AFRL-RQ-WP-TR-2017-0097

CONSIDERATIONS FOR FAILURE PREVENTION IN AEROSPACE ELECTRICAL POWER SYSTEMS UTILIZING HIGHER VOLTAGES

Daniel L. Schweickart
Electrical Systems Branch
Power and Control Division

Dennis F. Grosjean
Innovative Scientific Solutions, Inc.

Ian Cotton and Richard Gardner
University of Manchester

Donald G. Kasten and Stephen A. Sebo
The Ohio State University

JULY 2017
Final Report

DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.

AIR FORCE RESEARCH LABORATORY
AEROSPACE SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RQ-WP-TR-2017-0097 has been reviewed and is approved for publication in accordance with assigned distribution statement.

//Signature//

GREGORY L. FRONISTA
Work Unit Manager
Electrical Systems Branch
Power and Control Division

//Signature//

GREGORY L. FRONISTA, Chief
Electrical Systems Branch
Power and Control Division

//Signature//

BRYAN J. CANNON
Power and Control Division
Aerospace Systems Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)* July 2017

2. REPORT TYPE Final

3. DATES COVERED *(From - To)* 13 December 2015 – 23 March 2017

4. TITLE AND SUBTITLE
CONSIDERATIONS FOR FAILURE PREVENTION IN AEROSPACE ELECTRICAL POWER SYSTEMS UTILIZING HIGHER VOLTAGES

5a. CONTRACT NUMBER In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 62203F

6. AUTHOR(S)
Daniel L. Schweickart (AFRL/RQQE)
Dennis F. Grosjean (Innovative Scientific Solutions, Inc.)
Ian Cotton and Richard Gardner (University of Manchester)
Donald G. Kasten and Stephen A. Sebo (The Ohio State University)

5d. PROJECT NUMBER 3145

5e. TASK NUMBER

5f. WORK UNIT NUMBER Q1M4

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Electrical Systems Branch (AFRL/RQQE)
Power and Control Division, Air Force Research Laboratory
Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command, United States Air Force

Innovative Scientific Solutions, Inc.
7610 McEwen Road
Dayton, OH 45459

University of Manchester
Oxford Road
Manchester M13 9PL, UK

The Ohio State University
281 W. Lane Avenue
Columbus, OH 43210

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RQ-WP-TP-2017-0097

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RQQE

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RQ-WP-TP-2017-0097

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2017-3532; Clearance Date: 21 Jul 2017. The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

14. ABSTRACT

Electrical and electronic equipment used in aerospace applications must be designed to operate over a wide range of environmental conditions that include variations in pressure, temperature, and humidity. Electrical power systems for advanced aircraft utilize voltages well above the traditional levels of 12 to 42 VDC and 115/200 VAC, 400 Hz. Current airborne systems can contain 270 VDC, and bipolar systems with a 540 V differential are appearing in certain applications. Higher potentials create increased probability of arcing and flashover compared to the risks associated with traditional ac or low-voltage dc. The low pressures of high altitude environments only serve to worsen such concerns. This report reviews the development of an international guideline document [1] containing methods of managing higher voltages in aerospace vehicles. Based upon research under this project, current literature and archival work, the guideline document (1) provides a basis for identifying high voltage design risks, (2) defines areas of concern as a function of environment, and (3) illustrates potential risk mitigation methods and test and evaluation techniques. The document is focused on electrical discharge mechanisms including partial discharge and does not address personnel safety. Some of the key areas of concern are power conversion devices, electrical machines, connectors and cabling/wiring, as well as interactions between components and subsystems. In addition, the appendix to this report also provides detailed guidance for partial discharge testing of components in a simulated high altitude (low pressure) environment. The guideline document is intended for application to high voltage systems used in aerospace vehicles operating to a maximum altitude of 30,000 m. (approximately 100,000 ft.), and maximum operating voltages of below 1500 Vrms.

[1] *Managing Higher Voltages in Aerospace Electrical Systems*, AIR-6127, SAE International, 2017.

15. SUBJECT TERMS aircraft, electrical power system, electrical discharge, partial discharge, flashover, dielectric breakdown

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	SAR	37	Gregory L. Fronista 19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

TABLE OF CONTENTS

Section Page

LIST OF FIGURES

PREFACE

This report contains information acquired during the execution of an internal program entitled, “Robust Electrical Power Systems,” and through collaborations with Mr. Dennis Grosjean (Innovative Scientific Solutions, Inc.) as well as with Professors Ian Cotton and Richard Gardner (University of Manchester), and Professors Don Kasten and Steve Sebo (Ohio State University). The information contained herein is a review of technologies that were encompassed in a SAE-International publication, “Managing Higher Voltages in Aerospace Electrical Systems” [1]. The majority of its preparation was completed by the authors of this report. It is based upon current technical literature, archival works, and compilation of research collated during this project. This report focuses on some of the key technical issues that were identified in the development of the SAE document.

Section 1 summarizes the intent and scope of this work. Section 2 provides a brief introduction to the background for this work. Section 3 addresses key design issues that need to be considered when designing aerospace electrical power systems. Section 4 deals with concerns for testing of electrical components subjected to the aerospace environment. Section 5 presents the conclusions. Section 6 contains the references to the report. The Appendix provides detailed guidance for partial discharge testing of components in a simulated high altitude (low pressure) environment, along with a listing of Appendix-specific references.

ACKNOWLEDGMENTS

Special thanks goes to Vic McNier (University of Dayton Research Institute), along with Bill Bourne and Ben Sarka (Innovative Scientific Solutions, Inc.) for their technical support and practical expertise throughout the experimental portions of this program.

1 SUMMARY

Electrical and electronic equipment used in aerospace applications must be designed to operate over a wide range of environmental conditions that include variations in pressure, temperature, and humidity. Electrical power systems for advanced aircraft utilize voltages well above the traditional levels of 12 to 42 VDC and 115/200 VAC, 400 Hz. Current airborne systems can contain 270 VDC and bipolar systems with a 540 V differential are appearing in certain applications. Higher potentials create increased probability of arcing and flashover compared to the risks associated with traditional ac or low-voltage dc. The low pressures of high altitude environments only serve only to worsen such concerns. This report reviews the development of an international guideline document [1] containing methods of managing higher voltages in aerospace vehicles. Based upon research under this project, current literature and archival work, the guideline document 1) provides a basis for identifying high voltage design risks, 2) defines areas of concern as a function of environment, and 3) illustrates potential risk mitigation methods and test and evaluation techniques. The document is focused on electrical discharge mechanisms including partial discharge and does not address personnel safety. Some of the key areas of concern are power conversion devices, electrical machines, connectors and cabling/wiring, as well as interactions between components and subsystems. In addition, the appendix to this report also provides detailed guidance for partial discharge testing of components in a simulated high altitude (low pressure) environment. The guideline document is intended for application to high voltage systems used in aerospace vehicles operating to a maximum altitude of 30,000 m. (approximately 100,000 ft.), and maximum operating voltages of below 1500 Vrms.

2 INTRODUCTION

Aircraft are now being operated at higher voltages; both at the primary power system level as well as within aircraft sub-systems (e.g., flight actuation, invertors, window heating, etc.). The increases in the operating voltage of aircraft have been gradual. Aircraft electrical systems operated at 14.25 VDC in 1936, rose to 28 VDC in 1946 [2] which was slowly phased out in the 1950's for larger aircraft but kept as the standard for low voltage sections of aircraft electrical systems. In the 1930's, development of single- and three-phase alternating current systems began with the Boeing XB-15 having single phase 120 VAC-800Hz power, and the Douglas XB-19 having the first 3-phase 120/207 VAC-400 Hz system. In the late 1940's, the transition to a 115/200 VAC-400 Hz standard began with the British Brabazon commercial aircraft the American B-36 Peacemaker military aircraft Today, 115/200V AC 400 Hz systems are used in the majority of civil aircraft. 270V DC was selected by the military to provide further weight savings in the 1980s [3]. The current aircraft in operation with a more electric architecture include the Boeing 787 which has 500 kVA of electrical generation capability on each engine [4]. To support the generation levels without a significant weight penalty, the Boeing Company has moved from a 115V AC 400Hz system to a combined 230/400 VAC 360-800Hz and +/- 270 VDC (540 VDC) systems [4]. Airbus is also using high voltages for distribution on the A350 platform. Although various military aircraft have employed "double voltage" (230/400 VAC) primary power systems, these two commercial aircraft represent a significant change in the industry with potentially thousands of aircraft to be produced over the next few decades.

While these voltages are relatively low in terms of those found on land-based power systems, moving to higher voltage thresholds introduces an increased likelihood of electrical discharge [5], particularly the risk of continuous partial discharge that does not cause instant failure but reduces the life of insulation systems over time. While it is reasonably straightforward to design an insulation system that will prevent discharge, the need to minimize weight and the constrained volumes that are available in aircraft mean that there can be a conflict between achieving maximum reliability and the lowest possible weight and volume. The design of an insulation system is further complicated given that insulation systems may be designed for mechanical robustness well beyond the HV requirements in order to support installation or other needs.

An optimal design must be achieved in widely varying environmental conditions. Parts of the aircraft system that are in an unpressurised zone will see a low pressure for most of the flight and temperatures reaching average lows of around -56°C [6]. Using both simple simulations of the dielectric system and experimental measurement, it has been shown that this can lead to a reduction in partial discharge inception voltages in the order of 50% [7]. However, localized heat sources can lead to systems having to operate at very high temperatures up to several hundred degrees. Any systems located in the engine (including the starter generators that are being considered for future aircraft) can be subject to high pressure (HP) compressor delivery air which can be at around 400°C. Engine accessories, such as generators, can have ambient temperatures exceeding 180°C, and power terminations can exceed 240°C. In any pressurized location, flight critical equipment must be designed to ensure that failure does not take place should the aircraft suffer a loss of cabin pressure. This means that equipment has to be designed to function over a wide range of pressure and temperature.

There is a clear need to guarantee the reliability of any equipment operating at high voltage. Consideration must therefore be given to issues such as the insulating material lifetime. Insulation lifetime can be reduced by a number of factors including exposure to high temperatures, thermal cycling, vibration, chemical attack and electrical discharges. In addition to the bulk dielectric life issues, surface dielectric deterioration and effects must be considered as well. Primarily for maintenance and corrosion prevention reasons, civilian aircraft electrical power terminations are not coated. Therefore, an understanding of the material, voltage stresses and contamination exposure, nearly always reconstituted in aqueous form, over the life of the aircraft is very important.

3 KEY ISSUES FOR THE SAFE DESIGN OF HIGH VOLTAGE SYSTEMS

The following sections summarize the key design issues that need to be considered when designing aerospace electrical power systems.

3.1 Conductor Spacings in Air

Many components in any electrical system will have conductors at different potentials that are separated by air gaps. Typical examples include connectors, legs of components on printed circuit boards and connecting busbars. Failure to control these air gap distances may result in a disruptive discharge. Separation of the conductors can be set to a value sufficient to prevent a disruptive discharge taking place. For most small gaps which are generally uniform in nature (electric fields in which the ratio of peak electric field to average electric field is less than five can generally be taken to fulfil this condition), Paschen’s law [8] can be used to approximate the safe operating voltage for a given separation. The required separation for a given operating voltage is also subject to the inclusion of suitable safety factors to account for manufacturing tolerances, movement during vibration etc. From Paschen’s law calculations for air under ideal conditions, curves for sea level and selected altitudes are compared in Figure 1.

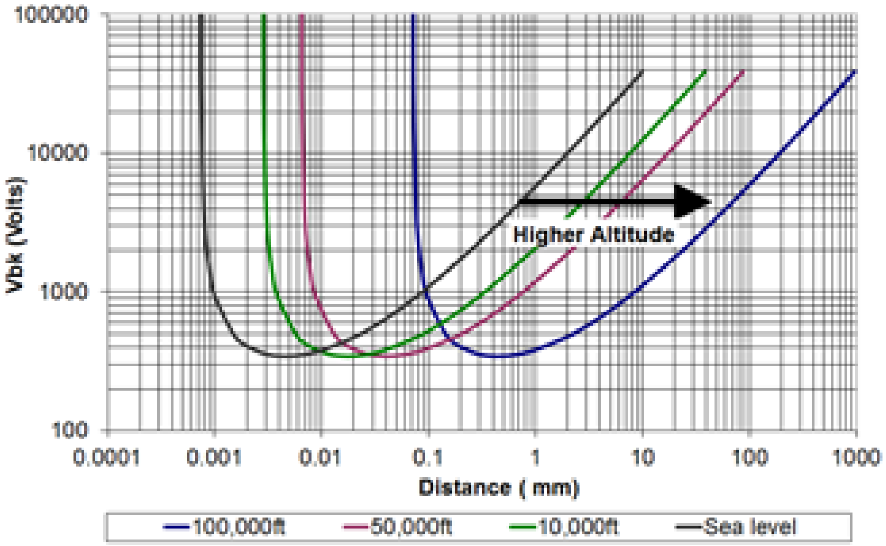


Figure 1 Breakdown voltage of air according to Paschen's law at a range of pressures (y-axis - breakdown voltage [volts-peak])

As an example of the impact of the aerospace environment, consider the calculation of the safe voltage associated with the use of a 1mm gap. At ground level, with a pressure of approximately 100,000 Pa, the peak voltage required to cause breakdown of this gap is approximately 5.5 kV. However, at an altitude of 50,000 ft. with an approximate pressure of 10,000 Pa, the voltage level that will cause a breakdown in this gap will reduce to approximately 1 kV. Placing the 1 mm gap in an aircraft engine where the temperature may reach as high as 200ºC the discharge voltage gap is reduced from 1 kV to approximately 800 V.

3.2 Cabling / Connector Insulation Thickness

Many systems on an aircraft use insulation to control the risk of disruptive discharge. However, partial discharge will occur in air gaps surrounding a cable (or the voids in a connector) in a situation when the cable insulation is not thick enough to reduce the electric field in the air gap below the value that can allow discharge to occur. The insulation thicknesses required to prevent this discharge can be calculated using the techniques detailed by Dunbar [8] and Halleck [9]. The calculations use the insulation thickness and the relative permittivity of the dielectric to determine a voltage at which partial discharge would take place. Such a technique appears to be also used to judge insulation thicknesses for the SAE standard relating to aircraft wiring [10]. This Aerospace Standard, AS50881 [10], provides guidance for choosing conductor and insulation sizes for aerospace wiring. Conductor size is based on an analysis of the required current carrying capability and takes the impact of altitude and the use of conductor bundles into account. Insulation size is determined by examining the required operating voltage, the insulation selected being thick enough to withstand partial discharges.

Examining these approaches using the approach by Dunbar and Halleck leads to the upper chart in Figure 2 that shows the RMS voltage rating that could be applied to a cable before partial discharge takes place. The figure describes cables with an insulation thickness ranging from 0.1 to 4.8mm. The lower chart in Figure2 shows that the higher the relative permittivity of insulation, the lower the voltage at which a single conductor cable can be operated without partial discharge. The use of materials such as PTFE, which have a low relative permittivity, is therefore useful in controlling partial discharge. The lower chart also shows that doubling the thickness of insulation does not double the voltage withstand capability; this non-linearity is likely to be important when considering whether future aerospace systems should operate at higher voltages than those presently in use. As a function of pressure, the voltage at which cables can be operated without partial discharge increases as expected.

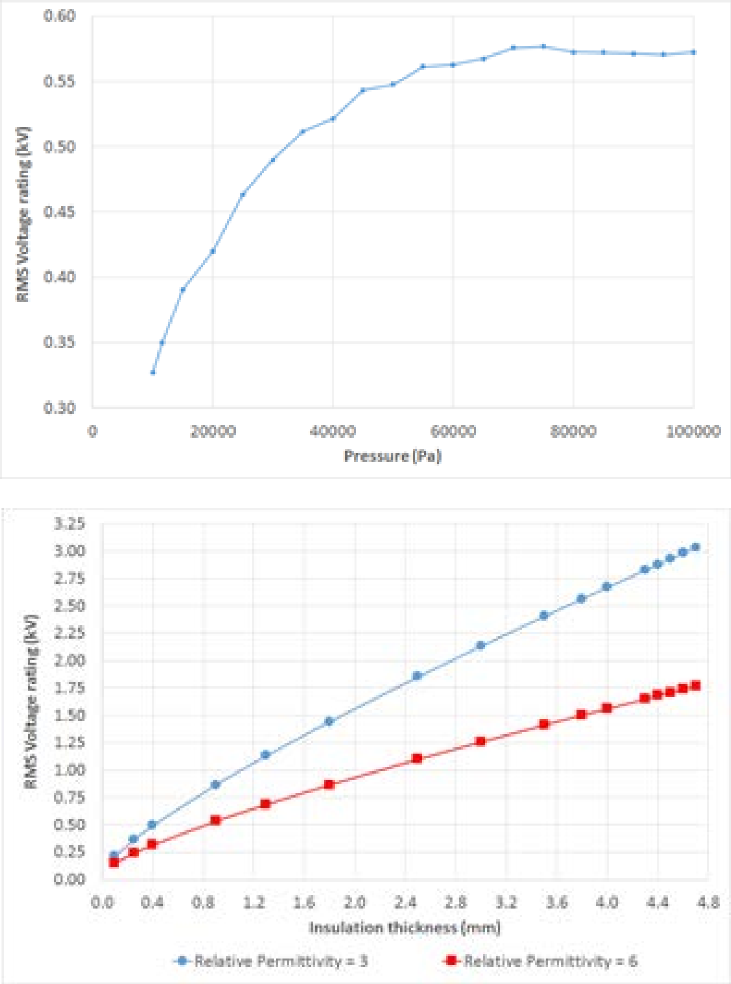


Figure 2 Variation of the safe operating voltage of an insulating material with increasing insulation thickness (on top). Comparison of two materials with different relative permittivity and the effect of increasing pressure (on bottom).

3.3 Electrical Machine Design

Partial discharge can also take place in the small air gaps in the insulation of electrical machines. In a machine, there is an increased need to keep insulation thicknesses at low values. Failure to do so will compromise the packing factor of the machine and will significantly increase the size. It is therefore common to find electrical discharge in the end windings of machines where the insulation thickness is not sufficient to prevent discharge in the air gap unless special precautions are taken. This discharge is due to the inability of the thin insulation layers to control the electric field in the air gaps as described in the previous section. The thin insulation thicknesses also increase the probability of discharge in voids between each turn of the machine, and between the turns and the core. Additionally, all types of machine insulation may have to cope with voltages higher than would be expected based on a simple analysis of the number of turns and the operating voltage. The use of square-wave voltage sources will lead to higher than expected voltages being imposed on the windings (these potentially doubling when a machine is fed from a PWM converter via a long cable). Additionally, as is the case with other transient voltages that the machine may encounter, the voltage stress could be non-uniformly distributed across the winding. It has been shown that the continual application of voltage surges, such as those seen by inverter fed machines, can cause degradation of the insulation and eventual failure [11].

The standards IEC 60034-18-41 [12] and IEC 60034-18-42 [13] deal with qualification of insulation in electrical machines. They state that type 1 electrical machines which are less than 700Vrms are generally random wound and are not expected to suffer partial discharge during their operating lifetime. The test regime specified is one where partial discharge inception voltage measurements are taken before and after thermal cycling. As stated by the standard, the measurements shall "… demonstrate the absence of partial discharges while the complete winding or machine is subjected to the voltage waveform appropriate to the selected stress categories, with the voltage enhanced by a safety factor of 1.3". In contrast, type 2 machines operating at more than 700Vrms and generally with form windings must be expected to suffer partial discharge. For this reason, required testing includes examining each component of the dielectric system including the turn-to-turn, phase to ground and phase-to-phase insulation systems (the latter two being the main-wall insulation and/or the phase separators). However, the value of 700Vrms does not take into account varying air density, as the standard is only intended for use at ground level. Partial discharge inception voltages in a machine will be lower when it is used in a low-pressure environment. It is therefore likely that the 700Vrms level is more likely to be in the order of 300-400Vrms when the aerospace environment is considered.

Figure 3 shows the results of experimental tests on the partial discharge inception voltage of turn-turn, phase-earth and phase-phase insulation within an aerospace electrical machine. A reduction in pressure from sea level to that seen at 50,000 ft. corresponded to a near 50% reduction in the partial discharge inception voltage of all the insulation systems.

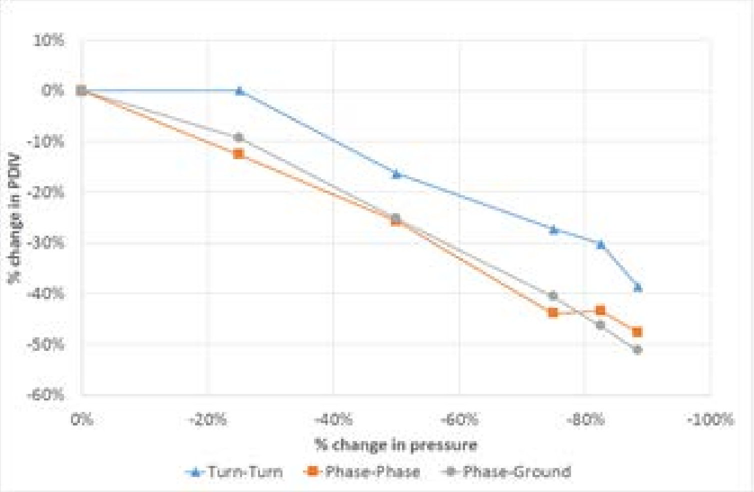


Figure 3 Effect of atmospheric pressure on PDIV of machine insulation systems.

3.4 Printed Circuit Board Systems

Printed circuit board systems are commonplace within the aerospace environment and are increasingly used in open-box designs (i.e. designs with no protection against varying pressure / humidity). It is important to manage the risk of electrical discharge in situations where conductors are used in combination with connectors, printed circuit boards, and power devices.

Appropriate creepage distances are usually stated for circuit boards operating in low pressure environments, for systems both with and without coatings.

There are a range of failure mechanisms that can occur on boards, particularly when coated. The impact of these failure mechanisms is also dependent on the environmental conditions experienced at various parts of the flight cycle. The presence of condensed moisture and conductive pollution on a coated surface can lead to tracking damage. Thermo-mechanical stressing due to large rapid temperature cycle changes can fatigue coatings, increasing the chance of cracking, pollution ingress, and subsequent failure, particularly at lower temperatures where material glass-transition temperatures are reached which potentially increases coating brittleness. Reduced pressure at altitude also increases the chance of partial discharge in accordance with Paschen’s curve, accelerating coating ageing.

IEC 60664-1 [14] gives creepage distances that should be used on equipment in a number of pollution categories. Pollution degree 1 is a clean and dry condition while pollution degree 2 refers to non-conductive or temporarily conductive pollution and pollution degree 3 refers to conductive pollution. In addition, it specifies creepage distances based on the material group (material group 1 implying a lower resistance to tracking than material group 2). The IEC standard, being applicable for ground based systems only, makes no attempt to correct for altitude. In contrast, IPC 2221A [15] makes no attempt to correct for surface pollution in any way but does account for altitude. Figure 4 compares these standards.

These curves (with the exception of the high altitude IPC B3 values) do not account for low pressure which has been shown to cause earlier failure of insulation samples than those tested at sea level [16]. Of particular note are the extremely low voltages that can cause tracking to take place over relatively small gap sizes on uncoated boards. In some cases, the voltages that can cause tracking damage to a polluted gap are nearly an order of magnitude lower than the voltages needed to cause breakdown of a clean dry gap.

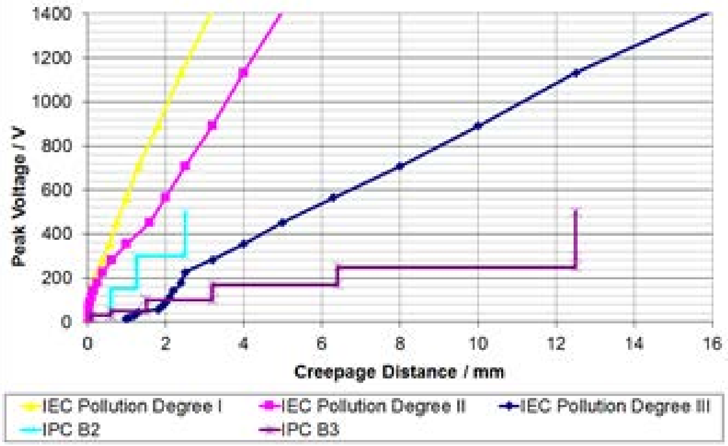


Figure 4 Required Creepage Distances According To IEC 60664 And IPC 2221A.

4 TEST TECHNIQUES

Many of the test techniques used on conventional high voltage systems are applicable to systems used in aerospace environments. As with other products, the absence of electrical discharge during initial qualification does not ensure the same over the life of the product. For example, when motor windings are subject to high electrical and mechanical stresses during their operational life, the capability of the insulation system degrades and may result in discharge if sufficient design margin does not exist. This needs to be considered alongside the specific challenges that exist to develop tests that mimic the aerospace environment.

Testing and qualification requirements for hermetic components need to consider leakage “time constants” of weeks or months. In aircraft, the parts tend to end up replacing dry N2 with humid air and ventilated components can end up containing significant amounts of water. Different parts of the flight cycle may also be critical for specific components. Open-box power electronics that have been dormant for most of the flight, and cooled to a low temperature may be exposed to warm and humid air on the descent phase just at the time when they are required to operate. There is therefore a requirement to understand the performance of insulation systems at all relevant parts of the flight cycle.

Partial discharge testing is becoming common-place within the aerospace industry as more equipment is operated at higher voltages. However, Grosjean et al. have noted that owing to the changing nature of partial discharges at low pressures, circuits based on IEC 60270 used for systems operating at atmospheric pressure may not have the appropriate sensitivity when tests are being carried out at altitude [17]. This issue has also been noted when impulse based partial discharge testing has been used on machine insulation samples [7]. Caution must therefore be applied when applying test techniques that have been commonplace in a high voltage laboratory to systems operating in these alternative environments. The Appendix to this report provides detailed guidance for partial discharge testing of components in a simulated high altitude (low pressure) environment.

5 CONCLUSIONS

This report provides a brief review of the SAE guideline document [1] that addresses methods of managing higher voltages in electrical power systems and components in aerospace vehicles. It focuses on some of the key technical issues that have been identified during the course this project and in archival work. It should prove to be a valuable resource for the designers of advanced aircraft, for both military and commercial purposes. The Appendix to this report also provides detailed guidance for partial discharge testing of components in a simulated high altitude (low pressure) environment.

The use of high voltages in an aerospace environment can lead to tracking, partial discharge or breakdown. This can result in the continual degradation of insulation or arcing. Designs must be analyzed to determine maximum peak/transient voltages and insulation materials, clearances, and geometries selected accordingly. Deratings are required that include manufacturing issues, making this somewhat vendor dependent. Partial discharge should always be prevented from occurring and not merely controlled using materials. Testing of equipment is essential. However, caution must be applied when using test techniques that have been developed for use in a laboratory at sea level, on equipment that will operate at high altitudes.

6 REFERENCES

[1] Managing Higher Voltages in Aerospace Electrical Systems, AIR-6127, SAE International, 2017.

[2] J. A. Weimer, “Past, present and future of aircraft electrical power systems,” AIAA 2001-1147, Proc. 39th Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 8-11, 2001.

[3] I. Moir and A. Seabridge, Aircraft Systems: Mechanical, Electrical and Avionics Subsystems Integration, ISBN: 1 86058 289 3, 2nd edition 2001.

[4] J. Lombardo, ed., “787 no bleed systems,” Boeing AERO Magazine, issue QTR 04.2007, 2007.

[5] I. Cotton, A. Nelms and M. Husband, “Higher voltage aircraft power systems”, IEEE Aerospace & Electronic System Magazine, vol. 23, no. 2, February 2008, pp. 25-32.

[6] Standard Atmosphere, ISO 2533, 1975.

[7] R. Gardner, I. Cotton and M. Kohler, "Comparison of power frequency and impulse based partial discharge measurements on a variety of aerospace components at 1000 and 116 mbar," in Proc. 2015 IEEE Electrical Insulation Conference (EIC), Seattle, WA, 2015, pp. 430-433.

[8] W. G. Dunbar, “High voltage design criteria”, Boeing Report D180-15179-1, 1972.

[9] M. C. Halleck, “Calculation of corona-starting voltage in air-solid dielectric systems,” Power Apparatus Systems, Part III, Transactions of the American Institute of Electrical Engineers, vol. 75, no. 3, Jan. 1956, pp. 211-216.

[10] Wiring, Aerospace Vehicle, AS50881, SAE International, 2006.

[11] G. Stone, E. Boulter, I. Culbert and H. Dhirani, Electrical Insulation for Rotating Machines Design, Evaluation, Aging, Testing, and Repair, 2nd ed., IEEE Press Series on Power Engineering, 2014.

[12] Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters – Qualification and quality control tests, IEC 60034-18-41, 2006.

[13] Qualification and acceptance tests for partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters, IEC 60034-18-42, 2008.

[14] Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests, IEC 60664-1, 2003.

[15] Generic standard on printed board design, IPC 2221A, 1998.

[16] F. Noto, “On the Test of Tracking Resistance by Means of Intermittent Discharges of a Condenser”, ETJ of Japan, Vol. 8, No.3-4, 1963

[17] D. Grosjean, D. Schweickart, D. Kasten, S. Sebo, and X. Liu, “Development of procedures for partial discharge measurements at low pressures in air, argon and helium,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 15, no. 6, Dec. 2008, pp. 1535 – 1543.

Appendix A: Recommended Guidelines for Partial-Discharge Measurements at Sub-Atmospheric Pressures

A.1 BACKGROUND AND SCOPE OF THE GUIDELINES

A.1.1 Background

Many aerospace flight vehicles, such as advanced aircraft and reusable launch-to-orbit systems, experience a wide range of operating pressures during their flight profiles. The reliable performance of the electric-power-system components and subassemblies of such vehicles under sub-atmospheric-pressure operating conditions is important to in-flight reliability and vehicle longevity. Therefore, characterization of the performance and behavior of the electrical insulation in such equipment during exposure to low-pressure environments is extremely important. Figure A-1 depicts the variation in atmospheric-pressure environment with altitude above sea level.

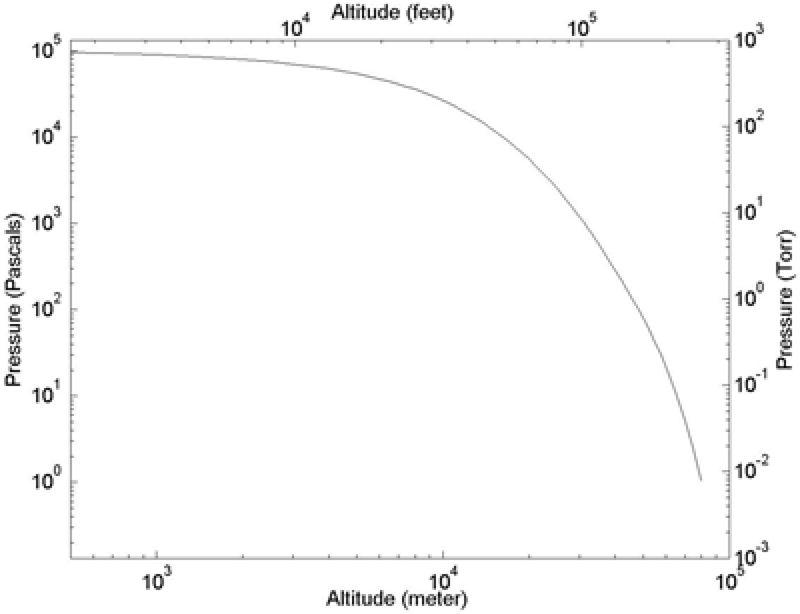


Figure A-1 Standard atmosphere pressure vs. altitude above sea level.

Partial discharges (PD) as well as corona and glow discharges are phenomena that can occur in the gaseous medium adjacent to solid insulation, prior to solid-insulation failure. These types of discharges can be the “silent killer,” that causes accelerated degradation of electrical insulation, leading to breakdown and effectively shortening the operating life of a system. PDs are generally considered to be localized, transient electrical gas discharges within a void or crack or in a pocket at an interface in an insulation structure. The gas at such locations breaks down long before the dielectric strength of the solid insulation is reached. PDs are undesirable since they typically lead to deterioration, degradation, and some permanent damage (e.g., erosion) of the section of the insulation in their proximity. (This is principally true for polymer-based insulation materials.) The principal factors that can influence PDs and other such discharges are 1) the pressure of the gaseous environment and gas composition, (2) the magnitude and frequency of the applied voltage, 3) the electrode arrangement and geometry, and 4) the properties, condition, and age of the insulation.

In general, discharge-degradation effects under atmospheric-pressure conditions in air are well known [A-2]. The degradation process caused by PD is both chemical and physical in nature. The actual failure mechanism may have electrical, mechanical, chemical, and thermal manifestations. The discharge process is erratic, and the sequence, phase, magnitude, rise time, and waveform of the PD pulses change during this process. PD measurements are standardized, for example, in IEC 60270 [A-3]. Specialized test systems have been developed to detect and characterize PD in electrical equipment at atmospheric pressures.

Although the behavior of electrical insulation in a low-pressure environment has been the subject of numerous studies, no adequate PD testing standards exist for low pressures. Some studies are related to airborne-equipment high-voltage specifications and tests [A-4]. Next-generation aerospace vehicles, however, will employ voltages much higher than the traditional 28-V-dc or 120/208-V, 400-Hz-ac power, e.g., 270-V-dc or 400-V, 20-kHz-ac voltages [A-5]. The combination of higher operating voltages and high-altitude flight profiles points to some serious concerns with respect to the on-board electrical-insulation systems. As a result, the existing specifications available for power-equipment manufacturers must be reviewed and revised for application in low-pressure environments. In addition, appropriate qualification test procedures are needed for the design of new equipment to ensure high operational reliability.

For low-pressure applications, it is anticipated that PD testing on power equipment would be an equally valuable tool for evaluation of insulation integrity as it currently is for terrestrial equipment. Numerous devices for measuring PD activity at atmospheric pressure are presently available on the market. However, these devices were not designed with the unique requirements of detecting low-pressure PD, as explained below.

It is well recognized that the physical phenomena that determine the collision-dominated nature of electrical discharges at low pressure influence the inception and temporal characteristics of the PD events. Hence, detection systems typically tuned to detect specific frequency ranges for terrestrial equipment can be ineffective for detecting PD events at low pressure.

Prior to the development of these Guidelines it has been shown that the frequency content of low-pressure PD is in a significantly lower range than that of atmospheric-pressure PD [A-6]. The experiments described by Kasten et al. [A-6] and several series of additional experiments [A-7, A-8] were performed to demonstrate these physical phenomena and to characterize PD and similar discharge events that may develop at sub-atmospheric pressures. Overall, the test equipment was designed to provide a controlled environment for demonstrating the variations in discharge temporal characteristics as a function of the conditions of the gaseous media.

Because of its widespread use in practice, the unit frequently used for pressure in the Guidelines is a non-SI unit--Torr. The sea-level normal atmosphere pressure is 760 Torr or 101.3 kPa.

A.1.2 Scope

These Guidelines are applicable to the measurement of PD of insulated conductors and their fittings and hardware at sub-atmospheric pressures, when tested with alternating voltages up to 400 Hz.

IEC 60270 identifies specifications for atmospheric-pressure condition; these Guidelines are for sub-atmospheric-pressure tests.

These Guidelines

- define the terms used
- define the quantities to be measured
- describe recommended test and measuring circuits
- define selected measuring methods required for common applications
- specify methods of calibration and requirements of instruments used for calibration
- give guidance on test procedures

These Guidelines have been developed during the course of experiments performed during the time period 2004-2007 [A-7, A-8], reflecting the following situations:

- pressures in the range 2 - 760 Torr
- electrode systems: needle-plane, single insulated conductor loop, twisted pair of insulated conductors, shielded multi-conductor cable
- 60-Hz-ac energization
- environments of air, argon and helium

A.2 NORMATIVE REFERENCES

Except where otherwise stated, the following standards are incorporated into these Guidelines:

- IEC 60270, High Voltage Test Techniques - Partial Discharge Measurements, International Standard, Third Edition, December 2000.

- IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition, IEEE, 1996.

- IEEE Std 4-2013, IEEE Standard Techniques for High Voltage Testing.

A.3 DEFINITIONS

All definitions of IEC 60270 [A-3] and IEEE Std 100 [A-9] are valid for these Guidelines. In addition, the following definition applies:

widest repeatedly occurring PD pulse: the time interval measured from a defined point on the rising edge to a defined point on the falling edge of commonly occurring wave-shapes of a test sequence. The defined points are typically 50% on the rising and falling edges but may be specified differently.

A.4 TEST CIRCUITS AND MEASURING SYSTEMS

A.4.1 Environmental Chamber

A.4.1.1 General Requirements

The equipment recommended for PD tests at sub-atmospheric pressures is described below.

The test item is to be located in a chamber that is suitable for providing the appropriate atmosphere. Chamber surfaces, electrical feedthroughs, electrical conductors, and supporting structures should be constructed of materials that exhibit low outgassing. All electrical connections to the item under test, including electrical vacuum feedthroughs, are to be corona-free at the test potentials and test pressures.

It is recommended that the chamber be constructed of glass and/or stainless steel (e.g., a commercial bell jar) and cleaned with a low-residue degreaser. Acrylic may also be used if cleaned with low-residue soap, rinsed thoroughly with distilled water, and dried. Acrylic may be wiped with a cloth dampened with isopropyl alcohol, but care should be taken to ensure that the alcohol does not wet the surface. Low-cross-section passages such as tight-fitting wire insulation should be avoided in order to minimize virtual leaks.

Because the test article, environmental chamber, interconnecting leads, and electrical feedthroughs will exhibit finite outgassing, it will be necessary to ensure that the gaseous environment remains within test specifications. It is recommended that a continuous flow of gas be maintained during testing. The flow rate should be sufficient to maintain the desired minimum purity level.

Flow Rate > Total outgassing rate ÷ (Allowable impurity level – Source impurity level)

For example, if the total outgassing rate from surfaces and crevices is 0.1 Pa-L-s^{-1} and the allowable impurity level is 0.0001 (= 100 ppm), the minimum flow rate of a gas having supply impurities of 10 ppm is 1.1 kPa-L-s^{-1}. Because most gas-flow monitors are valid only at atmospheric pressure (101 kPa), the metered flow rate will be > 0.011 standard-L/s (0.66 standard-L/min). Note that a standard-L is the quantity of gas that is contained in a 1-L volume at 101 kPa and 0°C.

A.4.1.2 Practical Example

Figure A-2 shows a vacuum chamber and gas-flow system that was used for research of PD characteristics at low pressures [A-6]. The acrylic chamber comprises a 4-in.-OD cylindrical tube and 6-in.-dia. flanges. The inside volume is defined by 3.5-in. ID of the tube and 10-in separation of the flange surfaces. After cleaning and pumping for ~10 hr with the gas source off, the outgassing rate of the 973-cm^2 inside surface is assumed to be $< 3 \times 10^{-7}$ Torr-L-sec^{-1} [A-10].

The sources of gases are K-size pressurized cylinders of 1) “zero” air (H_2O < 3 ppm, total hydrocarbon content < 1 ppm), 2) Grade-4.8 argon (< 20 ppm total impurity), and 3) Grade-5 helium (< 10 ppm total impurity). The bottle pressure is reduced in a two-stage pressure regulator to a line pressure of < 5 psig (34.6 kPa). The flow rate is indicated by a rotameter-style flow gauge that is located immediately upstream of a needle valve. Gas enters the chamber at one flange and exits at the opposite flange. The exit gas flows through course- and fine-adjust regulating valves to a molecular-drag pump that is backed by a diaphragm pump. A large-diameter bypass valve parallels the exit-regulating valves for pumping of the chamber system to a low pressure when the gas source is shut off. A shutoff valve is also included in the exit line in order to isolate the chamber from the surrounding atmosphere when the system is inactive.

In typical operation the chamber is evacuated for a period of 1 - 10 hr, with the source Shutoff Valve closed and the exit-line Shutoff and Bypass Valves open. In operation, the desired pressure and flow rate are set by proper adjustment of the Flow-Adjust valve in the high-pressure source line, and the Course-Adjust and Fine-Adjust Valves in the low-pressure exit line. Chamber pressure is monitored with a diaphragm-type pressure manometer.

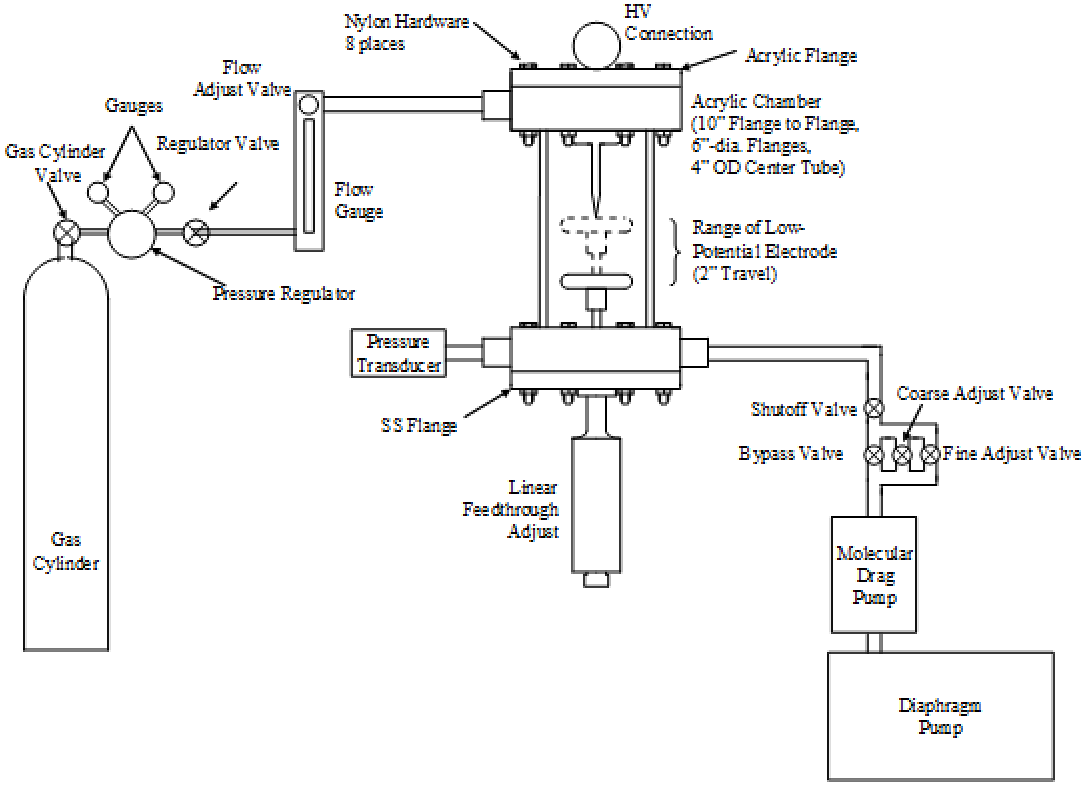


Figure A-2 Schematic diagram of example vacuum chamber and gas-flow system.

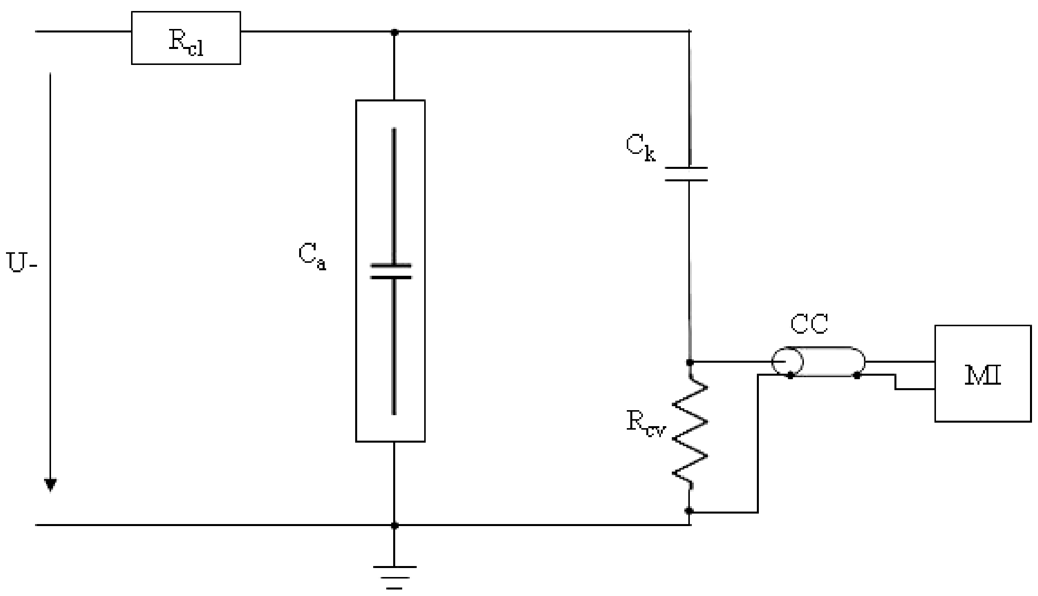
Typically, the high-potential electrical feedthrough is located in an acrylic flange that is secured to the chamber with non-conducting hardware (nylon bolts). The opposite flange, connected to electrical low potential, is made of stainless steel with a stainless-steel linear-motion feedthrough. A conductive screen is located in the pressure-monitoring line to prevent inadvertent electrical discharges from damaging the transducer.

A.4.2 Electrical System

A.4.2.1 General Requirements

General requirements of the test circuit and measuring systems are described in IEC 60270 [A-3], Clause 4, Subclauses 4.1 and 4.2. Test circuit principles for alternating voltages are illustrated by Figures 1a and 1b of IEC 60270. The basic PD test circuit recommended for low-pressure PD measurements, adapted from Figure 1a of IEC 60270 [A-3], is shown here in Figure A-3**.** The suggested coupling device is a low-inductance current-viewing resistor that is matched to the characteristic impedance of the connecting cable. Note that the current-viewing resistor is in series with the coupling capacitor; Figure 1b of the same IEC standard shows an alternative location of the coupling device--in series with the test object.

The voltage-adjustment resolution of the high-voltage source is recommended to be 1% of the anticipated PD inception voltage.



Components

U-	high-voltage source	C_k	coupling capacitor
R_{cl}	current-limiting resistor	R_{cv}	current-viewing resistor
C_a	test object	CC	connecting cable
MI	measuring instrument		

Figure A-3 Basic PD test circuit recommended for low-pressure measurements, adapted from Figure 1a of IEC 60270, Third Edition.

A filter (R_{cl} of Figure A-3, typically a large-value current-limiting resistor) protects the equipment from large surge currents in the event of a sparkover. The resistance should be sufficiently high to prevent damaging voltages and currents from reaching the coupling device and measuring instrument and sufficiently low to allow the desired voltage to appear on the test object (C_a). All high-voltage conductors and connectors must be corona-free or exhibit a sufficiently low level of background noise to allow measurement of PD in the test object.

A.4.2.2 Practical Example

A practical example of a PD test circuit is shown in Figure A-4**.** This circuit was used for most of the tests described in a final report [A-7]. Two cascaded 240-V variable transformers are connected to an isolation transformer. The 0 - 240-V-ac output is connected to the low-voltage terminals of a 7.6-kV high-voltage transformer. The resolution for the range of voltages in the example circuit is 0.5 - 1.0%.

The high-voltage applied to the test object is measured using a commercial 1000:1 resistive voltage divider and a digital multimeter. The PD-inception values are then obtained in units of volts rms. An additional resistive voltage divider is used for monitoring the supply

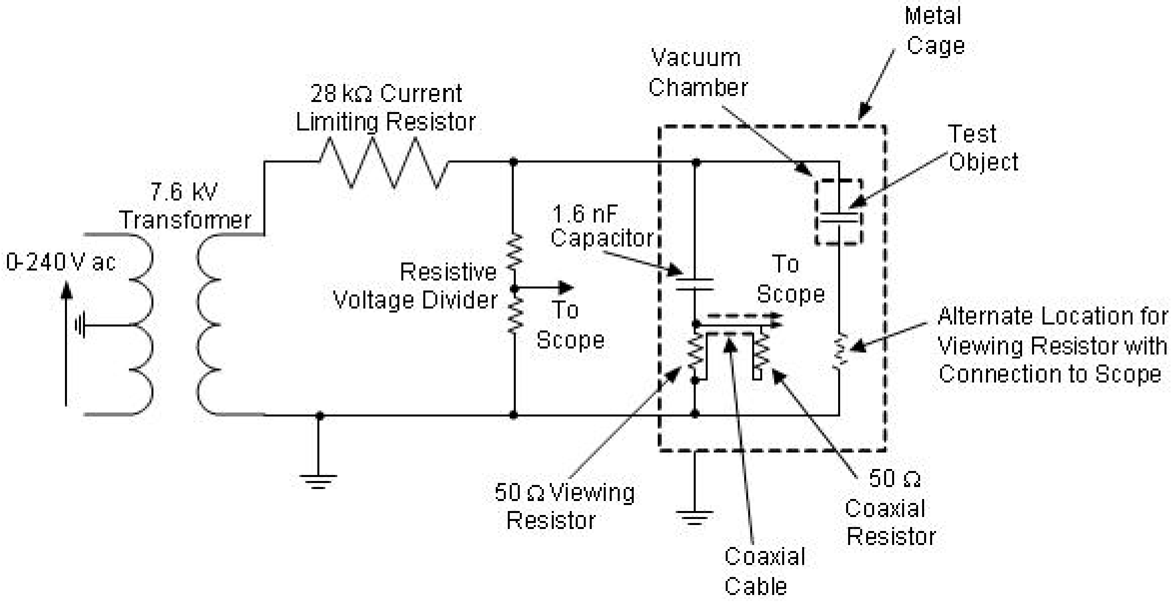


Figure A-4 Electrical schematic of example practical PD-test circuit.

waveform. This waveform is recorded in synchronization with the waveform of the current-viewing resistor by an oscilloscope or similar recording instrument. This allows determination of the temporal position of the PD-current pulse on an ac supply waveform.

Typically, a 50-Ω current-viewing resistor--connected between the coupling capacitor and ground--provides the current-to-voltage conversion of PD-initiated current pulses. For some tests an alternate location of the 50-Ω current viewing resistor--in series with the test object--was used. For safety reasons the current-viewing resistor in series with the coupling capacitor (see Figs. A-3 and A-4) is recommended.
The layout of the circuit of Figure A-4 is shown in detail in Figure A-5. Specific features of the connections are as follows:

- to ensure corona-free performance, 12.7-mm-dia. copper tubing is used for electrical connections within the main circuit
- the horizontal and vertical size of the coupling-capacitor circuit loop is small, to reduce the inductance of the circuit
- the coupling capacitor is a 1.6-nF ceramic capacitor
- the coupling capacitor, viewing resistor, and vacuum chamber are inside a metal safety cage
- the current limiter is a 28-kohm wire-wound resistor
- the corona-free resistive voltage dividers are at the downstream side of the current-limiting resistor
- typically, the current-viewing resistor is a 50-Ω non-inductive film resistor, although a 50-Ω coaxial load is sometimes used

- to better define the return conductor of the main circuit, the return path and the safety connections are separated
- the return conductor is grounded at a single point--called the electrical ground (Point G of Figure A-5)--connected to the main ground bar of the laboratory
- all other components to be grounded (metal safety cage, pumps, metal hose clamps of gas connections, bases of supporting insulators, etc.) are interconnected at one point--called the safety ground (Point H of Figure A-5)--and connected to the same main ground bar of the laboratory used above through a separate lead
- the high-potential leads of the voltage dividers are connected between the high-voltage conductor and Point G.

Measurement of the impedance-vs-frequency characteristic, Z(f), of the relevant components of the electric system such as the voltage dividers, coupling capacitor, and instrumentation cables is recommended. For these components, the wider the frequency range of the Z(f) characteristic with constant magnitude and constant phase angle, the more suitable the component for PD measurements.

The component with the most critical impedance-vs.-frequency characteristic is the 50-Ω current-viewing resistor. The use of a commercial non-inductive film resistor is recommended. That resistor used in the example described here displays a flat (constant) magnitude and zero phase angle-vs.-frequency characteristic up to ~ 95 MHz.

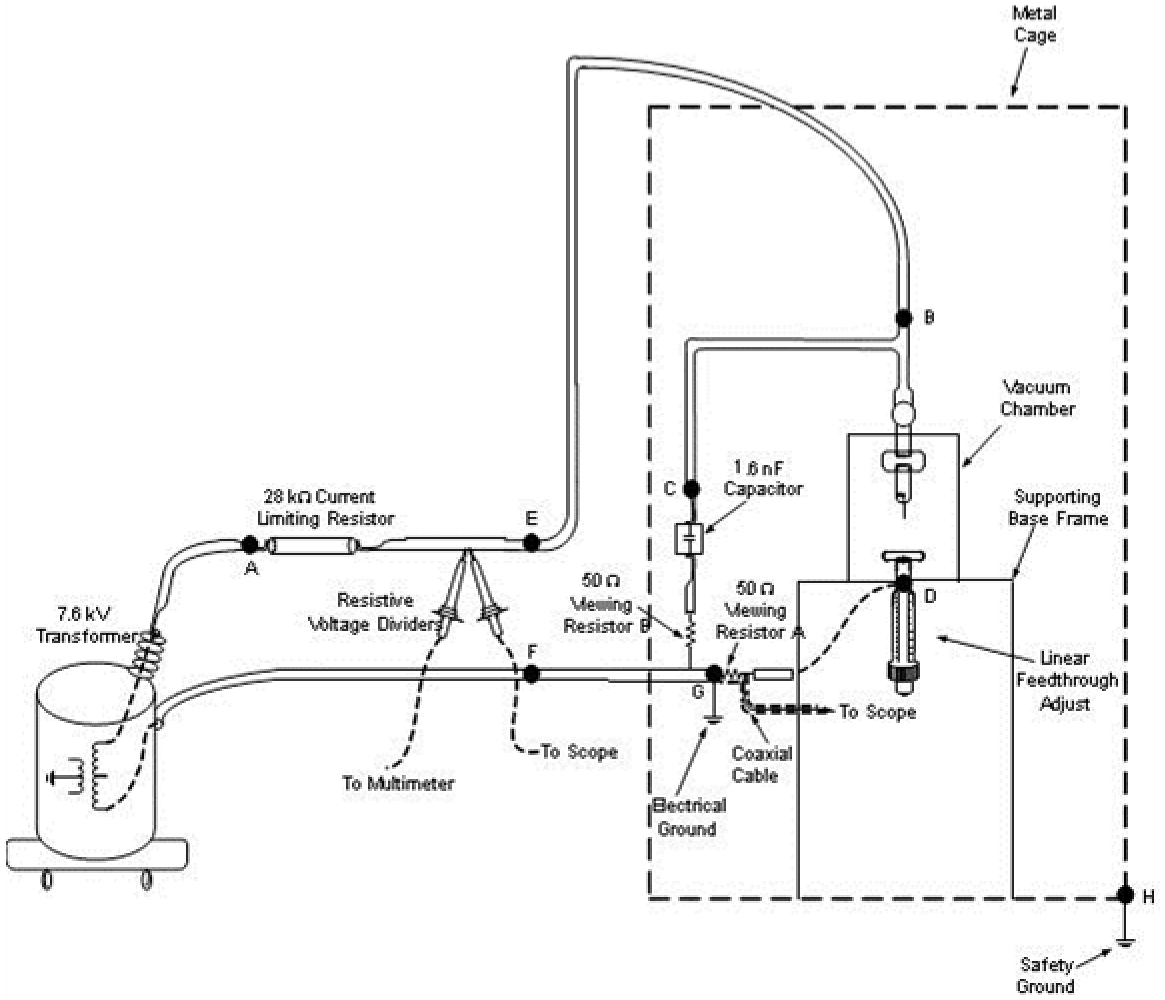


Figure A-5 Electrical schematic of PD-test circuit.

A.4.3 PD-Monitoring and Data-Acquisition System

A.4.3.1 General Requirements

The general requirements of the test circuit and measuring systems are described in IEC 60270 [A-3], Clause 4. The amplitude frequency spectrum of PD pulses occurring in a low-pressure environment differs from that of atmospheric-pressure pulses. The low-pressure pulse waveforms may contain significantly slower rising and falling edges and longer pulse widths than those at higher pressures.

The length of the **widest repeatedly occurring PD pulse** must be quantified to determine the validity of apparent-charge [A-3] measurements. The traditional response of an instrument is an output voltage pulse with a peak value that is proportional to the (unipolar) charge of the input pulse. This response is not valid if the frequency relationships differ from those depicted in Figure A-5 of IEC 60270. That is, the amplitude frequency spectrum of the PD pulse must be flat within the band pass of the instrument, and the lower and upper limit frequencies of the instrument must be significantly lower than the upper limit of the PD pulse and the calibrator.

If an active integrator is employed for charge measurements, the high-frequency cutoff of the instrument need not be lower than the high-frequency cutoff of the amplitude frequency spectrum of the PD pulse. However, the time constant of the integrator must be significantly greater than the pulse width of the **widest repeatedly occurring PD pulse**. In the case of a digital instrument, the period of integration must extend over an interval that is sufficient to encompass 95% of the charge within the input pulse.

Regardless of the method of integration, the low-frequency cutoff of the instrument must be sufficiently low that the pulse droop it causes does not significantly affect the charge determination. This should be verified with a variable-rise-time calibrator as described in Clauses 5 and 6 of this document. The low-frequency cutoff of the instrument, however, must also be sufficiently high that the test frequencies and their harmonics are prevented from affecting the results.

A.5 CALIBRATION OF MEASURING SYSTEM IN COMPLETE TEST CIRCUIT

A.5.1 General

The procedures specified in Clause 5 of IEC 60270 are to be followed. Because of the increased width of PD pulses at low pressures, calibration is to be performed in the relevant range of expected pulse widths as well as the specified pulse magnitudes described in the IEC standard.

A.5.2 Calibration Procedure

IEC 60270 specifies that the relevant range of calibration is understood to be 50% - 200% of the specified PD magnitude, but the calibration-pulse rise time is typically short--on the order of 60 ns. In the case of low-pressure PD, the **widest repeatedly occurring PD pulse** is to be determined, and instrument response is to be verified at multiple rise times of the calibration pulse. The necessary rise times may vary according to the test object and gas environment but should range from the traditional 60 ns to a period encompassing a minimum of 95% of the quantity to be measured. For example, if 95% of the charge is contained in a pulse of 5 μs, the (approximately linear) rise time of the calibration pulse should be 5 μs. It is recommended that a minimum of three calibration points be used to verify a constant response of the instrument over the relevant range of rise times and specified PD magnitudes**.**

A.6 CALIBRATORS

Clause 6.1 of IEC 60270 states that the calibrator "… shall have a rise time t_r (10% to 90%) of less than 60 ns." For calibration of instruments to be used for low-pressure PD measurements, additional rise times are needed. It is necessary that a constant response to all probable pulse widths be verified. The calibrator should provide a known charge at a rate corresponding to the expected pulse widths. The maximum rise time of a calibration step should extend to the approximate width of the **widest repeatedly occurring PD pulse**. The rising edge of the calibrator output should be linear within 10%.

The calibrator should follow all other features and specifications of Clause 6 of IEC 60270.

According to Clause 4.3.5 of IEC 60270, the integrator time constant must be much larger than the rise time of the PD pulse thus, relatively speaking, the pulse approximates a step input. A typical value for the integrator is 1 μsec, which is appropriate for air at atmospheric conditions with PD rise times and pulse widths in the order of nanoseconds. However, for low pressure, rise times can be in the order of a few microseconds and pulse widths in the order of tens of microseconds; thus, an integrator time constant in the order of hundreds of microseconds may be required.

A.7 MAINTAINING CHARACTERISTICS OF CALIBRATORS AND MEASURING SYSTEMS

The requirements and procedures of Clause 7 of IEC 60270 with regard to calibrators for use with low-pressure PD systems are to be followed.

A.8 TESTS

Test procedures to be followed for PD measurements at atmospheric pressure should be followed for measurements at reduced pressures. In addition, environmental conditioning should be performed to ensure that the test object has reached equilibrium with the appropriate gas constituents at the designated test pressure. The process will be test specific, recognizing that gas entry into, and migration within, a test object will depend upon numerous physical factors such as materials, availability of internal and external gas passageways, and gas conductivity within the test article.

A.9 REFERENCES

A-1. U.S. Standard Atmosphere, (U.S. Government Printing Office, Washington, DC, 1976), National Ocean and Atmospheric Administration, as listed in D. R. Lide, Ed., CRC Handbook of Chemistry and Physics, 74th Edition, CRC Press, Boca Raton, FL, 1993.

A-2. R. Bartnikas, "Partial Discharges, Their Mechanism, Detection and Measurement," IEEE Trans. DEI, **9**, 2002, pp. 763-808.

A-3. High-Voltage Test Technique - Partial Discharge Measurements, IEC 60270, 3rd Edition, International Electrotechnical Commission, Geneva, Switzerland, 2002.

A-4. W. G. Dunbar, “High Voltage Specifications and Tests (Airborne Equipment)”, AFAPL-TR-79-2024, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, OH, 1979.

A-5. H. Kirkici, "Electrical Insulation in Space Environment," in Proc. 2001 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Kitchener, Ontario, Canada, 2001, pp. 16-19.

A-6. D. G. Kasten, X. Liu, S. A. Sebo, D. F. Grosjean and D. L. Schweickart, “Partial Discharge Measurements in Air and Argon at Low Pressures With and Without a Dielectric Barrier,” IEEE Trans. DEI, vol. 12, 2005, pp. 362-373.

A-7. D. F. Grosjean, K. A. Rose, D. G. Kasten, S. A. Sebo, and X. Liu, “Health Monitoring for the Integrity of Electrical Power Wiring and Power System Components: Low-Pressure Partial-Discharge Measurements,” Final Report, SBIR Program, U.S. Air Force Contract No. FA8650-04-C-2485, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, August 2007.

A-8. D. Grosjean, D. Schweickart, D. Kasten, S. Sebo and X. Liu, “Development of Procedures for Partial Discharge Measurements at Low Pressures in Air, Argon and Helium,” IEEE Trans. DEI, vol. 15, 2008, pp. 1535-1543.

A-9. IEEE Standard Dictionary of Electrical and Electronics Terms, 6th Edition, IEEE Std 100-1996, Institute of Electrical and Electronic Engineers, Inc., New York, 1996.

A-10. G. Thieme, ‘‘Mass Spectrometer Investigation of Gas Emission from Plastics,’’ Vacuum, vol. 13, 1963, pp. 137-143.