Abstract— High voltage power electronic systems are increasingly being used in aerospace applications with a target of increasing the power density of such packages, minimizing weight and/or volume. The use of high voltages in an aerospace environment is creating additional challenges for the equipment supplier who must warrant that their equipment is free of electrical discharges (this term encompassing partial discharge, tracking and disruptive discharges. At present there are no clear standards that relate to how aerospace equipment should be shown to be free of electrical discharges.

While individual components of a system can be tested using existing laboratory techniques, the test of the complete system is more challenging. Of increasing interest is the use of radio frequency (RF) techniques which rely on monitoring the electromagnetic emissions associated with the electrical discharges. This experimental work reports the applicability of RF techniques in detecting electrical tracking in systems working at sea level and/or at high altitude (pressures between 11.6-101.3 kPa). The measurements that have been carried out have been undertaken in a controlled electromagnetic noise-free environment with different antennas.

Preliminary recommendations are made as to the applicability of RF measurements in detecting electrical discharges within aerospace power electronic systems.

Keywords-component: electrical tracking, IEC60587, RF detection, electrical discharges, aerospace systems, monitoring system

I. INTRODUCTION

The drive to miniaturize most power electric systems while coping with the increasing demand for power by seeing the voltage at which they operate be increase, puts a new level of stress onto the insulation systems they employ. High voltage systems are being placed in compact packages to minimize weight and volume. However, when minimizing package size increased care must be taken in the design of the high voltage insulation system which is likely to be operated closer to design limits. As a result there is an increased risk of electrical discharges (ED) including partial discharges (PD) and electrical tracking (ET). Monitoring of power electronic systems operating at higher voltages is useful but complicated by the fact that power electronic systems use high frequency switching which produces high levels of electromagnetic noise (EM noise) making the detection of ED more difficult.

Miniaturization and increases in voltage are difficult enough to manage but is further complication by many of these electric systems operating in extreme environments while having high reliability requirements. Examples include aerospace vehicles (fast changes in temperature and pressure, the latter of which can reach one tenth of atmospheric), offshore wind-turbines (adverse weather, marine pollutants and the difficulty of performing regular maintenance), ships (long working cycles at very high temperatures) and trains (vibration and high presence of electrical harmonics), etc.. There is therefore a need to develop methods that can be used in the detection and qualification of ED in equipment working in extreme conditions while, ideally, being able to work in the presence of high EM noise.

The main objective of this study is to find a method for detecting the presence of ET, PD and electrical tracking, in electrical systems for aerospace applications using RF antennas. For both the phenomena there are no standards but for the PD detection there is a wide knowledge that can retrieved in literature whereas for ET there is a lack of information, especially regarding the RF detection of them. It is hope of the authors to fill that gap and consequently enabling the development of such a monitoring system able to detect a wide range of ED in aerospace applications.

II. ELECTRICAL DISCHARGES

An electrical discharge is an undesired flow of charges that result in a current. The effect of this current on the equipment (fail/non-fail) provides a criteria for use in categorising discharges, into disruptive and non-disruptive types, see Figure 1 and [1]:

1. Disruptive discharges result in the flow of fault current and consequently an interruption of the power supplied is needed in order to clear the fault. Usually they are due to poor design, manufacturing defects or severe ageing/damage of the insulation system.
2. Non-disruptive discharges do not initially result in a flow of fault current and will not be detected by protective equipment. In presence of such events the device affected
by the discharges remains connected to the network and energised but will usually suffer degradation of the insulation system which can ultimately lead to failure and a disruptive discharge.

Non-disruptive discharges are either tracking discharges or partial discharge (PD). Depending on the nature of the electrical system, the location and the magnitude of the discharges, they may exist within the system for a prolonged time without any clear evidence of damage. However, in the long run, any discharges will cause deterioration of the insulating material resulting in disruptive discharges and failure of the system, see Figure 2.

III. TEST RIG AND MEASUREMENT SYSTEM

A test rig to evaluate the capability of radio frequency techniques (RF) for detecting electrical tracking has been developed in-house. The system is composed of two main parts; a tracking rig built according to IEC60587 [2] and a measurement system equipped with three sensors: a current transformer to detect the leakage current, a monopole antenna (bandwidth 25-2000MHz) and a TEV sensor. The whole system is housed within a screened room built according to EN 50147-1 [3] to allow the detection of RF emission in the absence of any external noise. An accurate description of the screened room can be found in [4].

IEC60587 describes two methods (constant tracking voltage and stepwise tracking voltage) for the evaluation of electrical insulating material used in severe condition; it describes in detail how to build the circuit and how to run the test (voltage applied, contaminant production and flow rate, electrode configuration, etc.). The authors chose to use this standard in order to produce an accurate and reproducible experiment. The method selected is the constant tracking voltage with every sample being stressed at 2.5 kV 50Hz while a contaminant with a resistivity of 3,95 \(\Omega\)m ± 0,05 \(\Omega\)m at 23 °C ± 1 °C was flowing at a rate of 0.15 ml/min. It should be noted that the voltages used in this test were high but the sample size is also significant (the electrodes 50 mm ± 0,5 mm apart [2, 5]). Further work will need to see the test repeated using lower voltages and distances more representative of those seen in an aerospace system. The electric schematic of the rig can be seen in Figure 3.

The measurement system comprises of a TEV sensor with a bandwidth of 1-50 MHz and a commercial RF monopole scan antenna with a bandwidth of 25-2000 MHz (already used in [6]). The leakage current is measured with a Fluke i30s AC/DC current clamp. The three signals are visualised and recorded via a LeCroy oscilloscope that also measures the voltage applied. The leakage current is measured with a Fluke i30s AC/DC current clamp. The three signals are visualised and recorded via a LeCroy oscilloscope that also measures the voltage applied.

The system is also equipped with a Canon digital camera to capture images of the specimens in the different phases of the experiment.

IV. EXPERIMENTAL PROCEDURE

In this experimental work, several specimens of different epoxy based materials (similar to materials used in circuit boards) were tested. Each specimen was prepared and washed according to the IEC60587 standard [2] (no abrasion on the specimen surface was required, see [2] 3.2).

As detailed in the standard, a constant flow of contaminant was applied to each sample and a voltage of 2.5 kV at 50Hz was applied to carry out the test. The tests were run as in [2] with the exception of the end-criteria point; the tests were stopped when the signals detected were not carrying any significant information or when the signals become illegible.
Before each experiment, a measurement was taken on the dry sample to measure the background noise and to verify the absence of unwanted discharges (due to imperfections within the specimens or the eventual corona discharges generated by the top HV electrode). After this preliminary test, the standard test was initiated as in [2].

During the tracking test, recordings of the signals detected with the 3 sensors and the voltage probe were performed at regular intervals of 600 sec. Additional tracks were recorded during moments of intense discharge activity. Screen shots from the oscilloscope were also taken.

Digital images of the specimens were captured at regular intervals during the whole tracking test. The time between images was 90-180 sec depending on the material under observation.

The digital camera was equipped with a flash; any time it went off a noise signal was therefore recorded on the measurement traces. As can be seen in Figure 4 the discharges from the flash are easily identifiable and all the recorded tracks and the screenshots showing these discharges were discarded.

Figure 3 Test rig

Figure 4 Flash discharge, it is interesting to notice how all the three sensors are able to detect it.
V. DATA ANALYSIS AND RELEVANT RESULTS

Several samples were tested and the results show a wide range of lifetime for the different specimens ranging from 88-307 minutes. To attain a degree of normalization of the data and to facilitate the study of the phenomena, the lifetime of each specimen has been subdivided in 10 stages of equal duration (e.g. a specimen with a lifetime of 220 minutes has 10 stages of 22 minutes). The discharges recorded with the three sensors (RF antenna, current clamp and TEV) were compared in each of these 10 different stages of the lifetime of each specimen.

When analysing the data it is possible to observe that the emissions due to the electrical tracking change as a function of time and it would appear that the phenomena can be subdivided in 3 phases. In the first phase, when the dielectric material presents no sign of degradation, the signals measured are derived from high frequency currents which are easily detected with the RF antenna. Towards the end of life of the specimens, the signals measured also contain low frequency components that can be detected by the TEV. The three phases can be more fully described as follows:

1st PHASE: The dielectric material is new and no degradation is observed as shown in Figure 5 (first picture on the left).

In this phase detection of discharges is only possible with the RF antenna although the current clamp detects some sporadic discharges. It is therefore reasonable to conclude that the emissions produced by the initial phase of tracking on new dielectrics have high frequency spectra. The signals detected are initially regular with a reasonably similar magnitude, see Figure 6. As the time passes the discharges tend to be distributed across the surface of the specimen, see Figure 5, and have an increasingly variable repetition ratio but are still of a similar magnitude.

During the final part of the 1st phase the current clamp detects more discharges. In the 1st phase only one discharge was observed/recorded for every half cycle of the 50 Hz applied voltage.

2nd PHASE: The 2nd phase commences when the surface of the material starts to present visible signs of degradation as shown in Figure 8.

The RF antenna remains the sensor that detects the majority of discharges but the magnitudes of these are not as regular in magnitude, as in the previous phase, and multiple discharges in each half cycle are recorded.

The current clamp now records more and more discharges and the TEV sensor starts to detect some sporadic discharges, suggesting that in the 2nd phase the frequency spectra of the emissions contain components at lower frequencies. See Figure 7.
At the beginning of the 2nd phase signs of degradations are visible on the surface of the sample. Picture was taken with an exposure time of 20 seconds and the assistance of a very short burst of flash to light the sample surface.

**3rd PHASE:** This commences when carbonized material and/or erosion paths are present on the surface of the sample.

In this phase all the three sensors (RF antenna, current clamp and TEV sensor) record significant levels of discharge activity as shown in Figure 9 and Figure 10. The discharges occur regularly and present irregular magnitudes. This phase usually corresponds to the last 10-20% of the lifetime of the specimen. In this phase AC and DC currents are flowing on the surface of the sample through multipath. This phase is terminated with the breakdown of the sample as defined by the end-criteria in the experimental. See Figure 11

The experimental data shows that a monitoring system using an RF antenna as a sensor will be able to detect the electrical tracking phenomena (at any phase of the tracking process) and can help to evaluate the severity of the phenomena (wave shape of the discharges and repetition ratio of them). The same type of sensor has also been shown to be able to detect emissions due to various forms of partial discharge: corona, surface discharges, internal discharges and so on. Some of these results can be found in [6] and more results will be released soon. Some videos of the phenomena can be seen at [9].

The major outcome of these studies is that with a simple and inexpensive sensor as a monopole RF antenna, it is
possible to monitor a wide range of discharge phenomena and assess the status of the dielectric system working in an environment subject to a sudden change in pressure (aerospace vehicle). This monitoring system can therefore help to enhance the reliability of the whole electric system present on the vehicle.

VI. Consideration about the Experiments

This experiment was based on the IEC 60587 in order to control as many variables as possible nevertheless there are still uncertainties due to several factors such as the construction of the electrodes and the filter paper used [5].

In future experiments it would be relevant, for the aerospace industries, firstly to run the experiments at voltages and sample sizes more akin to that one in an aerospace system and secondly to remove as many uncertain as possible.

VII. Future Work

This work and [6] shows that with a monitoring system fitted with RF antennas is able to detect the presence of electrical tracking and PD in high voltage system. In order to improve this monitoring system the next steps will be to:

1. Understand how and when the arc-discharge produce the RF emissions (during the arc or at the moment of the extinction of the arc) and how they vary as degradation of the material takes place
2. Study the spectra emission of the discharges in the different phases of the phenomena and with different materials
3. Run experiments at voltages and sample sizes akin to that in an aerospace system.
4. Improve the dedicated sensor: a smaller antenna would be useful but would only if be able to detect the frequencies relevant for the discharge detection (better signal/noise ratio)

After this, the development of an automated monitoring system able to detect a wide range of discharges will be realizable.

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