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A Round-Robin Test Study of Partial Discharge Inception Voltage in Aeronautic Cables

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Abstract – Future aircraft systems should consider the partial discharge (PD) phenomena as particularly critical, given the low-pressure environment and the stresses from pulse-width modulated (PWM) voltage at relatively high fundamental frequencies of 1 kHz and above. This work addresses the repeatability of PD Inception and Extinction Voltage (PDIV and PDEV respectively) measurements obtained on different configurations of aeronautic wires following the practical testing procedures described in different existing standards. We show that substantial differences in the results can be obtained according to sample configuration and according to the actual implementation of the standardized test procedures by different laboratories carrying out the experiments.

Keywords: All-electric aircraft, aeronautic cable, partial discharges, wire insulation, comparative methods

I. INTRODUCTION

The demand for electrical power continues to increase in modern aircraft. This in turn is leading to an increase in the operating voltages of the electrical systems. The voltage levels are now exceeding the values at which partial discharge (PD) can occur and this must therefore be managed when new components are designed and throughout the lifecycle of the aircraft. In legacy aircraft systems, the network voltage did not exceed the Paschen's minimum of 327 V and the failure modes of *Electrical Wiring Interconnect System* (EWIS) were dominated by mechanical, thermal and chemical processes acting on insulation [1]. The depressurized environment, stresses from pulse-width modulated (PWM) / high frequency voltage wave forms and the drive to minimize cable weight encountered in aircraft systems make the PD phenomena particularly critical [2].

Today, the way to address this issue tends to be by designing 'PD-free' rather than 'PD-resistant' solutions in order to avoid PD induced electromagnetic interference in complex wiring systems, which may bring together both power, control, and communication signals in a relatively narrow space. At the design stage, even though thermal and electrostatic modelling are a first step for defining cable characteristics, testing remains an indispensable part for comparing different possible solutions and validating a system. Notably, as far as PDs are concerned, the link between the maximum local field and PD inception voltage (PDIV) is not straightforward.

The measurement of the PDIV obviously depends on the experimental arrangement used during the tests. Although standards provide guidelines for performing the tests, the final result depends on the measurement set-up used, on the quality of sample preparation and on the different interpretation of the standard procedures. Some standards propose different configurations for test without a clear rationale on how these

have been developed / confirmed to provide results that are relevant to an aircraft installation. In order to assess the variation in results that can be obtained due to these issues, a round-robin testing campaign has been organized. It involved four different labs testing three different arrangements of test samples. Testing complied with the recommendations contained in EN 3475-307 [3] and ASTM D3032, section 25 [4].

After describing the test objects and the experimental arrangements used, the results obtained in these tests are presented and compared.

II. EXPERIMENTAL SECTION

A. Cable samples

The test object was a AWG12 (DZ12) wire with extruded perfluoroalkoxy (PFA) polymer insulation having a nominal thickness of 0.42 mm. The outer diameter of the insulation was 3.0 mm. The cable was already carrying a metal shielding braid. This braid could therefore easily be removed and reinstalled according to the test method used. PFA is a melt processible polymer having properties closest to those of PTFE among fluorinated polymers family [5]. Using extruded insulation instead of tape wrapped insulation in principle reduces the probability of having internal defects. Therefore, the PD phenomena will likely occur at the outer surface of such cables, although the probability of PD activity in voids between the conductor / insulation system cannot be discounted due to conductor stranding.

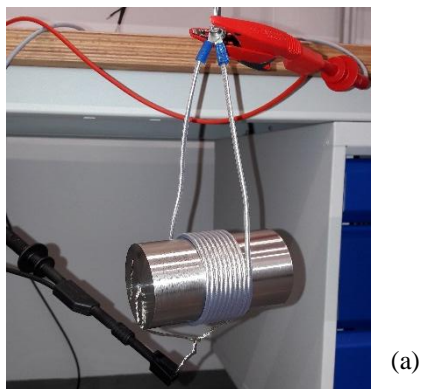
B. Test configurations

The test configurations consisted of single layer insulated cables either wound around a metal mandrel or with a section laid flat against a metal plate (ASTM methods) or by pulling a metal braid along them before testing (EN method). Below is a description of the methods with indication on the way it was implemented by the different labs, designated as A through D.

1) Method 1: Mandrel

The method follows ASTM D3032-2016, section 25. The original metal braid is removed from the cable as to expose the insulation. The test specimen is prepared by wrapping 10 turns of the insulated wire around a mandrel of approximately 10 times the wire diameter. Each end of the cable is extended beyond the mandrel so that the ends of the conductor can be joined and connected to the high voltage, see Fig. 1. The number of turns of the wire and the mandrel diameter were the same for all labs. The mandrel is connected to ground. The "tightness" of turns on the mandrel and their arrangement on the mandrel could result in a variation of results.

Lab A used the mandrel weight to maintained sample on it. Duty wire lugs were used for the both wire terminations. The setup was suspended by duty wire lugs and the mandrel weight allowed to apply the same tension and tightness for all tests. Some jigs and fixtures were used by Lab B in order to ensure consistency between the different samples: two holes in an insulating PMMA plate for fixing the lateral tightness between adjacent turns and two screwed pass-through connectors for keeping the mechanical tension of the individual turns around the mandrel during test. Lab D did not use a dedicated test fixture instead using an insulating tape to secure the wire to the mandrel. Lab C on the other hand fixed the sample on the mandrel (aluminum) only by using an adhesive tape. Both sample ends were connected directly to the banana plug. As the diameter of the banana plug is smaller than twice the AWG12 conductor some strands were cut off.



(a)



(b)

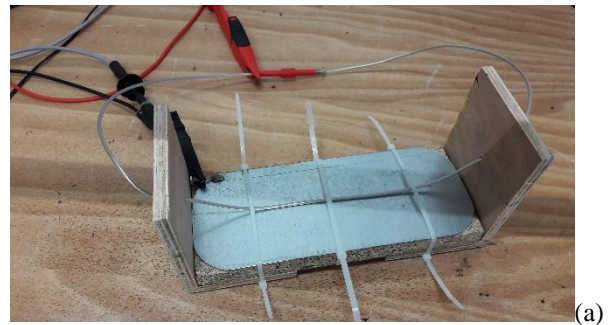
Figure 1. Sample arrangement for Method 1 (mandrel) – (a): Lab A; (b): Lab B.

2) Method 2: Plate

An alternative method described in the ASTM D3032-2016 standard consists of taping the wire specimen on a flat metal plate and bending both ends of the wire away from the plate. Ends are connected together and to the high voltage lead of the test cell. As previously, the braid is removed. Variations in the results may arise from the way the cable departs from the plate and the way it is attached to the plate.

Instead of taping the wire, Lab B used grooved metal counter-plates to hold the wires against the ground plate, see

Fig. 2. The grooves were semi-cylindrical of about 1.1 times the wire diameter, with all the edges rounded in order to avoid artificial electric field enhancement regions. The counter-plates were fixed against the ground plate by four equally torqued screws (equipped with elastic ripple washers) as to ensure consistent pressure for each sample. As with the mandrel method, Lab D did not use a dedicated test fixture in the same way as Lab B and instead used an insulating tape to secure the wire to a flat metal plate as per the standard. The wire was bent to allow connection to the high voltage supply for testing. Lab C again used just an adhesive tape to fix the sample on an aluminium plate. The length of the contact zone on the plate was 20 cm. Both cable ends were connected to a banana plug as in method 1. Lab A used cable tie to maintained sample on a inox plate. The contact surface was same as Lab C.



(a)



(b)

Figure 2. Sample arrangement for Method 2 (plate) – (a): Lab A; (b): Lab B.

3) Method 3: Braid

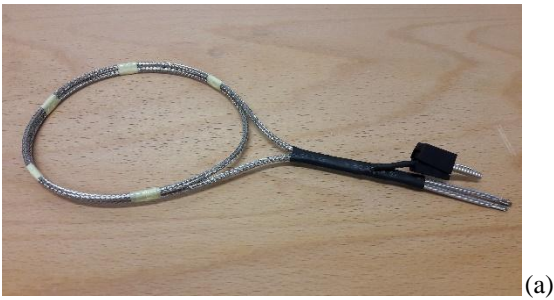
In method 3, the EN 3475-307 standard Method B was used. In that method a metal braid, which serves as the ground electrode, is pulled on the wire. The braid is already on the cable having been applied with a braiding machine. According to the standard, the cable should be bent with a bending radius 4 times the diameter. The loop should be maintained without crushing or twisting the loop geometry. The exact number of loops is not specified in the standard. Only a minimum sample length of 850 mm is specified where the zone covered by the braid shall be at least 700 mm. The maximum length is limited by the maximum capacitance the test system can handle (from the perspective of energizing the test object / implications for PD noise levels). Here deviations

in preparation may arise from the way the shield is installed and the terminations are prepared.

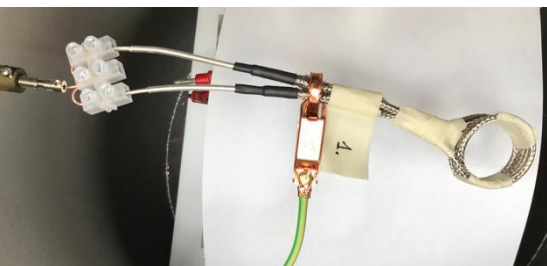
At Lab B, the braid was removed from the wire, cut, and pulled back on the cable, and kept under mechanical longitudinal tension. Then, 3 cm long heat-shrinks were applied at 7.5 cm from both cable ends. The braid was then pulled back over those tubings as to ensure an even termination of the braid, and a second 4 cm tubing was applied over this termination region to fix the configuration, see Fig. 3b. 5 turns of a such prepared cable were wound around a forming mandrel, and the resulting loop and the straight portions remaining were fixed into their relative positions using masking adhesive tape.

For Lab D, the braid was applied to the test object before each test. The braid was secured 7.5 cm from the wire ends using insulating tape rather than the heat shrinkable tubing used by Lab B. A second difference in the procedure was the use of two turns of the test object in contrast to the five used by Lab B. Lab A also used two turns per sample; the corresponding arrangement is shown in Fig. 3a. The braid was not removed from the wire.

Lab C in contrary to the other labs did not remove the braid and pulled it on again but did the measurements on samples with the original braid. This is considered being the best-case situation. Otherwise the sample preparation is like for Lab B and the connection to the HV electrode as in Method 1.



(a)



(b)

Figure 3. Sample arrangement for Method 3 (braid) – (a): Lab A; (b): Lab B.

C. Test Protocol

Measurements were realized on 10 samples per configuration. Each sample of each configuration was measured 10 times, providing 100 data points per lab per configuration. Measurements were achieved at ambient temperature, humidity and pressure, which were recorded.

All tests were carried out under 50 Hz sinusoidal test voltage, which was shown to be representative of the behavior at higher frequency considering inception voltage [2]. PD Inception and Extinction Voltages, PDIV and PDEV were recorded, along with Phase Resolved PD patterns for the 1st measurement. Not all the data will be presented herein. We focus mainly on the dispersions obtained on PDIV according to the test configuration.

At Lab A, the sample was energized by a TREK amplifier with a function generator. A software allowed to increased voltage by steps of 10 V until persistent PDs were observed and the PDIV was recorded. A Power Diagnostic GmbH equipment coupled with a high speed scope and a specific capacitance sensor designed by Lab A were used. Signal trigger was set to 2.5 times the noise. Temperature and RH% were recorded at 25°C and 60%.

The measurement device used at Lab B was an ICM System from Power Diagnostix GmbH and the sample was energized using a variac/step-up transformer combination operated manually. Calibration was performed at 10 pC in order to check the signal/noise ratio. Voltage was slowly increased until continuous PD activity was observed and the PDIV was recorded. After 10 s, voltage was risen about 50 V over the PDIV and then slowly decreased until no PD activity was present for more than 10 s. This new value of PDEV was recorded. Temperature and RH% were recorded at 25.6°C and 59.4%.

Lab C used a turnkey test system from SES2I with a step-up transformer operated semi-automatically. Calibration was performed with 5 pC. The voltage was increased with 100V/s up to 80% of the expected PDIV. Then the voltage was increased in steps of 50 V which were held for 15 s before the next step until continuous PD activity was observed and the PDIV was recorded. After 15 s the voltage was decreased in steps of 50 V until PD activity extinguished for at least 15 s and the PDEV was recorded.

All measurements at Lab D were performed in a room designed to shield the test object and detection system from sources of radio-frequency interference and improve the signal-noise ratio. Partial discharges were detected using a coupling capacitor and an MPD detection system from OMICRON Electronics GmbH (Austria). Calibration was performed at 5 pC. As with Lab B, the test object was energized using a step-up transformer and the voltage was increased manually using a variac until persistent PDs were detected and the PDIV was recorded. The method for determining the PDEV was the same as Lab B. The temperature and relative humidity were 22°C and 45% respectively.

III. RESULTS AND DISCUSSION

A. Outlook

Fig. 4 shows an overview of the results obtained considering the different laboratories and the different test configurations. Data are given with the 95% confidence interval as error bar over the 100 measurements realized for

one data point. There is an obvious dependency of the values obtained according to the lab and to the method that has been used. Indeed, the values of PDIV span from 1320 V to 2080 V as averaged values (see Table 1), and from about 1100 to nearly 2400 V as individual values.

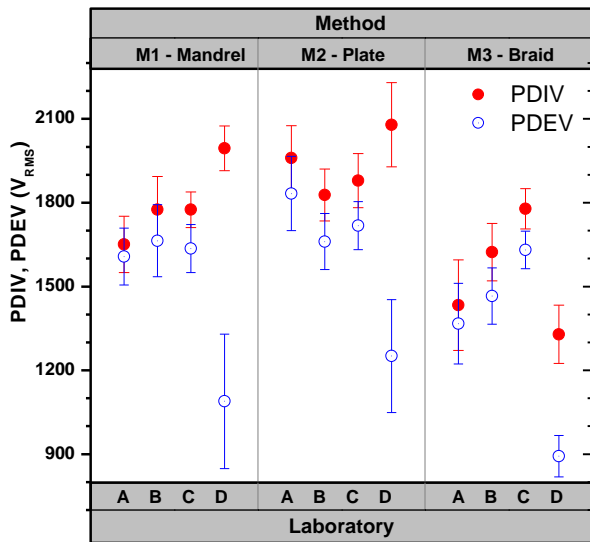


Figure 4. Overview of the results on PD measurements: Mean of PDIV and PDEV vs. lab for the different methods.

B. Variability according to Lab

Clearly, there is a significant impact of the operational conditions on the results on PDIV. Most often, the values for a given method are outside the error bars for the different labs. There is no systematic deviation according to the lab – i.e. not a systematically higher PDIV for a given lab irrespective of the method. This trend discards some problems of sensitivity of the experimental set-ups being used or on the criterion used in defining the inception voltage. Instead, it points to differences in the way the tests are implemented, especially the samples preparation. Ambient conditions (temperature, pressure and humidity) were not under control during these measurements. No obvious correlation was extracted between site localization and results.

TABLE I. VALUES OF PDIV AND STANDARD DEVIATIONS SD

A B C D	M1	M2	M3	M1	M2	M3
PDIV (V)	1651	1960	1433	1775	1828	1623
SD* (V)	101	116	162	119	93	103
<SD>** (V)	42	90	80	44	45	62
PDIV (V)	1775	1879	1778	1995	2079	1329
SD* (V)	64	97	72	80	151	104
<SD>** (V)	45	47	55	74	83	56

*SD on all PDIV measurements

**Average of SD over 10 samples

Concerning PDEV, in general, it follows the trends obtained for PDIV, comparing methods for a given lab. The noticeable difference from lab to lab is with the gap between PDIV and PDEV. In general, Lab A obtained a small difference between the two values (80 V in average), followed by Lab B and Lab C (150 V) and Lab D (720 V, with a large standard deviation on PDEV). These large differences clearly arise from the test method. It can correspond to differences in the duration of the voltage

application under discharges conditions, in the estimation of the extinction conditions, or in voltage variation rate. Depending on the maximum voltage reached after PDIV determination, the discharge behavior during stepping voltage down can be changed. Lab D used a screened room to make all the measurements, leading to a noise level typically less than 1 pC. Other labs used facilities with unscreened environment. This can be the reason for the especially low PDEV obtained for Lab D. Standards do not define PDIV/PDEV in terms of magnitude but just on occurrence.

C. Variability according to Method

The methods that have been defined in standards and applied here aim at probing and comparing the design of the insulated wires vis-à-vis PD inference. Fig. 5 provides a family of possible sources of PD in case of unbraided wire [6] According to the method, the source of PD is expected to be at different locations, around the contact between insulation and mandrel or plate for Methods 1 and 2, and between the braid and the insulation in case of Method 3. In addition, in all cases, PD could be generated in voids internal to the insulation or between the insulation and the conductor. Regarding the latter possibility, a drawback of tape wrapping process is that it generates voids along the cable axis in which partial discharge may be incepted. In principle, the extrusion process reduces this risk as the material can flow in the gaps during extrusion. It also removes the risk of voids appearing at the tape overlap and between tapes.

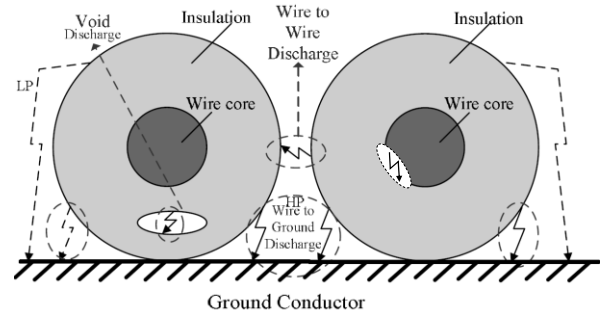


Figure 5. Potential sources of discharges [6]

The fact that the results depend considerably on the method and on its implementation conditions suggest that the discharges occurring inside the insulated wire are not dominant. It was not expected at the outset that PD are generated at the terminations of conductor or of the braid, but actually we don't have definitive proof to discard this possibility. Ideally, PD should be initiated between the insulation surface and the ground conductor, being the mandrel, the plate or the braid, according to the method. In these conditions, the tests would inform on the quality of the design.

The dispersion in the data could give a further indication on the origin of the defective region. In general, the standard deviation for repeated measurements on one sample is less than with changing sample, however some large error bars appeared for some samples, without relation between the PDIV and the measurement number. Table 1 shows the global standard deviation and the average of SDs for the measurements repeated on one sample. Fig. 6 shows examples of the distribution of results for the 3 methods.

In the examples shown here, the dispersion appears broader for Method 2, but again this is not a systematic observation, see Table 1.

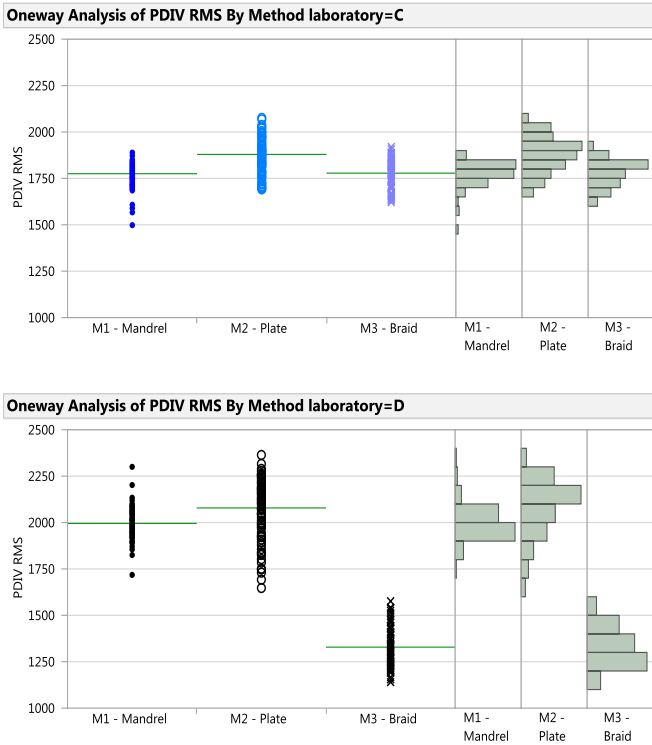


Figure 6. Examples of distribution of PDIV (Labs C and D)

1) Methods 1 and 2

Definitively, according to the various results, PDIV for Method 2 is higher than for Method 1. The dispersion of results according to Lab (Fig. 4) is larger for Method 1, pointing on some effect of implementation conditions on the results. Results obtained by Lab B who used for Method 2 a more specific arrangement than described by standard did not show deviation in respect to other labs regarding PDIV; The SD was pretty narrow, pointing to improved repeatability of the measurements. The reasons for smaller PDIV in Method 1 can be that the interaction length between cable surface and earthed surface is longer. Hence the larger the number of sites where partial discharge may occur leads to higher probability of a lower PDIV.

2) Method 3

For a wire with tightly installed braid, with no gap between the braid and dielectric surface, the PD activity related to the outer part of the wire should be normally lower than for unbraided wires. Here clearly, the PDIV is lower in case of Method 3. The use of a braided configuration poses the problem of treating braid ends. It is possible that cable ends are involved in the trend obtained here.

Discarding braid end effects, the decrease in PDIV compared to other methods could be ascribed to the discharges occurring between braid and wire insulation surface. In addition, braided wire offers long length of wire with small gaps between ground and insulation surface, increasing the probability of reaching the required conditions for discharge to occur. In a similar study on comparison of methods, Christou and Cotton [6] reached the same conclusions for measurements at atmospheric pressure.

It is interesting to recall that lab C did not use a manually milked on braid, but the original braid put on by a braiding machine. In that optimum configuration lab C obtained higher

PDIV and less dispersion compared to the other labs, see Figure 7.

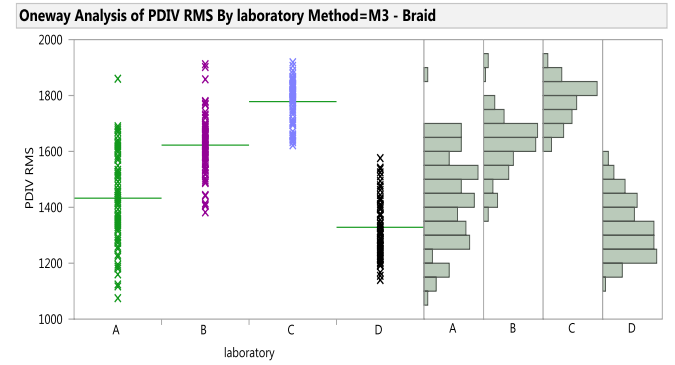


Figure 7. Distribution of PDIV for Method 3 obtained at different labs

D. Representativeness of aeronautic conditions

The test conditions used here are not representative of aeronautic conditions. A 50 Hz AC test was used when PWM stresses under much higher frequency are used on aircrafts. Using 50 Hz sine represents a simplification for comparison purpose as all labs have the facilities. It also conforms to standard specification regarding frequency. Pressure can be a more questionable parameters regarding notably the response according to the Method used. Referring to [6], it was shown that the PDIV in general is substantially decreased – of the order of 60%- when moving from atmospheric pressure to a pressure of 116 mbar. The decrease is not the same for all methods: it was large for Method 2. What was the 'best' case at atmospheric pressure became the worst and this can be explained by the distribution of distances from ground the insulation surface produced by such configuration. At low pressure, Method 3 gave highest PDIV presumably because only short distances were available when longer are needed to sustain discharges at lower pressure.

Above considerations show that it is not easy to define which method is most suited to probe designs. Certainly, the conditions in which the object are to be installed must guide the test conditions.

IV. CONCLUSION

PD inception and extinction voltages have been determined by 4 labs on the same object, using 3 different methods and a statistical analysis of the results was achieved. Relative large dispersion of the results was observed when considering different Labs and different methods for PD measurements.

According to the obtained results, it appears relatively risky to draw figures of merits from results obtained in different labs. This may suggest that existing standards do not define process in sufficient detail to allow comparison of methods and brings real question as to whether the standards are fit for purpose as they are. The positive aspect is that the same trends in the evolution of PDIV with method were obtained between the different labs, without exception, therefore validating comparison achieved by a given lab.

Method 3 represents a worst case in ambient conditions due to most probably loose fit of the braid on the wire and to the distribution of distances it provides. Also the braid ends may contribute to discharge activity, which represents a weakness of the method.

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