary works need to be performed to understand these phenomena. Hence, to compare the PDIVs obtained from two techniques in mineral oil, the inception threshold value for electrical detection was set at 2 pC while for optical detection it was just above its background noise level. The PDIV values thus presented are average of thirty measurements for PVC and pressboard barriers and eighteen measurements for AlN (3 samples of each thickness were tested, Table 2). It can be observed that the average PDIV values acquired by electrical and optical detection are almost similar for each barrier type. A similar correlation was found between PDIVs obtained from electrical and optical detection with synthetic ester, however by choosing threshold value of 10 pC (Fig 6).

Nevertheless, the PMT was able to detect PDs for different barriers in tested dielectric liquids during the same phase as the electrical measurement and almost matches the PDIV values for the chosen threshold values with electrical measurement. Thus, it can be considered as a good indicator to confirm the occurrence of PD activity. Moreover, as it is not impacted by electromagnetic interferences (EMI) unlike electrical detection technique, therefore, it can be used to detect PDs under non-sinusoidal waveforms in future.

B. PRPD patterns

For many cases, the PD activity was found to have initiated with the appearance of PDs at the peak of negative polarity, such as for 1 mm thick PVC in synthetic ester, (Fig. 7). On increasing the voltage above PDIV, PD events mainly occurred during the first and third quadrants of the sinusoidal waveform for different barriers (Fig. 4 and 8). As stated in [6] for oil-impregnated pressboard with needle-bar electrodes, PD events occurring at the peak of a sinusoidal waveform indicate corona-like discharges in oil while those in first and third quadrants are due to surface discharges. Fig. 8 shows PRPD patterns for an AlN barrier of thickness 0.63 mm in Nytro 4000X and MIDEL 7131 respectively, acquired after 30 s at 10 kV, from electrical measurement. As can be observed, the magnitudes of PD events are quite higher for synthetic ester as compared to mineral oil. The higher moisture content of synthetic ester as compared to mineral oil might be

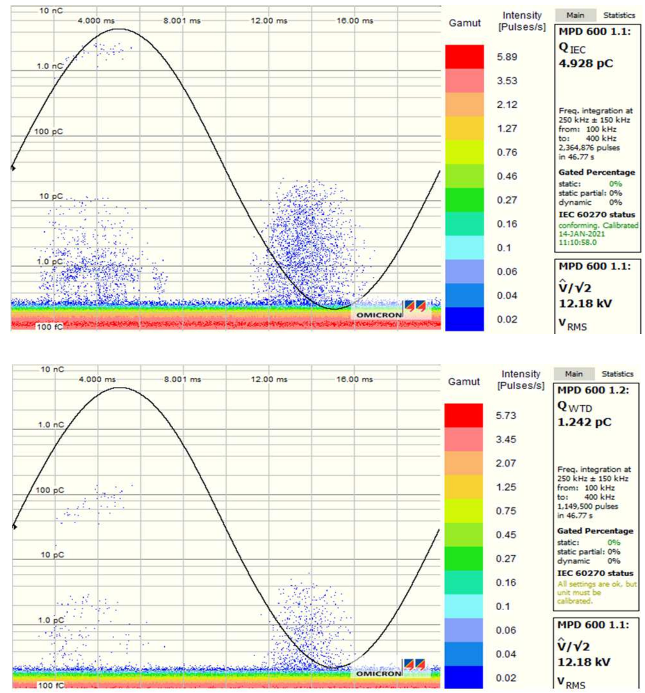

Fig. 4. PRPD pattern of 2 mm thick pressboard in Nytro 4000X taken at same instant from electrical (top) and optical (bottom) detection at a voltage higher than PDIV

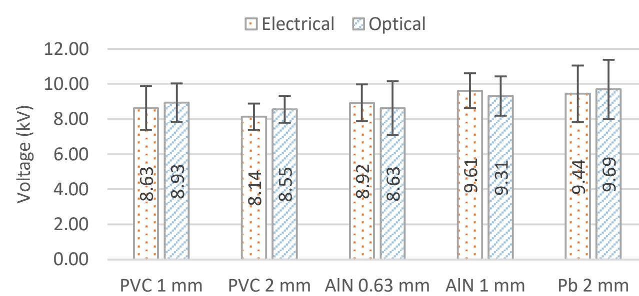

Fig. 5. Correlation between PDIV observed from electrical with threshold of 2 pC and optical detection in Nytro 4000X for different barriers

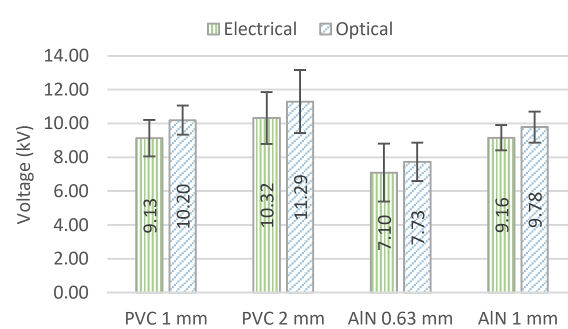

Fig. 6. Correlation between PDIV observed from electrical with threshold of 10 pC and optical detection in MIDEL7131 for different barriers

the reason of larger PD events, which corresponds to a similar concept discussed in [6] and [7].

C. Comparison of PDIV of barriers in two dielectric liquids

Fig. 9 presents the average and standard deviation of PDIV values obtained from electrical measurement for different solid/liquid combination tested with a threshold value of 500 fC. The PDIV values with PVC barriers are higher in MIDEL 7131 than in Nytro 4000X. The opposite is observed with AlN barriers. The PDIVs of thinner PVC and AlN barriers are in the same range which may be due to small variation in gap adjustment between the tip and the barrier. However, from the PDIVs of 2mm PVC we can wonder if the differences between the liquids could be more underlined by increasing the thickness of the barrier. The electric field generated by 1 µm needle tip radius and very small gap chosen for tests is high enough to initiate an PD event. But further investigation needs to be done to understand how PDIV in different dielectric liquids is impacted by parameters such as relative permittivity, thickness of barrier and the possible presence of space charges.

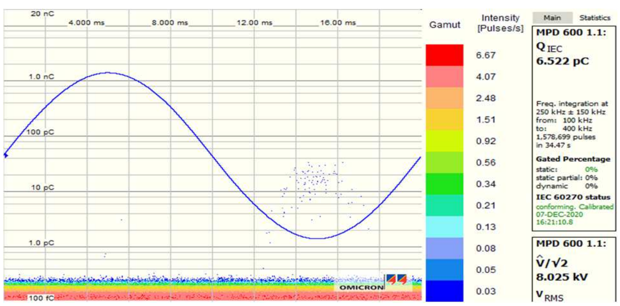

Fig. 7. PRPD pattern of PVC (1 mm thick) in MIDEL 7131 at PDIV from electrical detection

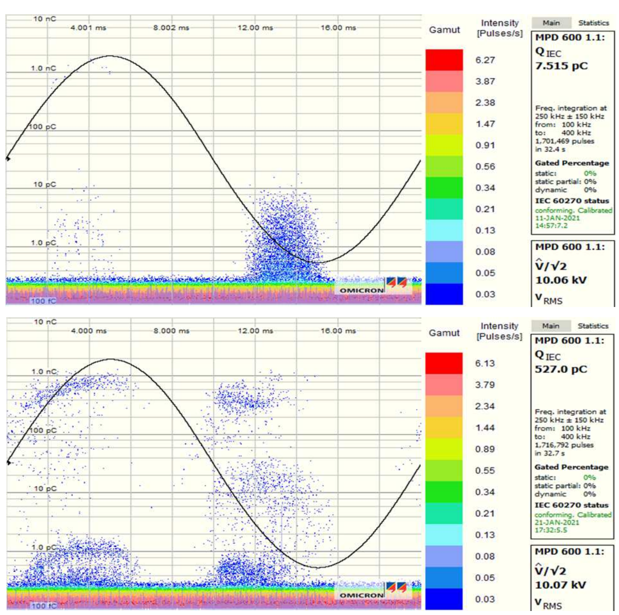

Fig. 8. PRPD pattern of AlN (0.63 mm thick) in Nytro 4000X (top) and MIDEL 7131 (bottom) at 10 kV from electrical detection

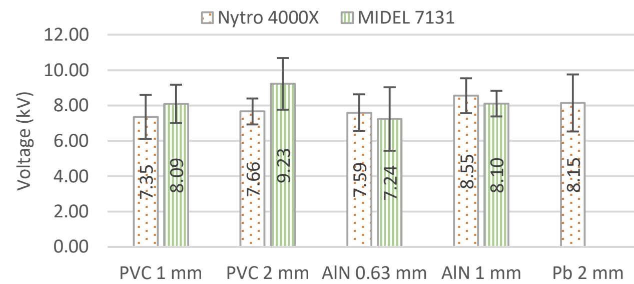

Fig. 9. Comparison of PDIV values for different barriers in Nytro 4000X and MIDEL7131 from electrical detection with threshold at 500 fC

V. Conclusion

During this work, PD measurements were performed with barrier sample of different materials in mineral oil and synthetic ester under needle-barrier-plane configuration. The PMT was found to detect PDs during the same phase as the electrical method. A correlation between PDIVs obtained from electrical and optical detection was presented. Therefore, PMT can be used as an indicator to detect occurrence of PD activity.

For the DUT used in this work, the PD events mainly occurred during the first and third quadrants. The PRPD patterns of synthetic ester showed large PD magnitudes which might be due to higher moisture content. The PDIV results obtained from different solid/liquid combinations seems to be impacted by various parameters and therefore needs further investigation.

This study establishes optical detection as an alternative method to monitor PDs, which can be a beneficial technique with non-sinusoidal waveform due to its immunity against EMI. Further it provides an understanding of PD behavior for different combinations of solid/liquid insulation in AC. Also, it will assist in understanding the discharge process in synthetic ester liquid which can be a possible substitute to mineral oil.

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