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Recent advances in on-line PDs' detection in power conversion chains used in aeronautics

Thibaut Billard, Cédric Abadie and Thierry Lebey

Abstract - At the dawn of this new millennium, transportations facing a much greener approach, the main aircrafts manufacturers have to change their paradigms: to replace the combination of hydraulic, pneumatic, electrical and mechanical power by a «More» (and «All» in the future) Electrical Aircraft approach consisting in drastically increasing the power density of electrical power systems without compromising on reliability. The increasing demand for more on board electrical power has led to increase the voltage and/or to change its shape. Such an increase may lead, depending on many parameters related to the electrical characteristics of the power chain (power converter, voltage waveform (dV/dt, frequency, ...), the cables length, the type of machine driven) or to the environment (pressure, temperature, relative humidity) to the Partial Discharges Ignition in systems which were not supposed (and have not been designed) to endure them.

Partial Discharges are voltage-dependent electrical discharges in insulation, which:

- do not lead to a direct breakdown of the system,
- lead to a gradual deterioration of the insulating material and to its premature failure
- is often defined as “the silent enemy”

Recent advances made in the related different topics i.e on line PD detection under PWM voltage, influence of the pressure, influence of the components types...will be presented and discussed regarding their consequences.

Index Terms-- Partial Discharges measurement, Pulse width modulation, Aircraft, Motors, Pressure effects, Wavelet transforms

I. NOMENCLATURE

FT: Fourier Transform
IGBT: Insulated-Gate Bipolar Transistor
MSE: Mean Squared Error
PD: Partial Discharge
PDEV: Partial Discharge Extinction Voltage
PDIV: Partial Discharge Inception Voltage
PWM: Pulse Width Modulation
SiC: Silicon Carbide
SNR: Signal to Noise Ratio
WT: Wavelet Transform

II. INTRODUCTION

In aeronautics, the concept of the “more electrical aircraft” was able to grow thanks to the evolution of power electronics in recent years, the increase of power density, accompanied

by a decrease in cost, which had considerably spread the use of power converters for Adjustable Speed Drive (ASD) applications [1]. Until recently, one could find various energy sources used in aircraft: pneumatic, hydraulic, and electric energy. The concept of the “more electric aircraft” involves replacing pneumatic and/or hydraulic energy by the electric one. These two axes of evolution are respectively called “Bleedless” and “Hydraulicless” architectures. The interest in removing one of these energy vectors is to increase the reliability and safety of onboard equipment while reducing weight and maintenance costs. However, due to the power demand, developing the electrical network resulted in an increase of the voltage magnitude.

There are two main families of motors: first, low-voltage motors with winding formed of cylindrical conductors wound randomly, and second, high-voltage motors with winding formed of rectangular conductors, are classified respectively as Type I and Type II [2].

Like any equipment, electric motors undergo more or less severe aging over time, influenced by various phenomena. These degradations can come from thermal, mechanical, or electrical phenomena. For electric motors, the weakest part is usually the electrical insulation system [3]. The failure of this system generally results in complete motor failure. The use of long cables connecting the inverter to the motor may cause significant overvoltage at the motor terminals [4]. In addition, the shape of applied voltage using “Pulse Width Modulation” (PWM) is comprised of pulse trains. Because of these pulses, voltage is no longer distributed homogeneously along the coil [5]. In that case, large differences in voltage between turns are present [6], [7]. Moreover, associated with the low-pressure conditions present in depressurized areas of the aircraft, these important voltage differences may cause partial discharge (PD) ignition. PDs are electrical discharges that partially short-circuit the insulation. These discharges induce a phenomenon of erosion, due to the bombardment of charged particles, chemical deterioration, and local thermal stresses on the insulation system. Partial discharges are the sign of the next insulation system failure.

It is necessary to detect the partial discharges ignition voltage to assess the quality of electrical system insulation in the equipment and to qualify the system. For systems operating under AC or DC, there are many well-known detection methods. However, this detection is much more complex under PWM in low-voltage motors and more particularly in Type 1 machines that are used in more electric aircraft. The main problem with PWM power supply is that partial discharge signals are embedded in the electro-magnetic noise generated by the switching.

In order to determine the PD appearance in a motor, it is

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important to carry out these tests under real operating constraints (electrical, environmental, mechanical ...): on-line measurement is mandatory. However, despite the representativeness of the test, if the detection system modifies the constraints present on the system under test, the results will be biased. It is therefore necessary to use a system which does not affect the reliability and the test configuration of the system under test. A non-intrusive measurement makes it possible to satisfy these conditions.

III. PDS DETECTION IN LOW-VOLTAGE MOTORS

In the recent works related to the detection of PD in machines fed by a PWM inverter, the more promising track has been the pioneering work done in [8] when conventional technique for measuring technique could not be used anymore due to noise generated by the inverter. Still, the use of a high pass filter has proven to be successful to detect PDs in a small machine (0.3 kW) fed by a commercially available bipolar square voltage generator. Based on this work, an experimental set-up has been developed to go one step further in the field of EV electric motor and detect partial discharges on-line in electric motor. It consists in 4 key parts: non-intrusive sensor, high-pass filtering, controllable high voltage PWM power supply and high speed acquisition.

A. Sensor

Using non-intrusive sensors is mandatory for equipment reliability. A simple sensor was developed for this purpose. Initially, the sensor was developed to offer a less expensive (regarding cost) alternative to inductive sensors. This sensor was made using a 1.5 m coaxial cable, then stripped on its cut extremity to expose the metallic inner core over a length of 1 cm. The coaxial cable is stripped further, but only to expose the inner insulator for 1 cm without any ground shield. This was done to prevent any undesired contact between the metallic inner core and the shortened ground shield. This sensor is not an antenna. It is sensitive to distance and must be placed as close to the discharge area as possible. In the case of stator tests, it is placed on the power cable close to the stator terminals.

B. PWM like power supply

The power supply is a PWM like inverter. This PWM inverter has been entirely conceived, designed, and built at the Laplace Laboratory. This PWM inverter can simultaneously supply two phases with bipolar controllable voltage waveforms. The high voltage source generates voltages up to 1.7 kV DC on the converter input and supports peak currents up to 50A. The IGBTs are designed to support up to 1.5 kV, which allows testing low voltage motors and searching for the partial discharge inception voltage (PDIV). The inverter provides modular bipolar voltage. The pulse duration, the time between pulses, and the switching frequency are adjustable, making it possible to create PWM voltage.

This system enables to perform various tests, for example along one phase, or between two phases, or between phase to ground allowing to perform off-line testing relatively close to

the actual stress that the test equipment can withstand. Voltage measurement is performed using a differential voltage probe.

C. Filtering

The use of filters is essential in partial discharge detection, and more particularly in the case of PWM power supply [9]. The difficulty of detecting PD during steep voltage edges is to increase the signal-to-noise (SNR) to measure low amplitude signals with high-frequency components among large amplitude signals with low-frequency components. The bandwidth of the filter and its cutoff frequency are the most important parameters in this filter's design. The frequency spectrum of a discharge extends up to at least 1 GHz, as the noise generated by the PWM supply seems to not exceed a few hundred MHz (for the power supply used at the Laplace laboratory). The filter cutoff frequency should be greater than the frequency for noise suppression of commutations and must be adapted to the voltage rise time.

D. Acquisition

The acquisition tool used is an oscilloscope (Tektronix MSO 5204 Digital Oscilloscope) with a digital bandwidth of 2 GHz and a sampling frequency of 5GS/s. The frequency spectrum of a discharge extends up to at least 1 GHz, and with the cutoff frequency of the filters used being a few hundred MHz, it is possible to detect partial discharges.

E. Off-Line experiments

An example of the experimental set-up used to perform the off-line tests is summarized in Fig. 1.

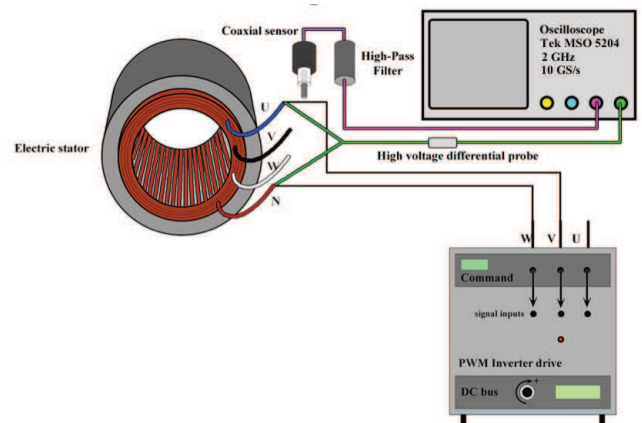


Fig. 1. Scheme of the complete off-line detection system

The interest of the filter is shown in figures 2 & 3. Due to the noise induced by switching, it is impossible to observe anything (Fig. 2) whereas the effect of adding a high-pass filter allows to detect the partial discharge signal as witnessed by the observation of the figure 4 showing a “glow” or “pseudo-glow” discharge [19].



Fig. 2. detection without filtering

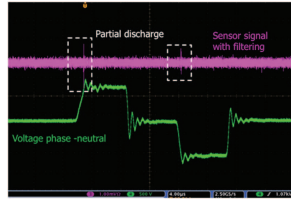


Fig. 3. detection with filtering

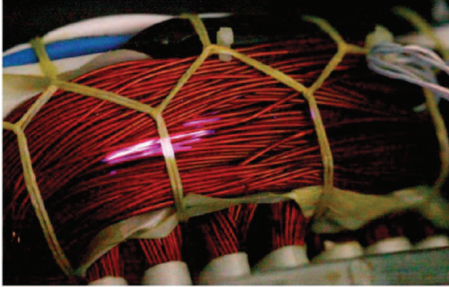


Fig. 4. Presence of PDs for the previous voltage conditions

It is important to note that, up to now, on-line testing had never been reported. It is the aim of the work reported here to present these characterizations in the aeronautical environment for voltage close to the PDIV.

IV. IMPROVEMENT OF THE DETECTION METHOD

A. Sensor study

One of the issues with home-made sensors is the inherent lack of repeatability in their elaboration. Clearly, slight variations can occur and may lead to changes in their responses. Furthermore, sensor properties can evolve over time with handling. The solution we found was to use a Jack-SMA connector, connected to the end of a coaxial cable (Fig. 5). This sensor is robust, inexpensive, and standardized. It also has about the same geometry and size as the home-made coaxial cable sensor. Another problem is the positioning of the sensor. Due to its geometry, achieving good contact and adequate holding on the power cable can be complex particularly due to vibrations during on-line testings. For this reason, we developed special 3D-printed pliers to ensure good contact regardless of the cable gauge.

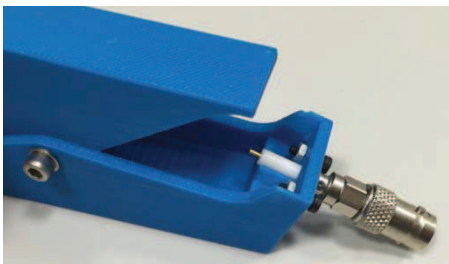


Fig. 5. Jack-SMA sensor mounted on its holding system

The sensor is based on a capacitive coupling. Sensor sensitivity can therefore be increased simply by improving the coupling capacitance value. This is achieved by increasing the contact surface by putting copper tape on the surface of the power cable to control the interacting area and thus the value of the induced capacity (Fig. 6).

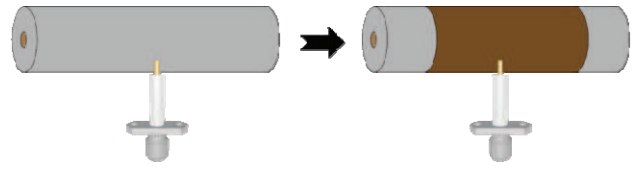


Fig. 6. Simple optimization of the sensor sensitivity

B. Development of a digital processing method to remove noise

In literature, different techniques for extracting PD signals from raw data are proposed. The article [10] performed a comparison of some of these noise suppression methods based on several parameters. All these methods are compared according to the Mean Squared Error (MSE) between the raw signal and the noise-suppressed signal as well as the execution time of filtering. Based on these criteria, Wavelet Denoising and Low-pass Filtering methods have proven to be the most effective. In our case, since the electromagnetic noise induced by switching has low-frequency components, the low-pass filtering is not possible. The best technique for extracting PD signals is therefore the Wavelet Denoising method.

The wavelet transform (WT), just as the Fourier transform (FT) is a mathematical signal processing tool that decomposes a signal into different basic functions. The basic functions of the FT being the sine and cosine, the result of applying this method provides information only on the frequency content of the signal of interest. The disadvantage lies in not knowing the moment at which each frequency component appears.

Besides that, the basic functions of the WTs called “wavelets” allow two-dimensional resolution in the frequency and time domains. Moreover, in comparison, the FT shows extreme efficiency for analyzing periodic phenomena, time-invariant and stationary techniques, while WT screens all components produced by transients, of variable time and non-stationary [11].

Therefore, with the PD signal being of a non-periodic nature and exhibiting very fast transient characteristics, the WT approach seems more suitable in this context. More details on the denoising method may be found in [12].

1) Noise source

The aim of our work being to perform on-line measurements on real industrial test benches, the presence of noise in the signal of interest cannot be avoided. To be considered as a PD, the signal should therefore appear with sufficient recurrence and be large enough to be considered other than just random noise.

The main sources of noise may be divided into different categories, classified by the interference produced [11], [13]:

- Periodic pulse interference caused by power electronics or other periodic operations.
- Discrete spectral interferences (DSI) embody a continuous sinusoidal signal caused, for example, by AM/FM radio emission or power line communication systems.

- Stochastic pulse interference amplitude and moments of random occurrence caused by operations of occasional workers, power electronics, lightning strikes...

Fig. 7 shows that it is impossible to measure PD signal, the amplitude of the noise induced by switching being too large compared to the PD amplitude.

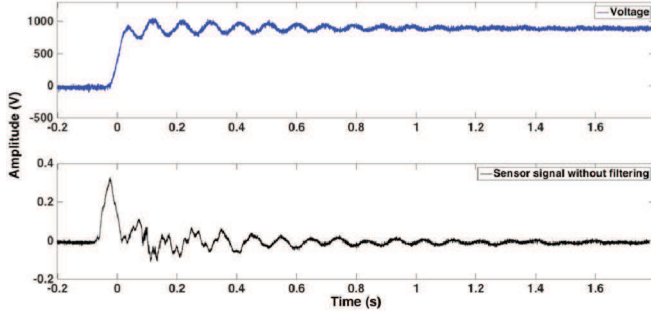


Fig. 7. Noisy signal induced by switching (black)

2) Method validation

For validation of the proposed WT, PD measurements were achieved on twisted pair of enameled wires (nominal diameter $\varnothing = 1.31$ mm) fed by a PWM like power supply at atmospheric pressure. Twisted pair samples were made according to usual norms and recommendations [14]. This type of samples is representative of the winding that can be found in randomly wound motors. The signals denoised by wavelet transform are compared to analogic filtered signals.

Fig. 8 shows the reconstruction signal similar to the filtered analogical signal. The only difference between the two signals being the amplitude. Reconstruction with the automated choice enables retrieving a PD signal having an amplitude four times larger than the one filtered analogically.

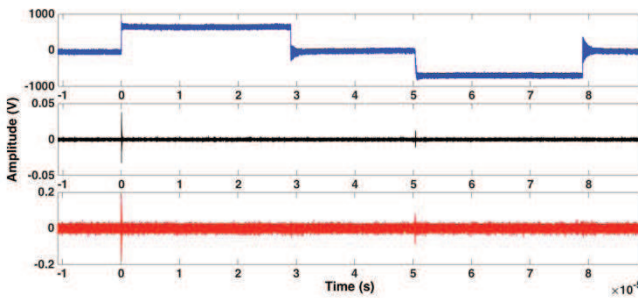


Fig. 8. PWM like voltage shape (blue), sensor signal filtered at 200 MHz (black), PD signal reconstructed by WT with the automated choice of the mother wavelet ("coif1" in this case) (red)

The digital denoising method based on continuous wavelet transform is functional and it sets all the wavelet transform configuration parameters automatically. This method has real interest compared to high-pass filtering since human expertise is no longer required to remove noise in signals.

On the other hand, it is important to note the limitations of this technique. First, to be functional, it is necessary for the signal to be discretized with a large sampling frequency in order to represent fast signals. Then, it is worth to be noted

that the amplitude of the signal reconstructed by the method may present a significant error due to the frequency band overlap corresponding to each level of decomposition. But, another type of error is also induced when using a high-pass filter since all frequency components below the cutoff frequency are removed. The pros and cons of each method must therefore be considered prior to any choice.

C. Influence of pressure

Some of the electrical equipment devoted to aircraft applications may be located in depressurized areas, and while operating, the temperature can vary widely. Pressure and temperature parameters have an influence on the discharge inception voltage and may also modify their nature. Therefore, for such operating conditions, it is important to pay particular attention to the detection system characteristics in order to achieve the best SNR while filtering the noise induced by the voltage switching.

The works described in the following is focused on the pressure since it is the most impacting factor on PDs' ignition.

1) Experimental set-up

To perform tests close to aeronautical conditions, a vacuum chamber was used with a sufficiently large volume to be able to perform tests on samples ranging from twisted pairs to stators. Pressure could vary from atmospheric pressure up to a few tens of millibars. In order to study the influence of pressure on the ability of the method to detect PDs, tests were performed at different pressures under AC voltage and under PWM like voltage for sake of comparison. The main idea is to compare the impact of this parameter on the discharge characteristics while enabling a comparison between the different sensors.

This involves two hypotheses:

- The partial discharge ignition voltage is the same, whatever the voltage waveform
- The nature of the discharge remains the same, whatever the voltage waveform

Experiments were performed on twisted pair samples of enameled wires. Last, non-intrusive current transformer sensor (Rogowski type sensor) was also tested in such an environment. This sensor essentially behaves like a transformer. The primary winding is actually the circuit in which partial discharge must be detected, with one cable going through a tore ferrite loop representing the magnetic circuit. The output secondary winding thus provides an image of the current going through the primary winding. The bandwidth at -3dB is between 0.5 and 80MHz.

2) Influence of pressure under AC

a) Influence of the sensor on detection

PDIV and PDEV are first checked at different pressures and AC voltage. A decrease in PDIV is clearly observed in Fig. 9 with decreasing pressure. This phenomenon corresponds to expected behavior and is in good agreement with Paschen's law. The PDIV values measured for each sensor is compared. Jack-SMA sensor with an additional

capacitive effect is the most sensitive one.

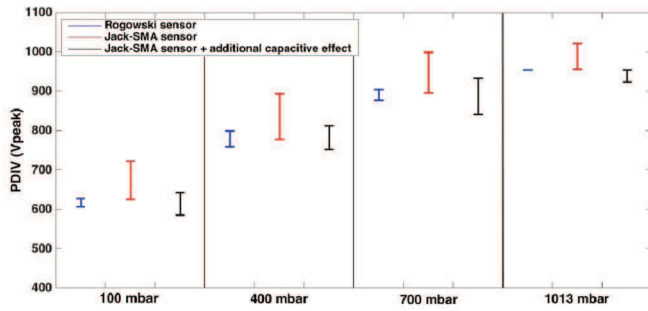


Fig. 9. Influence of pressure on PDIV for three sensors under AC voltage

b) Influence of the cut-off frequency of the filter on detection

The main idea is to study the impact of pressure on detection, with respect to the change in the nature of the discharge. Since the frequency content may be modified in that case, adapting the cut-off frequency to detect PDs must be envisaged. As the filter is suspected of inducing errors on PDIV, its impact under AC voltage at different pressure values is studied. These tests were performed at different pressure values with high-pass filters presenting cut-off frequencies of 50, 90, and 200 MHz and the Jack-SMA sensor with an additional capacitive effect.

The measured PDIV is artificially increased using high-pass filters (Fig. 10) and it is all the more so true that the higher the cut-off frequency, the larger the PDIV at 100 and 400 mbar. It is therefore assumed that the high-frequency components of the spectrum are too small under such conditions. It is therefore necessary to increase the voltage to detect partial discharge (which already appeared at 444 Vpeak). As an example, with the 200 MHz filter, the PDIV is about three times larger than the one measured with the sensor without filtering.

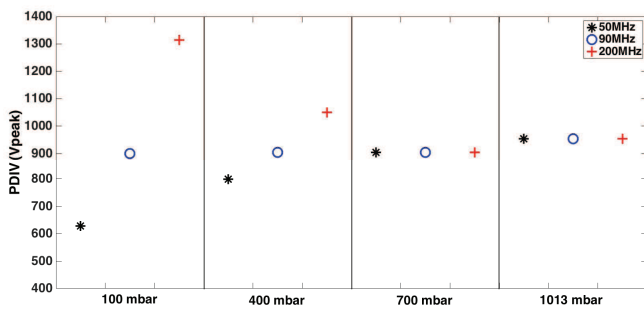


Fig. 10. Influence of filter cut-off frequencies on the PDIV at different pressure values under AC voltage

This same phenomenon was not observed at atmospheric pressure and 700 mbar: the filter cut-off frequency had no impact on the PD. This is a proof that modifying the pressure leads to a modification of the discharge spectrum.

c) Spectral analysis

A study on the discharge frequency spectra for the different pressures under study is performed. For each pressure level, 30 acquisitions of PD were recorded using the

Jack-SMA sensor. The spectrum of each of them is determined and their average value is plotted (Fig. 11).

Since PDIV is a function of the pressure, it can therefore be assumed that the amplitude of these discharges will vary as a function of the pressure and the results are normalized in order to compare the shape of the PDs frequency spectra. For each pressure, the frequency spectrum has been normalized with respect to its maximum value. This normalization prevents the comparison of the amplitudes of these spectra as a function of the pressure. Nevertheless, it makes it possible to highlight the evolution of the most energetic frequency ranges as a function of the pressure.

It is obvious that the amplitude of the high-frequency components (40MHz – 100MHz) decreases with a decrease of the pressure while the amplitude of the low-frequency components (9MHz – 40MHz) increase. Moreover, at 100 mbar, for frequencies above 30 MHz, the signal amplitude is almost null despite some rays around 50 MHz that may contain a small portion of the discharge energy. Some rays around 100 MHz can be observed at 100 mbar, though these rays do not match PD signals, but rather to noise induced by external systems during tests.

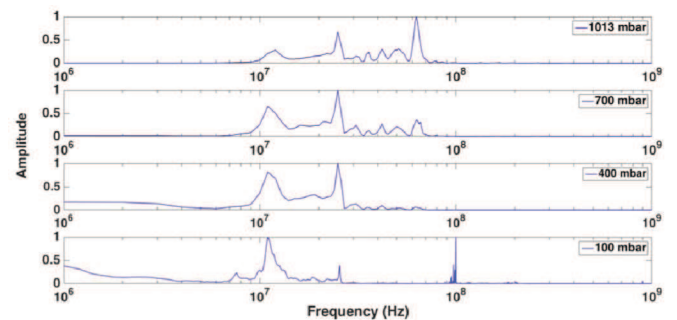


Fig. 11. Normalized changes of PD spectrum under AC voltage as a function of pressure

3) Influence of pressure under PWM

a) Influence of the sensor on detection

In the case of detection under PWM, it is not possible to detect the PDs without filtering the electromagnetic noise associated with the dV/dt . The response of the sensors without filtering and with high-pass filtering at 290 MHz is compared. This cut-off frequency allows a complete denoising for the three sensors, nevertheless in the case of the Rogowski sensor the PDs signals also appear to be filtered. This is due to the fact that the bandwidth of this sensor is not sufficient when using high-pass filters. Indeed, the bandwidth (at -3dB) of the sensor does not exceed 80 MHz and since the filter cut-off frequency is higher, all the signals are filtered. Subsequently, only the optimized Jack-SMA and Jack-SMA sensors will be presented.

PDIV and PDEV were measured for different pressure values. Discharges were detected using a Jack-SMA sensor filtered analogically using different cut-off frequencies (185,290 and 390 MHz). The PD signals were observed for the three different cut-off frequencies simultaneously. For the conditions under study, only the filter cut-off frequencies above 290 MHz provides full electromagnetic dV/dt noise

removal. Not surprisingly, the PDIV value decreases with pressure and whatever the filter for each pressure (from 100 mbar to 1013 mbar), PDIV remains the same (Fig. 12).

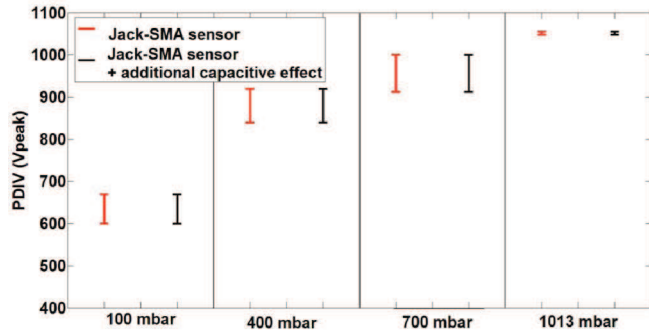


Fig. 12. Influence of pressure on PDIV for two sensors under PWM like voltage

b) Influence of the cut-off frequency of the filter on detection

As previously mentioned, the cut-off frequencies do not influence the measured PDIV, but it is interesting to observe their influences on the amplitude of the PDs measured. Not surprisingly, it can be seen that an increase in the cut-off frequency of the filters induces a decrease in the amplitude of the measured PD signals. However, under PWM, the cut-off frequency does not lead to errors on the PDIV. It is therefore important to study the spectrum of the PDs under PWM to understand this difference with the AC case.

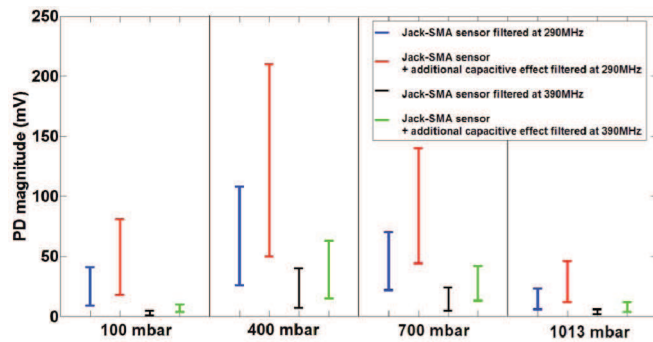


Fig. 13. Influence of filter cut-off frequencies on the PDIV at different pressure values for two sensors

c) Spectral analysis

In order to confirm the influence of pressure on the amplitude of high-frequency components, the same study as the one performed under AC was undertaken for PWM-like voltage. Nevertheless, it is more complex in this case to analyze the frequency content since it is necessary to remove all the noise induced during the switching while maintaining the “entire” PD signal.

Hence, a special procedure is proposed to carry out this study:

- Measure of PDIV (using the appropriate filter)
- Acquire the signal without any filtering, for a voltage value of 90% of PDIV (signal without PD)
- Acquire the signal without any filtering at PDIV (signal with PD)
- Calculate the difference between the signal with PD and

the signal without PD

- Calculate the frequency spectrum of the difference

This procedure has, nevertheless, some limits:

- If the filter is not adapted, there may be an error on the PDIV
- Generally, for a voltage value of 90% of PDIV, the PDEV is reached but in some cases this may not be the case
- This procedure is only valid if the noise is repeatable, if the noise varies too much from one acquisition to another the analysis will be totally false

In this case, it can be seen that the amplitudes of the frequency components are in the same range for all the pressure values. It has therefore been decided to normalize all the frequency spectra with respect to the amplitude of an identical frequency component for the four pressure values. This makes it possible to observe the variation in the shape of the frequency spectrum as well as the modification of the amplitude of the frequency components as a function of the pressure.

First of all, it is important to note that the spectrum of the PD signals under such conditions extends over a wider frequency range than that observed under AC voltage. The question is to know if this is due to a change in the discharges nature.

The magnitude of high-frequency components (80 – 400MHz) decreases with pressure while the amplitude of the low-frequency components (8MHz – 80MHz) increase. Such behavior may be detrimental to the accuracy of the PDIV measurements. For a pressure of 100 mbar, the magnitude of the components above 300 MHz for the PD spectrum is very small.

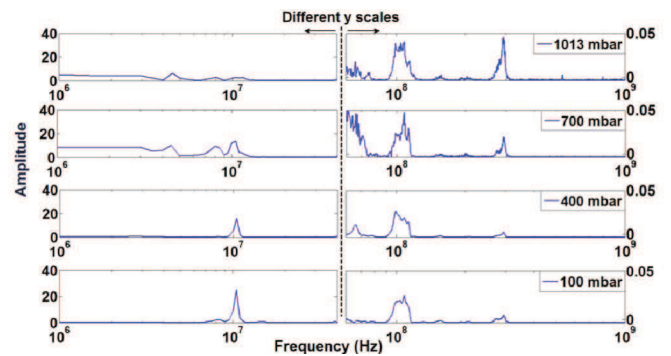


Fig. 14. Normalized changes of PD spectrum under PWM-like voltage as a function of pressure

Pressure has a significant influence on the detection of partial discharges, and specifically on their characteristics. A decrease in pressure causes a change in their frequency spectrum. High-frequency components of the discharge signals tend to decrease or even disappear at very low pressure. In addition, the sensors used are sensitive to rapid current variations. If the frequency components are shifted to lower frequencies, the bandwidth of the sensors may not be sufficient to detect them. An error in determining the PDIV can be made in this case. As detection in PWM voltage requires the use of high-pass filters to remove the noise

induced by switching, there may be a complete suppression of the frequency components associated with the PDs. However, we observed that the discharge frequency spectrum covers a much larger frequency range than with AC. Therefore, the method is functional regardless of the pressure and voltage form tested.

V. VALIDATION ON ENGINE TEST BENCHES

The purpose of investigating industrial test benches is to check the validity of the detection method, particularly the sensor used. As a matter of fact, this sensor was tested in a laboratory environment but a few tests were also carried out on industrial test benches [15], [16].

A. "Simple" PD detection

For this test, it was possible to vary the speed and bus voltage over a wide range. First, a test with a DC bus voltage of 554V was conducted. This test was intended to adjust oscilloscope calibers and optimize selection of the filters. Fig. 15 shows the voltage at the machine terminals and the output signals from the different sensors.

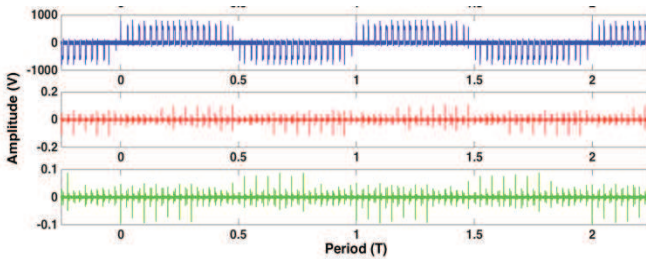


Fig. 15. Phase to phase voltage UW (blue), sensor signal on U without filtering (red), sensor signal on W without filtering (green)

Overvoltages are observed on the phase to phase voltage measurement. These surges have a maximum amplitude of 770V peak. Since the sensors are saturated by switching, using high-pass filters to suppress electromagnetic noise is mandatory.

1) Study on the winding

In the case below, the filters were replaced by filters with a lower cutoff frequency (100 MHz). A signal similar to a PD signal can be seen in Fig. 16.

The temporal position of the signal was observed to compare it to the maximum voltage in order to confirm the assumption that these signals correspond to discharges. Fig16. shows that the sensor signal appears at the maximum value of the phase to phase voltage UW.

Fig. 17 shows a comparison of the different sensors.

They all detect the same signal but its magnitude is a function of the sensor type: the largest signal being obtained for the jack SMA+ additional capacitive effect.

These tests detect signals similar to partial discharges on representative equipment operating under normal conditions.

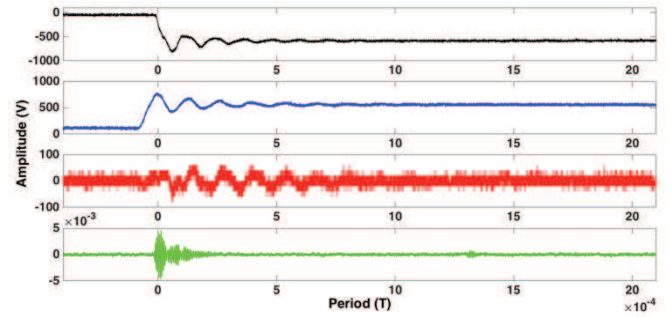


Fig. 16. Phase to phase voltage UV (black), phase to phase voltage UW (blue), phase to phase voltage VW (red), sensor signal on phase U filtered at 100 MHz (green), Zoom of the sensor signal and all the maximum voltage

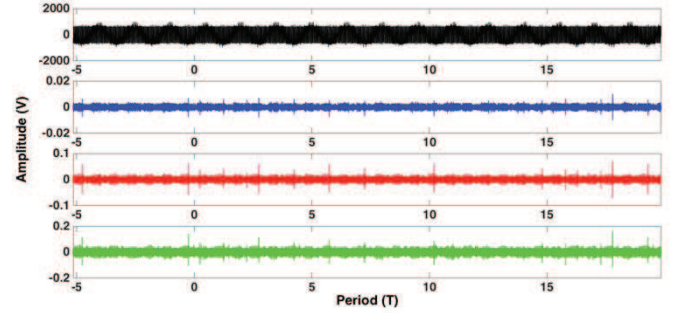


Fig. 17. Phase to phase voltage UV (black), sensor (jack SMA) signal on phase U filtered at 100 MHz (blue), sensor (inductive) signal on phase U filtered at 100 MHz (red), sensor (jack SMA + additional capacitive effect) signal on phase U filtered at 100 MHz (green)

These signals have all the features of partial discharges:

- Low recurrence
- PD signal temporally coinciding with peak voltages
- Consecutive signals at different voltage polarities.
- Signals appearing from the same voltage as the PDIV measured under AC supply voltage

The proposed detection system is functional. The increase in the sensor's coupling capacitance can increase the magnitude of the measured signals significantly. Ten times greater amplitude can be seen compared to the "single" sensor. Twice greater amplitude was observed relative to the inductive sensor.

2) Denoising by CWT method

The denoising method based on wavelet decomposition has only been validated on laboratory samples. It is therefore particularly interesting to apply under real constraints in an industrial environment.

The results of the denoising method applied to the previous case are given in Fig. 18. Our method allows suppressing the noise (blue curve) and leads to a good reconstruction of the PD signal. Moreover, the amplitude of the signal reconstructed thanks to the numerical method is five times greater than the signal filtered analogically. In the case under study presented before, there was few doubts regarding the presence of discharges, but in other cases, not shown here, the proposed method improves the denoising.

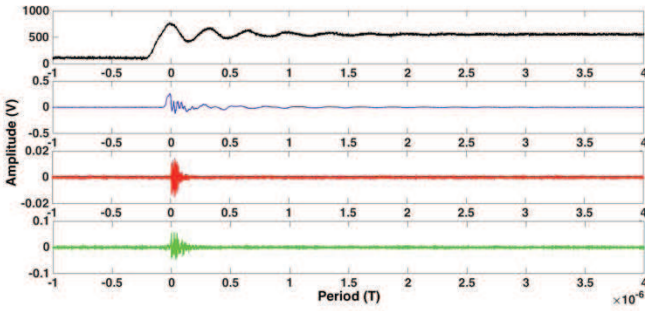


Fig. 18. Phase to phase voltage UW (black), sensor signal on phase U without filtering (blue), sensor signal on phase U filtered at 100 MHz (red), sensor signal reconstructed by CWT (green) (note the scale changes)

B. PD detection in machines fed by SiC inverter

With the concept of “more electric aircraft”, higher voltage levels and changing electrical architectures (notably the increased use of converters) was observed. Future projects (related to hybrid propulsion for e.g.) are considering a further increase in voltage levels. In a relatively near future (20 years), voltage up to several kilovolts may be envisioned. In addition, silicon carbide-based (SiC) power components will probably replace the current silicon-based components in some high efficiencies and high power density applications. The use of high voltage will increase the risk of partial discharge occurrence, while the evolution of electronic components will result in an increase in switching speed and consequently an increase in the noise frequency spectrum.

In this context, it is important to determine whether our detection method will always be functional. Currently, some domains already use voltages on the order of kilovolts and are operating converters using SiC components. Some tests were carried out on an industrial test bench using on SiC converters on prototype motors with an important length of cabling, allowing a clear demonstration of the ability of the method to detect PDs.

a) PD detection

Tests were performed with a SiC converter supplied by a 750 V DC bus and the cable length between the inverter and the motor was about ten meters.

Under such conditions, the overvoltages amplitude is about 1100 V and the dV/dt have a value of 10 kV/ μ s. To eliminate the noise induced by these voltage fronts, it was necessary to use high pass filters having a cut-off frequency of 500 MHz. There are no characteristic signals that coincide temporally with all fronts, indicating that the filter is adequate for removing noise-induced switching. The observed signals in Fig. 19 and Fig. 20 have many of the characteristics necessary to determine the presence of discharges:

- Low recurrence
- Signals seem to coincide temporally with peak voltages

Another interesting result of this study concerns the ability of detecting PDs despite the use of filters having a high cut-off frequency. Generally, the amplitude of the frequency components of PDs, appearing under PWM for 3

kV / μ s edges, is very low beyond 300 MHz.

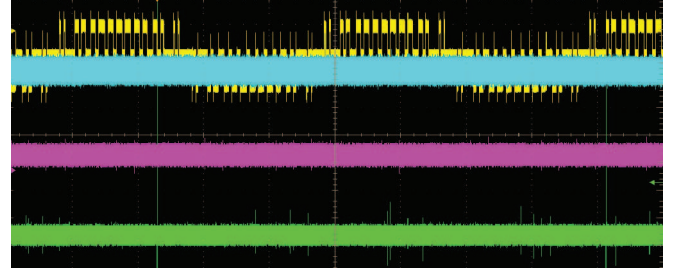


Fig. 19. PD research on a motor supplied by a SiC converter

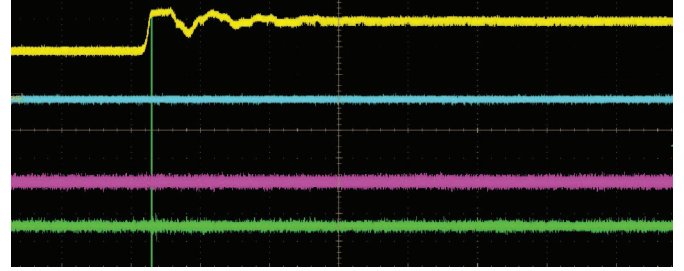


Fig. 20. Zoom on a partial discharge for a 1 kV overvoltage

In this case, despite of the use of filters having a cutoff frequency of 500 MHz, signals related to PDs have been detected, which proves that in this case the frequency spectrum of the PDs spreads over a higher frequency range than for 3 kV/ μ s edges. The dV/dt thus appears to have an influence on the frequency spectrum of the PDs. The method is functional and the characteristic signals of PDs coincide temporally to overvoltage occurrences. Additionally, the variable distribution of the amplitude of the sensor signals corresponds to the stochasticity of partial discharge.

b) Temporal position of PDs

In today's aircraft applications, low-voltage motors working at voltage levels generally lower than the PDIV are considered and it is only the overvoltage that lead to PDs ignition. This is why discharges appear during the voltage edge and why denoising is such a big problem.

During the tests using SiC inverter, the rating voltage was high compared to the PDIV. It seemed therefore particularly interesting to study the distribution in time of the PDs. Hence Fig. 21 and Fig. 22 clearly illustrate that PDs appear not only during the voltage front but also during the plateau part of the voltage. Such a behavior corresponds to the PDs pattern observed and reported in the literature for motors operating at high voltage. The detection during the continuous part (plateau) of the voltage being much simpler because there is no need to filter the signals.

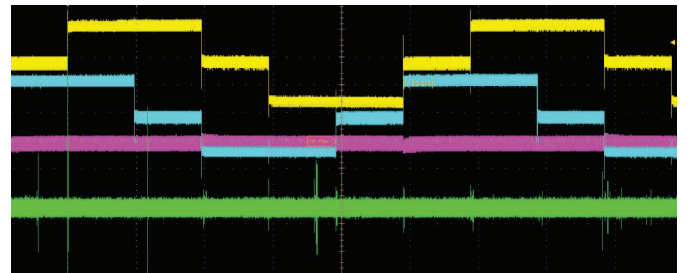


Fig. 21. Temporal position of PDs on two periods

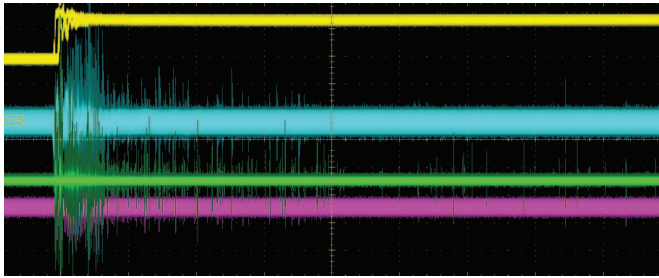


Fig. 22. Zoom and persistence on a voltage edge to observe temporal position of PDs

In the case of motors operating at higher voltages, the PDs not only appear during the front but also on the continuous part of the square waveform (Fig. 23). The appearance of PDs in this type of machines is much more studied [17], [18]. Due to the similar behavior, it may be stated that the method is also efficient under such conditions.

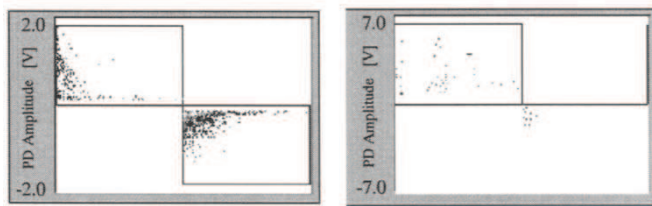


Fig. 23. PD patterns at 1.8 kV (peak value) with bipolar and unipolar square waveforms [17]

VI. CONCLUSION

The proposed method proved its efficiency through tests on different motor test benches and enabled to highlight various phenomena that can lead to false positives to take into account when analyzing results. In industrial scenarios, partial discharge tests must be superimposed on other tests, which means that it is important not to disturb the existing set-up and testing. Our method fulfilled all these requirements.

From a general point of view, the detection system can be transposed to other areas than aeronautics. The method has already been tested in the field of railway and automobile for nearly equivalent voltage levels. Moreover, the current trend is an increase of voltage magnitude for future aircrafts. The method has demonstrated its ability to detect PDs in the case of motors operating at higher voltages and will therefore be transposable to future equipments that will operate with these new voltage levels.

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