Partial Discharge Testing Of Aerospace Electrical Systems

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Abstract

Modern aircraft are using more electrical equipment and are therefore using higher voltages. These higher voltage systems will become increasingly common in the future. The forms of system that are being used operate under frequencies/waveshapes different to those normally used on ground based electrical power systems and the testing regimes are relatively undeveloped in comparison to the other standardized tests available for aerospace components. This paper firstly introduces the reasons why higher voltage systems in aircraft may be susceptible to partial discharge. It then introduces two electrical test techniques that can be used to measure partial discharge activity. One of these, the balanced technique, is used to examine the partial discharge performance of four test objects that are stressed with high voltages at varying frequencies of both sine and square waveforms. The results that are presented show that while the level of damage that can be attributed to partial discharges can be significantly increased as frequency rises, the inception voltage of such discharges does not significantly vary.

Index Terms— Aircraft power systems, Aircraft testing, High-voltage techniques, Partial discharges, Insulation testing, Insulation
I. INTRODUCTION

Electrical systems in the generation of aircraft currently in use tend to be a mix of AC and DC. DC systems are typically operated at 28 V while the AC system operates at 115 V rms (equivalent to 163 V peak phase to earth or 282 V peak phase to phase). The use of these voltages has historically provided a safe and reliable means of energy transport with the main risk being from electrical tracking. With the advent of technology such as the More-Electric-Aircraft, there are increased electrical power demands on the engines and this power must be transmitted across the airframe [1]. The increase in electrical power demand is due to the desire to eliminate heavy mechanical systems such as air-starter pipework and hot-air anti-ice systems. The replacement of such systems with electrical alternatives will provide significant aircraft efficiency benefits resulting in better environmental performance due to reduced fuel consumption. Boeing quote that the advantage of the new electrical architecture used on the 787 will lead to a 35 % power reduction as a result of using electrical power to displace pneumatic air demands on the engine (such bleed air having largely being used for the environmental control system) [2]. Some authors suggest that hybrid AC/DC systems will be used in the future with both of these operating at higher voltages [3].

The significant levels of electrical power that will need to be transmitted between systems on these More-Electric-Aircraft cannot, however, be efficiently transported at current voltage levels. The continued use of low voltages to transmit the required power is unsustainable as voltage drop becomes an increasing problem as does the conductor size / weight which would increase. An increase to higher voltages would help solve these
problems but would introduce others, namely the increased probability of electrical discharge. The use of modern power electronic systems and generators driven directly at variable speeds from the engines will also result in the existence of these higher voltages at varying frequencies in the form of both sine wave and variable duty cycle square wave forms.

In a system with a peak voltage below approximately 327 V, there is no possibility of electrical discharge across an air gap during normal operating conditions. This statement is based on the well established Paschen’s law that is illustrated graphically as shown in Figure 1.
The figure shows that the breakdown strength of air varies according to the product of the gap size and the gas pressure. The shape of the curve is defined by the processes governing ionization of particles by electrons being accelerated by the electric field within the air gap. Importantly, the figure shows that no breakdown is possible in an air gap when a voltage of less than 327 V (231V_mns) \[4\] is applied to it (this figure being Paschen’s minimum and changing slightly depending on the electrode material). The exact shape of the curve, particularly the ascending portion on the right hand side, will also depend on electrode geometry.
As the voltage levels used in most previous generations of aircraft have been lower than 327 V peak, they have effectively been designed with electrical systems that cannot be subject to an electrical discharge across air gaps during normal conditions (transients from events such as lightning could, however, always cause a discharge event). This is clearly desirable from a safety perspective. Raising the operating voltage of future aircraft introduces the prospect of breakdown taking place in the electrical system should the 327 V threshold be passed (as would be the case in the modern aircraft systems that are intended to operate at either 230Vrms phase to earth or +/-270DC).

The electrical discharges that could occur in the aircraft operating at higher voltages can be subdivided into two types; partial discharges (PD) and disruptive discharges. The first of these, the partial discharge is the formation of an electrical discharge that does not completely bridge the gap between two conductors. It is often described as corona but this is just one form of partial discharge. A partial discharge is characterized by a small flow of charge, often in the region of 10-1000 pC, the production of light/sound and the degradation of surrounding insulation (thermally, by chemical attack from resulting ozone, by electrical discharge machining or by the impact of UV light). The duration of a partial discharge varies between a few nanoseconds and a few microseconds.

A disruptive discharge, otherwise known as an electrical breakdown, occurs when the gap between two conductors is fully bridged by a discharge. A disruptive discharge will result in the flow of fault current and would normally require the operation of a protective
device such as a fuse or circuit breaker to end the flow of current. This paper does not
discuss the testing of electrical systems with respect to disruptive discharges as this is
normally achieved by a simple high voltage (flash/HIPOT) test.

Two main issues are investigated in this paper in order to further understand the behavior
of partial discharges in an aerospace environment. Firstly, the dependence of partial
discharge behavior on the type of voltage waveform stressing the insulation is an
important factor to understand when designing insulation systems. Systems could operate
under DC, variable frequency AC or pulse width modulated (squarewave) voltage and the
partial discharge behavior of the insulation system will not necessarily be the same for
each of these. Secondly, testing of insulation systems using voltages that are ‘non-
standard’, i.e. not 50 Hz/60 Hz is difficult for reasons that will be explained. The paper
therefore ascertains the suitability of standard 50 Hz/60 Hz test methods in determining
the partial discharge inception voltages of insulation systems operating at other
frequencies / under non-sinusoidal waveshapes.

Before the experimental testing that was performed as part of this work is described, it is
appropriate to discuss the significant work that has been reported by other authors in
relation to the development of higher voltage systems in low pressure environments.
Much of this work has been related to space applications with the remainder mainly
examining the application of higher voltages to military systems. Bilodeau, Dunbar and
Sarjeant in a paper from nearly twenty years ago discussed the increased demand for
higher voltage usage in space power systems owing to the need to reduce the weight that
would result from the use of lower voltage systems [5]. The paper discussed different ways in which components could be tested and proposed an adjustment in the partial discharge test voltage at 50/60Hz to account for reduced partial discharge inception voltages at higher frequencies.

Many other papers examine some of the basic issues relating to the operation / testing of higher voltage systems in a low pressure environment. An experiment was conducted by Dunbar et al [6] in which a wire was stressed with high voltage to determine the effect of high frequency at high altitudes. His results indicate a reduction in the partial discharge inception voltage of around 15% at frequencies above 40 kHz for an altitude of 33000 ft. This is compared with other authors work and is found to match with other results. Dunbar suggests in another paper [7] that partial discharge can cause significant numbers of failures in high voltage systems. In [8], along with Dobbs and Tarvin, Dunbar describes a high voltage design guide that was developed for the US Air Force Materials Lab and that gives guidelines on electric fields, material and processing choices, packaging, manufacturing and testing. One of the issues discussed is that encapsulation that can be sometimes be used to try and prevent high voltage problems can actually be a source of them through the introduction of void discharge. Another general paper is that by Brockschmidt [9] who discusses the problems associated with the operation of higher voltage systems in a low pressure environment and discusses the fact that the voltage required to sustain partial discharge can be lower than that required to initiate it. Karady et al [10] examined the corona inception voltage of simple electrode geometries including ones that involved thin layers of electrical insulation. The authors show that for certain
experimental arrangements, corona inception can take place at voltages lower than Paschen’s minimum.

In 1994, Hammoud and Stavnes [11] conducted a breakdown test on different types of cables. A reduction in the breakdown voltage of 20% occurred when using a testing frequency of 400 Hz at 200°C. In this case, the reduction in breakdown strength was attributed to an increased dielectric loss at the higher frequency (this being a solid test object and not a gas). A study was conducted on polypropylene cable by [12] at different frequencies, ranging from 50 to 400 Hz. The results of these tests correlated with [11] in that breakdown voltages of such insulation could fall as a function of frequency. This paper also examined the corona initiation voltage of wires coated with this insulation and found the impact of frequency was not as severe as that seen on the breakdown voltage.

Many other pieces of literature exist that examine the impact of voltage frequency on breakdown and partial discharge inception at sea level. A number of these are useful in further understanding of the topics discussed within this paper. Kurihara et al [13] discuss the effect of a higher frequency voltage (created by superimposing a higher frequency signal onto a lower frequency fundamental) on an air filled void. As the frequency of the higher frequency component increased, the partial discharge inception voltage fell. In contrast, they reported little change in the inception voltage of partial discharge within an air filled void for a fundamental frequency between 6Hz and 1kHz. A dramatic increase in the number of partial discharge pulses per second did however occur. Cavallini [14] provides a theoretical analysis of the impact of frequency on partial discharges taking
place within voids of solid insulation. These are then contrasted with test results that show a significant effect of frequency on the phase distribution of partial discharge pulses. The main conclusion of the work was that systems operating at lower frequencies may be subject to lower numbers of partial discharges but that these would be larger in magnitude.

Not all authors agree on the variation of inception voltage and/or discharge magnitude as a function of frequency (although generally test objects vary). Plessow and Pfeiffer [15] have carried out work examining the impact of frequency on the partial discharge inception voltage of various materials including a ceramic, a polyester and a phenolic resin. They report increases in partial discharge inception voltages as a function of frequency. They also report higher discharge magnitudes as a function of frequency [15]. Meanwhile, work by Wilder and Hebner states that no variation in inception voltage is reported as a function of frequency [16]. They also showed a different in behavior between samples that had been previously exposed to high voltage and those tested as new.

A number of authors have examined the impact of squarewave voltages on partial discharge but such work has usually been focused on enameled wire [17],[18]. One exception is [16] that looked at material samples of PVC and PE. Discharge inception voltages are shown to reduce with temperature in [17] but there is no comparison with standard test frequencies within this work. An analysis of the impact of space charge on partial discharge in enameled wires is presented in [18]. The work shows a difference in
partial discharge inception voltages depending on whether a bipolar or monopolar waveform is applied, the difference being a result of space charge accumulation. The work suggests that the partial discharge inception voltage is largely unchanged as a function of frequency. An increase in the partial discharge inception voltage of PVC samples was attributed to a decline in permittivity as frequency increases in the tests carried out in [19].

II. EXPERIMENTAL ARRANGEMENTS

A. Test Objects

Within this paper, four specific types of partial discharge are produced in experiments. They are corona discharge, void discharge, surface discharge and discharge in an air gap formed by an insulated wire and a plane. The test objects will now be described in more detail. Reference should be made to Figure 2 which details the design of the different test objects and Table 1 which describes the environmental conditions during the test. It should be noted that the tests for corona discharge and surface discharge were carried out at atmospheric pressure so the magnitudes of voltages reported for these cases should not be directly applied to the aerospace environment.

Corona discharge occurs when the highest electric field in a gap with a non-uniform field distribution exceeds a threshold value. Local ionisation takes place without breakdown as the field is too low in other parts of the gap for the discharge to propagate between the two electrodes. For these experiments, the non-uniform field required was produced using a (sharp) needle to plane electrode geometry where the needle was connected to the high
voltage test supply and the plane was earthed. A separation distance of 2 mm was maintained between the two electrodes and the specific details of the needle type are contained in [20]. In an aircraft, corona discharge could take place where sharp edges are found whether these be created inadvertently or by design. A loose wire strand would be a typical source of corona discharge.

Void discharge occurs in inhomogeneous areas of bulk insulation formed by gas bubbles. These gas bubbles enhance the electric field owing to a difference in permittivity between the gas and the surrounding bulk insulation. The shape of the void can therefore contribute to field enhancement within the void. If the electric field in the void becomes high enough, a partial discharge will take place within that void. As long as enough bulk insulation remains, a disruptive discharge will not take place but cumulative damage over time could lead to this situation. To produce this test object, an insulated wire had silver paint applied to it to ensure that the electric field was contained within the insulation. A semiconducting varnish was then used to paint the two extreme ends to provide local electric field control and ensure that only void discharge would take place in this test object. In an aircraft, this form of electrical discharge could take place in any wiring system irrelevant of whether screening was present on the outside of such wires.

Surface discharge occurs when the electric field on the surface of a material exceeds the electric strength of that interface, the discharge typically propagating in the air across the surface. For these tests, a brass disk with a 12.75 mm diameter was attached to a square sheet of Teflon (PTFE) material that was 400 mm² in area and 2 mm thick. This sheet
was then placed onto a copper ground plane. In an aircraft, surface discharge could take place on surfaces of connectors, the outside of power electronic modules, across circuit boards and other similar locations. Other materials other than PTFE have been tested and some photographs of the type of damage that occurs to these is presented later in this paper.

Wire to plane discharge can occur when a large enough insulation thickness is not defined in an aerospace system. In any small air gaps formed between the wire insulation and another grounded electrode, the electric field can exceed that required to a partial discharge. A disruptive discharge will not occur as long as the bulk insulation of the wire remains sound. For these experiments, a wire with an insulation thickness of 0.3 mm and a conductor radius of 0.3 mm was placed above a plane electrode. This wire is a type that is designed for use in modern aircraft power systems. The wire was in contact with the plane electrode for an approximate distance of 5 cm, the ends of the wires then rose off the plane. Discharge was expected in the region where the wire lifted off the plane. In an aircraft this form of discharge could take place between two wires, where a wire moves against a grounded object (a ground plane or a duct) or when wires move into a connector.
Fig. 2. Block diagram of the four test objects. (a) Corona (b) Void (c) Surface (d) Wire To Plane

<table>
<thead>
<tr>
<th>Test Object</th>
<th>Temperature(°C)</th>
<th>Pressure(bar)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corona</td>
<td>20 ±2</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>Void</td>
<td>20 ±2</td>
<td>0.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Surface</td>
<td>20 ±2</td>
<td>1</td>
<td>25%</td>
</tr>
<tr>
<td>Wire To Plane</td>
<td>20 ±2</td>
<td>0.1</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 1: Environmental Conditions During HV Tests

B. Test Circuits

Many methods exist for partial discharge detection exist. Historically, most measurements have used electrical systems to detect partial discharge. These systems will be discussed in more detail below as they are the ones that have been used within this paper. However, alternatives do exist and these are summarized in detail in [21]. A brief discussion of possible alternative measurement techniques is, however, presented.

- Electromagnetic Radiation (RF): When a PD pulse takes place, it is accompanied by the emission of electromagnetic radiation. The measurement systems used to detect discharge in this way tend to focus on the frequency range from 5 to 100MHz. While RF measurements may not always be as sensitive as electrical measurements, according to [22] they are able to measure discharge as low as tens of pico-coloumbs and have the added benefit that they can distinguish between more than one discharge site. They are not, however, able to give a measurement of partial discharge that can be directly correlated with the typical measurements given by electrical detectors.
- Acoustic method: This method is based on detecting the pressure waves that are
associated with a discharge in the test object. The higher the energy on the PD pulse, the higher the intensity emitted of the acoustic waves [23]. The detected signal measured by acoustic sensor significantly depends on the characteristic of the test object (in terms of the acoustic propagation path from source to sensor), the location of the discharge and the sensor itself. A sensitivity of around 10pC at best is claimed in the referenced paper.

- Optical techniques: The final method used for partial discharge detection measures light emission from PD sites. Some types of partial discharge, especially corona, produce light with a magnitude proportional to the PD pulse energy [21]. The spectrum of the emitted light depends on the surrounding dielectric material [24]. A sensitivity as low as 0.3pc is claimed in [25] when a photomultiplier is used. However, a clear disadvantage of this technique is that it cannot detect internal forms of discharge.

The advantage of all of these methods is their immunity to interference, their ability to detect PD no matter what waveform is used to energise the test object and their ability to not be subject to electrical noise from surge voltages any other lower frequency signals that are conducted through the electrical circuit. However, owing to the relatively low sensitivity of the RF/Acoustic techniques, the inability to directly measure charge values with any method and the inability of the optical technique to see internal discharges, electrical techniques have been used for this study.

1) Unbalanced Detection Method

The basic PD detection circuit used by many laboratories is the unbalanced (or straight) detection circuit as shown in Figure 3 and described by IEC 60270 [26]. The current
generated by the test object (TO) as a result of a partial discharge is very fast with a maximum time duration in the order of tens to hundreds of nanoseconds seconds. This pulse current flows through the measuring impedance (MI) and then through the coupling capacitor (CC) which is provided to form a low impedance loop for the PD current. A resistive impedance is often included between the test object and the voltage source to limit current flow in the event of test object failure.

![Block diagram of straight detection circuit (unbalanced detector)](image)

**Fig. 3.** – Block diagram of straight detection circuit (unbalanced detector)

The measurement impedance can also be connected between the coupling capacitor and the ground. In this case, the circuit would not have the disadvantage of significant levels of current flowing through the measurement impedance should the test object fail.
However, any PD signal is split between the coupling capacitor and any circuit stray capacitance reducing the sensitivity of the circuit. In this configuration it would be normal to maximize the value of the coupling capacitance to reduce the effect of any stray capacitance.

In either case, the PD current passes through the measurement impedance along with any current flowing as a result of the voltage used to energize the circuit [27]. It is the current that flows from the power supply and through the measurement impedance that means that there is an inherent difficulty in carrying out measurements at high frequency. The reasons for this stem from the characteristics of the measurement impedance.

The wide band system used in most commercial PD detectors requires a measurement impedance that is effectively a bandpass filter with a pass band magnitude of between 100kHz and 400kHZ. The filter has a high pass cut-off frequency between 30kHz and 100kHz and a low pass cut-off frequency of less than 500kHz. All of these values are taken from the IEC standard on partial discharge measurement [26]. Other commercial systems do exist that do not use these exact filter values. The use of this filtering arrangement means that the output of the circuit is a voltage pulse whose pulse height is proportional to the integral of the current, i.e. the pulse height is proportional to charge. As partial discharges are normally quantified in terms of charge, this is a useful experimental arrangement. The use of a band-pass filter also means that the narrow partial discharge pulses are widened as the high frequency components are removed. This means the system has a prescribed pulse resolution time. This is typically in the range of 2
µs to 10 µs and means that partial discharges occurring more frequently than this will appear overlapped on the recording instrument.

However, in the context of this paper, the response of this LCR impedance to higher frequency or non-sinusoid voltages is a fundamental consideration. For a circuit supplied by sinusoidal voltages, the amount of current flowing through the measurement impedance increases with frequency as the reactance of the test object falls. This therefore reduces the detection sensitivity in the circuit as a larger PD pulse is required for it to be seen over the ‘noise’ produced by the flow of power frequency current. In addition, as the frequency of the noise moves further into the pass-band of the filter, the measurement impedance does not filter this as significantly as it would lower frequencies. The result is a dramatic reduction in the detection threshold when using the circuit at higher frequencies. Experience has shown this circuit adequate to frequencies of a few hundred hertz. The response of the circuit to a squarewave source of the form produced by a PWM voltage supply gives more significant difficulties. The application of a squarewave voltage across the circuit will cause a large current to flow through the test object and the coupling capacitances during the rising and falling edges. This significant level of current will swamp any signals produced by PD pulses taking place during this transition period.

Figure 4 shows the noise levels measured in an unbalanced test circuit for sinewave energisation with a test object capacitance of 750 pF, a coupling capacitance of 1 nF and a test voltage of 1kV pk-pk. The 10 pC threshold that is often taken to be acceptable for measurement is passed for frequencies above 400 Hz. The noise during the squarewave
voltage energisation is constant as a function of frequency as it is based on the rise time of the voltage pulse that in this work was fixed at around 40µs. A noise level of 10,000pC was measured in this case using an unbalanced test circuit for a 1kVpk-pk waveform, a value well in excess of the partial discharge levels that need to be measured in a circuit.

![Graph showing noise level measured in a test at varying frequencies using a straight detection method.](image-url)

**Fig. 4.** Noise level measured in a test at varying frequencies using a straight detection method

Several techniques are mentioned in literature that could allow these noise problems to be overcome. These methods include Fast Fourier transform-based techniques (FFT), wavelet transform techniques (WT) and digital filter techniques [28]-[31]. In FFT-based methods, the time domain signal is transformed into the frequency domain before being
manipulated to eliminate unwanted noise. The de-noised signal is then converted back into the time domain by using an inverse Fourier Transform (IFT). In contrast, while Fourier transforms decompose the PD signal into sine-waves of various frequencies, wavelet transforms involve multi-resolution decomposition techniques that owing to the non-periodical and broadband nature of PD signal means that they have an enhanced ability to extract information from a noisy signal [28],[32]. Digital filters can be classified into two types: Finite impulse response (FIR) and Infinite impulse response (IIR). In such methods the input signal is transformed into a digital form using digital signal processing techniques. Filter coefficients of theses approaches can then be implemented either in hardware (Digital Signal Processors) or software. While these two filters work well with noise of a specific frequency spectrum (i.e. narrowband), they may become inefficient with broadband noise signals.

All of these methods have been able to reduce noise in partial discharge measurement circuits to acceptable levels. However, they all rely on post-processing and the input signal has to firstly be captured. If the magnitude of the noise produced in the circuit is significantly higher than the signal itself, no post-processing of that signal will be able to denoise it should the resolution of the measurement system be unacceptably low. For this reason, an alternative means of reducing the noise level was used that also complies with the requirements of IEC 60270.

2) *Balanced Detection Method*

The alternative PD detection circuit that can be used for measurements is a balanced
circuit where two test objects are tested, each one acting as the coupling capacitor for the other. If the test object impedances are perfectly matched, the equal flow of power supply current through each test object can be removed using an LCR impedance made up of differential windings. This will significantly reduce noise levels if operated properly. However, the test objects need to be clearly matched or additional tuning impedances need to be provided in the circuit and this is not always straightforward.

Fig. 5. Block diagram of balanced circuit

The balanced circuit shown in Figure 5 can be practically realized by forming L1, L2 and L3 from a three winding transformer with 1:1:1 turn ratios. The transformer should be wound so that L3 gives the output of the signal through L1 minus that of L2. The transformer windings can be designed to provide a given inductance and extra
resistance/capacitance can be placed in parallel to achieve the bandpass characteristic desired.

This type of experimental arrangement was used in the testing described to minimise noise levels. It would not normally be required if tests were to be carried out with 50 Hz/60 Hz only. The maximum noise level in the testing carried out was 12 pC. This was achieved even under squarewave voltage energisation.

III. EXPERIMENTAL TEST RESULTS

A. Experimental Apparatus

The circuit diagram of the test arrangement is shown in Figure 6. A Trek power amplifier rated at 2.5 kW and 20 kV peak supplied the test voltage. It was controlled using a 20 V pk-pk signal generator. Experimental data was collected using a fast oscilloscope with results then being processed by Matlab. A commercial PD detector was not used as while they are available from various manufacturers, they only work for sinewave and generally not for frequencies above 400 Hz. However, the filtering characteristics of the circuit used matched the requirements of IEC 60270. When testing with a squarewave, the rise time of the voltage pulses was approximately 40 µs. The duty cycle of the waveform was 50 %. When the frequency is reported in the following sections, this frequency refers to the inverse of the time between two rising edges (the rise time always being around 40us). The experiments were carried out at room temperature.
In all of the experiments, the partial discharge inception and extinction voltages were first measured over a frequency range of 50 Hz to 1 kHz. The inception voltage is the voltage at which continuous PD activity is first recorded, the extinction voltage is the voltage at which it stops. At each frequency, partial discharge data was then collected by applying a voltage 10% above the inception voltage. An average of 100 cycles of data was collected for each frequency measurement.

B. Test Results

The test results for each sample are discussed in detail in the sections below.
1) Corona Discharge

Corona discharge occurs when the electric field in an area of air is elevated to a value that allows local ionisation to occur. The exact discharge processes are different for positive/negative polarities and are discussed in detail in [4]. For negative corona, the mode produced in the experimental arrangement used to produce the results for this paper, partial discharges are seen at regular intervals whenever the electric field in the gap remains high enough. In practice, this means that corona discharge only depends on the voltage exceeding a given threshold. The form of discharge seen when applying a 200 Hz sinewave or squarewave is observed in Figure 7. The y-axis in these figures corresponds only to the magnitude of the signal coming into the PD detector and not to the energisation voltage. This has not been converted to a level of apparent charge, this information is presented in Figures 8 & 9.

Fig. 7. Corona discharge patterns for squarewave and sinewave voltage energisation

In both cases, corona discharge can be seen to occur on the negative polarity waveform and only when the voltage exceeds a given value. Corona would occur on the positive half cycle if the voltage was increased further [33]. As the squarewave maintains the
voltage at a constant value over the full half cycle, corona discharge can be seen for the entire time of that half cycle. For the sinewave, the partial discharge only occurs in a narrow window either side of the negative peak. This would imply that the expected damage to insulation caused by corona discharge would be greater when produced by a squarewave in comparison to a sinewave.

Figure 8 shows the inception and extinction voltages for corona discharge. For the squarewave case, the peak to peak voltage given includes any overshoot (this is also the case for graphs in future sections). The inception voltage required to cause corona discharge was around 5% higher with squarewave energisation in comparison to sinewave. As there was around 10% overshoot on the squarewave voltage, it is likely that the corona persisted for the full half cycle as the steady-state portion of the voltage was above the extinction level. Both of the waveforms showed a reasonably consistent level as a function of frequency. This is in contrast to Plessow’s finding in [15] in which an increase in PDIV as function of frequency was noticed. An assessment of the damage that could be caused by corona discharge has also been made by multiplying the average charge of the corona discharge by the number of discharges per second.
To understand why the damage that could be caused by corona does not vary significantly, further information in the form of the number of discharges per unit time and the average charge level are given as Figure 9.
As a function of frequency, the number of discharges in each cycle was seen to decrease. This is to be expected as the time between negative corona discharge Trichel pulses is driven by the degree of overvoltage applied to the gap [34]. In these experiments, a constant level of overvoltage was applied to the gap so the time between pulses can be expected to be constant. With a smaller half cycle time and a constant time between discharges, fewer discharges could occur in a half cycle for higher frequency waveforms. However, more cycles occur per second and it can be shown that this leads to an effectively constant relationship between the number of partial discharges per second and
the supply frequency. This is a simplistic analysis but broadly fits the weak increase in the level of damage as a function of frequency that was observed in measurements.

The significant findings from these tests were the clear increase in level of damage caused by squarewave voltages, the weak impact of supply frequency on either inception voltage levels or damage and the fact that a test with a sinewave voltage would over-estimate the inception voltage for a system energised with a squarewave.

2) Void Discharges

Void discharges take place within gas filled cavities in solid insulation. In most cases, these voids will not be connected to an electrode and if discharged must be recharged by the flow of current through surrounding insulation. For this to take place quickly, a changing electric field is required. Models have been used by other authors to show the variance of partial discharge within voids as a function of frequency and explain the governing processes in more detail [35].

Figure 10 shows the partial discharge pulses and the voltage waveforms for both sinewave and squarewave energisation. In the case of the squarewave, a single discharge can be seen at the transition between half cycles. The absence of any change in voltage between these transitions stops further discharges taking place in that half cycle. This is due to the constant voltage between transitions allowing no charging through the capacitance of the surrounding insulation but forcing them to recharge through the large insulation resistance, a process that takes too long in comparison to the cycle time. In
contrast, multiple pulses can be seen on the rising edges of the positive and negative half cycles of the sinewave.

Fig. 10. Void discharge patterns for squarewave and sinewave voltage energisation

Figure 11 shows the inception voltage and damage effect of void discharge as a function of frequency. The inception voltage was highest for a squarewave, being around 13 % above that of a sinewave when the supply frequency was low and around 6 % for higher frequencies. Again, the peak to peak squarewave voltage is given. This now includes a significant overshoot component (as can be seen in Figure 10).
Fig. 11. Inception/extinction voltages and cumulative damage level for void discharge

The damage caused by the discharge increased as a function of frequency in both cases. This mainly due to an elevation in the number of partial discharge pulses as a function of frequency as shown in Figure 12. The average charge of the discharges as a function of frequency was fairly constant for both energisation types. Void discharges created by a squarewave were of higher average charge. It is thought that this is a result of the increased charge that can be deposited in the surrounding insulation during the steady state period of the half cycle.

Considering damage done by partial discharge during squarewave energisation, with only
one partial discharge per half cycle a linear relationship with frequency would therefore be expected and this is what was found. The increase in damage as a function of frequency for sinewaves is also due to an increase in the number of partial discharges per second, this effect also being shown by Kurihara et al [13].

Fig. 12. Void discharge repetition rate of discharges and average charge as a function of frequency

In summary, for void discharges high frequencies increase the level of damage to insulation but do not significantly affect the inception voltage of partial discharge measurements. Inception voltages measured with sinewaves were more conservative, i.e. lower than those measured with squarewaves.
3) Surface Discharge

Surface discharge takes place when the external electrical field strength exceeds the dielectric field strength of the material. It is well known that this type of discharge is highly influenced by charge accumulated on the surface, which will disappear or be reduced when the field changes its polarity [36], [37]. The material used in these tests, Teflon, is characterized by slow charge decay with time as it has a high surface resistivity (low conductivity) [36]. Usually, surface discharge exhibits a higher charge magnitude (in the order of nC) than other forms of discharge.

Figure 13 shows the PD pulses obtained from the two types of waveform. For squarewaves, they appear at transitions between voltage polarities and they are very high in terms of magnitude. For sinewaves, the partial discharges occur on the rising edges of the positive and negative half cycles.

Fig.13. Surface discharge patterns for squarewave and sinewave voltage energisation

Figure 14 shows the inception voltage and damage caused to the PTFE. The maximum
difference in inception voltages between the waveform types was less than 10\%, squarewave inception voltages being the lower. Both the squarewave and the sinewave cases show an increase in the level of damage as a function of frequency although this is realized by different mechanisms.

![Graph showing inception/extinction voltages and cumulative damage level for surface discharge](image)

**Fig. 14.** Inception/extinction voltages and cumulative damage level for surface discharge

For a sinewave, a roughly linear increase in damage as a function of frequency is observed. As shown in Figure 15, the number of discharges per second increased as a function of frequency while the average charge level remained the same. For a squarewave, the number of discharges per second increases linearly (1 discharge per half cycle) but the average charge level falls. However, as the average charge level falls slower than the rate of increase number of discharges, the damage level still increases but
at a slower rate. The fall in charge level as a function of frequency can be attributed to the lower amount of charge deposition that can take place on the surface between discharges as the frequency increases.

![Graph showing charge and frequency relationship](image)

**Fig. 15.** Surface discharge repetition rate of discharges and average charge as a function of frequency

With surface discharge, it is easy to visually show the damage that can be caused to materials. Figure 16 shows the severe damage done to acrylic and PVC material exposed to a 50 Hz sinewave and a 1 kHz squarewave for a period of 24 hours. As dust can be collected on this form of sample through electrostatic precipitation during testing, these samples were cleaned before the photos were taken. The photos show very clearly that those samples exposed to higher frequency voltages suffered more serious damage than those exposed to 50 Hz. However, some materials are particularly resilient to such
damage. One of these is PTFE, a material often used in aerospace applications. Figure 16 shows the damage done to PTFE material exposed to a 50 Hz sine wave (after 16 hours) and a 1000 Hz squarewave. The amount of damage is not as severe as in the previous two cases, partly owing to the high melting point of PTFE of around 327 degrees.

(a) Virgin Sample (Acrylic)  (b) 50 Hz/Sinewave  (C) 1 kHz/Squarewave
(d) Virgin Sample (PVC)  (e) 50 Hz/Sinewave (f) 1 kHz/Squarewave
(g) Virgin Sample (PTFE)  (h) 50 Hz/Sinewave   (i) 1 kHz/Squarewave

Fig. 16. Results from ageing tests of three different materials. Photos magnified by a factor of 8.

In summary for surface discharge, high frequencies increase the level of damage to insulation but do not significantly affect the inception voltage of partial discharge measurements. Inception voltages measured with sinewaves were higher than those measured with squarewave.

4) Wire To Plane Discharge

Wire to plane discharge occurs when the insulation thickness of a wire is not thick enough and the electric field in the air surrounding the wire is high enough to cause a discharge between the outside of the wire insulation and an earthed object such as a ground plane. Figure 17 shows the form of discharge seen when applying the two waveforms at 200 Hz.
Fig. 17. Wire to plane discharge patterns for squarewave and sinewave voltage energisation

Figure 18 shows the inception, extinction voltage and damage to the wire as a function of frequency. The inception voltage values for the two waveforms were very close and tended to decrease slightly with increasing frequency. This is in contrast to [19] where inception voltage was increased at high frequency.
Figure 19 shows the repetition rate and average charge used to calculate the expected damage from wire to plane discharge. The level of damage seen by combining the discharge rate with the average discharge magnitude increases as a function of frequency for both the squarewave and the sinewave. The squarewave damage function is again driven by the linear relationship between the number of pulses per cycle and frequency. The sinewave damage rate is also determined by an increase in the number of partial discharges as a function of frequency. In both cases the average charge seems to decrease over the frequency range but more significantly in the case of the squarewave.
Fig. 19. Wire To Plane repetition rate of discharges and average charge as a function of frequency

In summary, for wire to plane discharge high frequencies increase the level of damage to insulation but do not significantly affect the inception voltage of partial discharge measurements. Inception voltages measured with sinewaves were higher than those measured with squarewave.

IV. IMPLICATIONS OF TEST RESULTS FOR AEROSPACE SYSTEM TESTING

While scientifically interesting, the real benefit of the measurements presented is the ability to use them to develop an understanding the behavior of higher voltage systems
within an aerospace environment.

The first use of the results is to examine whether systems intended for use at higher frequencies or those systems used squarewave voltages can be tested with a 50/60 Hz sinewave system. In such a test being carried out for aerospace applications, the importance would not be the magnitude of or the number of discharges. The inception voltage would be the key measurement as you would not want a system to be discharging in use.

The results show a contrast in behaviors of different test samples. Some show a higher sinewave inception voltage, some show a higher squarewave inception voltage. The magnitude of the difference varies but is no more than 20%. This could partly be explained by accuracies/tolerances of measurement equipment. As sinewave testing is much easier, has lower noise levels and is very established as a laboratory technique, it would seem prudent to recommend that testing was always carried out using this technique. If necessary, a safety factor could be added to the inception voltage criteria to account for operation of the insulation system under squarewaves. The testing showed a bigger variation in the inception voltages according to whether a sinewave or a squarewave was used in comparison to the frequency of the test. In this case, the maximum variation in inception voltage was 15.6% for sinewaves and 13.4% for squarewaves.

The results clearly showed that with the exception of corona, all the types of discharge
exhibited a strong link between the level of damage that could be caused (measured through the product of the average charge magnitude with the number of discharges per second) and the frequency. The use of higher frequency systems in aircraft will mean that partial discharges could have a severe impact on insulation. This was shown by tests on PVC and acrylic materials. PTFE was also tested and was shown to be very resilient to partial discharges.

V. CONCLUSIONS

The use of higher voltage systems in aircraft will lead to an increased likelihood of partial discharge and the need for testing of equipment before it is used on an airframe will therefore exist. The problems associated with standard partial discharge test circuits were described, higher frequencies and squarewaves increasing the noise levels in the circuits. This could be solved by the use of a balanced test circuit.

Inception voltages, average charges and repetition rates were measured for a range of sample types of various frequencies for both a sinewave and a bipolar squarewave. The inception voltages were shown to vary by no more than 20 % depending on the waveform used within the measurements. The level of damage caused by partial discharge increased significantly as a function of frequency in the majority of cases.

It is concluded that 50/60 Hz testing could be used for aerospace systems as long as a safety margin is attached to the inception voltage criteria.
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