TESTING METHODS FOR DETECTION OF INSULATION DAMAGE IN AEROSPACE WIRING HARNESS

Josef Hanson

WEE Electrotest Engineering GmbH, Hafenstrasse 1, D-97877 Wertheim, Germany
Tel.: +49 9342 875-0, Fax.: +49 9342 875-75, e-mail: jhanson@wee.de

ABSTRACT

Electrical wires are widely used for power management and distribution systems in aerospace and spacecraft applications (fly-by-wire) [CAR-98]. The insulation materials are of lightweight, low volume and provide resistance against high service temperatures up to non-flammability and excellent dielectric properties. By the high number of implemented cables and wires buried deep in the frame structure the insulation itself involves certain dangers due to the fact that insulation degradation is gradual (aging), but failures are sudden and very difficult to detect. However, if the wires are mechanically damaged, electrical arcing may occur causing the insulation to become conductive. Resistive heating leads to further damage of adjacent cables and the surrounding area.

In order to avoid those incidents and to achieve a high reliability of the wire harness, during the design process safety analyses are already considered which aim at checking and eliminating failures in manufacturing and during assembly. However, an analysis of error events from space and air technology shows that some failures can be attributed to the loss of wire harness during operation. This might be due to a lack of care during installation, e.g. surface damaging of insulation without complete penetration. Further stress factors such as cold weather, moisture condensation and vibration or other complex climatic and mechanical stresses may cause the loss of insulation capability with serious consequences. Although the operability and reliability of the electrical network is of highest priority, presently during maintenance intervals the electrical system is not subjected to checks, which were able to identify such weak points.

A maintenance check for the electrical system should be a non-destructive test similar to mechanical tests on modules during maintenance. A wiring harness with numerous insulated conductors, which might touch themselves within some areas irregularly have complex geometry, which does not allow the simple application of known tests, such as the classical Partial Discharge measurement in order to identify insulation damages.

This paper describes test philosophies and results of performed laboratory tests, which contributes to a possible "diagnostic tool" that can assess the state of the wiring insulation. A discussion of the described testing methods and the experimental results show, whether the testing methods are suitable for an automated test sequence as part of a maintenance strategy at the airplane.

1 INTRODUCTION

The insulated wire ages in service from a number of factors, caused by mishandling and environmental effects. The latter includes high ambient temperatures up to 70 °C, different pressures (flight altitude), normal and shock vibration, moisture, hydraulic fluid, "blue water" (restrooms) and fungus. Due to vibration over time aluminum shavings (residuals from the manufacturing process) or sharpen edges close to the wire routing may penetrate the brittle insulation and could cause arcing between individual wires or between the wire harness and the aircraft structure. Initial arcing usually is of very short duration, but causes very hot localized temperatures in the range of some 1000 °C. It effects a gradual insulation degradation [CAH-89] that leads to conductive paths originated from the thermal destruction of the organic insulation. If the circuit is not interrupted this may lead to high-voltage / high-current arcs with serious consequences, such as the creation of electrical fire [FUR-01].

Intermittent arcing, even in the range of five times rated current, would not trip a conventional bimetallic thermal circuit breaker if the arc duration is within the milli-second-range. Efforts are being made to develop arc fault circuit interrupters (AFCI´s), which are focused on arc fault currents greater than the rating of the circuit breaker. For example a solution from EATON looks at how current peaks vary from cycle to cycle. If they are consistent, they are described as a "load characteristic" current, if an erratic current waveform is identified over pre-defined time duration, a burning arc is assumed and the standard circuit breaker is tripped [DOR-01]. However, this concept works in case of a fault arc is initiated and therefore this measurement could be described as a **passive** protection against accidental fault arcs.

To prevent fault arcs, a methodology for the assessment of the status of the wiring harness could be an important tool due to an **active** protection. At the moment an installed wiring system is evaluated only by a visual inspection, but this method presents difficulties in detecting hidden breaks behind and in the middle of the wire bundles, as well as microscopic tears hidden under clamps and ties. Based on the analysis of the wire installations of certain aircraft [REP-00] among others, the Aging Transport Systems Rulemaking Advisory Committee (ATSRAC) recommends an increased research on better non-destructive test techniques for wiring.

The following sections give some technical approaches, how weak insulation points can be detected in the context of a non-destructive test philosophy.

2 PRINCIPLE INVESTIGATION METHODS

Since a fleet inspection has shown that aircraft wire shows breaches in the insulation even when the wiring is relatively new, a lot of activities have arisen to avoid serious malfunctions of the electrical system. The common aim is to enable a replacement of wires in key locations before problems occur. In principle these activities can mostly be divided into statistical and physical based measurements.

2.1 Statistical based Examination

One philosophy is to shift the maintenance of aging electrical systems from a reacting to a predictive approach, whereby partial rewiring of aircraft can be scheduled in advance. With the help of a well-considered database this technology enables the determination of the "life remaining" of wire insulation with statistical calculation methods (Lectromec Design Co, VA, US).

The procedure involves the following steps [AVI-01]:

- Dividing an airplane into "typical zones". These zones highlight where the most and the least wiring problems occur. The trouble zones include:
  - Electronic and Equipment (E&E) bays.
  - Wheel wells (where wiring is subjected to flexing, temperature and moisture extremes).
  - The "cess pool," an area where the wings join the fuselage known to accumulate dirt and moisture.
  - The "swamp" at the bottom of the fuselage.
  - Leading and trailing edges of the wings.
  - Lavatories, Galleys, etc.

- Extracting wire specimens. Each wire sample is about 1.5 ft (0.5 m) in length; about six specimens will be removed from each zone. Replacement wire will be spliced in.
- Extracting the wire samples.
- Proof testing. The insulation of the wire samples is checked with a wet insulation test, a test procedure, which is similar to a Voltage Withstand Test according to ASTM D 3032 [AST-98]. When the point of breach hits the air, the change in current flow indicates clearly an insulation breach.
- Accelerated testing. Wire samples that survive proof testing (i.e., no insulation breaches) are subjected to accelerated testing, involving exposure to high humidity, temperature and strain. This testing continues for a period of a few days to a few weeks, until the insulation is breached. Every ten hours, the wire samples are subjected to a test voltage of 2.5 kV to assess if a breach in the insulation has occurred.
- Determination of life remaining.

The test data generated by accelerated testing are used to describe the "aged insulation characteristic" of the airplane's wire by zone. This type of information can be used to target wire replacement efforts to those areas where the insulation has been shown to be highly aged.

2.2 Physical based Examination

A further possibility of making a status evaluation of the wire insulation is a direct measurement of the insulation characteristics at the installed wire bundle. In the following, three different non-destructive testing methods are introduced, which enable an evaluation of the wire system. In Chapter 3 for the last two specified procedures some orienting investigations are presented.

2.2.1 High Insulation Resistance Measurement

Normally the electrical wiring and the connectors have excellent characteristics when they are new. However, during in-service conditions the aircraft environment ages the wires itself and their installations, which leads to a degradation of their functionality. Once this degradation process has started the wiring ages slowly, but continuously and becomes more susceptible to the harshness of the environment. Also a voltage strength test by its own [DIN-96] does not provide any information to the state of the wire insulation due to aging, a sensitive High Insulation Resistance Measurement is necessary.

In order to determine the damages in the wire insulation, caused by aging, at many laboratories several efforts were already executed. One method is to determine the remaining insulating capability of an "artificially aged" cable bundle. A statement of the pre-damaged wire insulation can be obtained with the help of a leakage current measurement. For this the insulation is pre-damaged in several phases, which are different in the kind of stress. After each phase a measurement of the insulation resistance is performed. A more comprehensive description of the procedure and a detailed evaluation is given in [GOU-01]. Figure 1 shows different insulation resistance values of certain wire segments, measured at the end of the damage phases 2 and 5. It is shown, that for an individual assessment of the remaining insulation capability an insulation measurement in the GΩ-range is necessary.

While very precise single measuring devices can measure high resistance values exactly, restrictions are given for commercially available measuring systems. For applications described here a measuring system consists of a measuring device and a test point matrix. With a test point matrix, several lines of a bundle, also several bundles, can be connected and the wire insulation can be checked in an automated operational sequence.

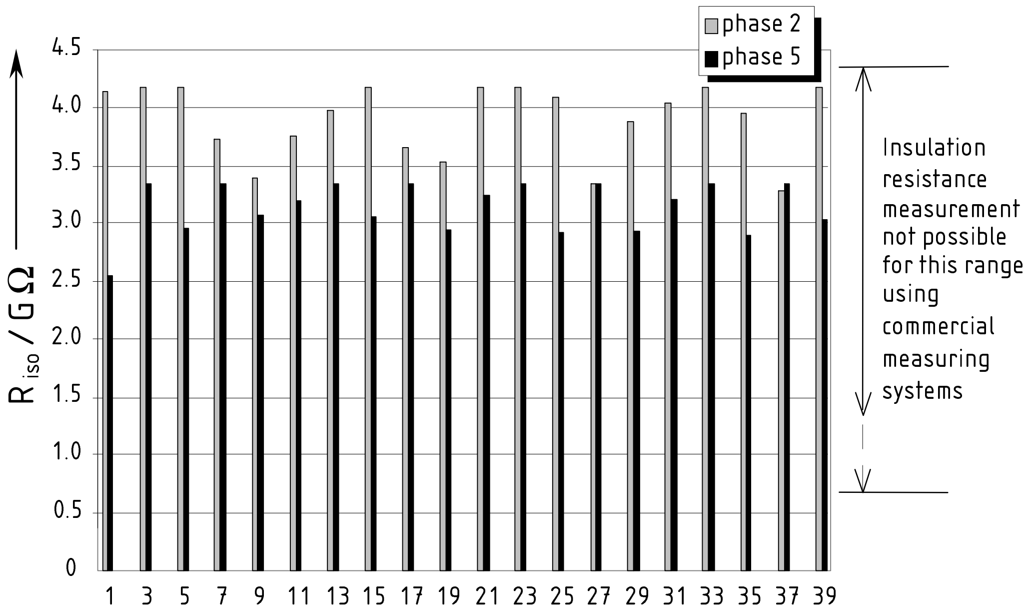

Figure 1: Damaged harness testing on wire segments (1 – 39). Measurements indicate a definite increase in leakage in the damaged wire; testing voltage: 500 V DC [GOU-01].

For testing the wire insulation of assembled bundles after installation in an aircraft resistance values of maximum 50 MΩ (10^6 Ω) are required [DIN-96]. This is why, current available measuring systems have internal impedances not higher than a few GΩ. However, if a measuring system should be used to check changes in the wire insulation in a precise way to have the possibility to conclude aging processes (10 GΩ to 100 GΩ), increased demands to the test point matrix are required because of its influence on the internal impedance.

Design studies for an appropriate testing setup have shown, that a special hardware design would enable a measurement of leakage currents down to 2 nA (10^{-9} A). Such equipment would enable the measurement of insulation resistances in the upper GΩ-range (up to 100 GΩ). However, this permits the determination and the classification of changed insulation characteristics in the wire insulation due to starting aging processes. A sensitive High Insulation Resistance Measurement would be an objective method to check the insulation characteristics and to indicate the so-called "early degradation phase" of the wire insulation. Such a maintenance procedure, e.g. performed on wires in key positions during service checks, would be able to "highlight" the early beginning aging processes in the wire insulation.

The measuring based determination of "aged" insulation areas within a wiring harness enables the selective replacement of defective areas, and can be part of an **active protection** concept during maintenance of the electrical system (infrequent examination).

2.2.2 Time Domain Reflectometry

The Time Domain Reflectometry (TDR) can be used when a wiring problem is already suspected. The reflectometer sends a short signal along the wire. Changes in the impedance cause a reflection, which can be measured to locate the distance of the fault location. In case of an open circuit a full-strength in-phase reflection takes place, while a short circuit causes a full-strength out-of phase reflection. This is true for a loss-free arrangement. Any flaws covered by this extreme failure scenarios result in less reflection and intermediate phase shift. Though the reflection plot of a healthy wire system shows a complex shape, the indication of changed wire characteristics seems possible if a stored "base-line-plot" from the healthy system is compared with the actual measurement from an aircraft where problems in the wiring system are assumed. The distance of the fault location can be calculated when the differences between both plots are extracted .

In Chapter 3 some experimental investigations at a partially reproduced wiring system are presented. Aim of the investigations is to get principal information about the applicability of the reflection measurement, when different failure configurations are present, e.g. low resistance shorts caused by electrical faults.

2.2.3 Gas Discharge Phenomena

Traditionally, for the detection of damaged insulation in a wiring harness, comparatively high testing voltages are necessary [DIN-96]. These testing voltages have a short application time in order to avoid pre-discharges within non-critical areas. To initiate a flashover at the weak insulation point, however, a sufficiently high amplitude is necessary, which may lead to the destruction of voltage-sensitive components. Therefore only certain error configurations with a limited distance d_1 between the damaged wire and the appropriate counter-electrode can be detected (Figure 2a). However, at unfavorable error configurations as shown in Figure 2b) this concept fails.

The necessary breakdown voltage U_d depends on the product of the electrode gap d and the ambient pressure p of the prevailing gas atmosphere (Paschen´s Law). In air and during atmospheric pressure this relation is limited to $U_d \sim d$. Because of maximum allowable amplitudes for the testing voltage, and therefore for U_d, at present no reliable test procedure is applied to detect such weak points within the insulation.

If the gaseous dielectric air is replaced partly or completely within the area of the wiring harness, e.g. by an inert gas (helium, argon...), this favors an increased current flow even at comparatively low testing voltages, whereby a reduction of the breakdown voltage U_d is achieved. This principle can be used as a "low-energy" detection of insulation damages. For example, the increased current flow or a trop of the testing voltage in the area of their maximum can be evaluated.

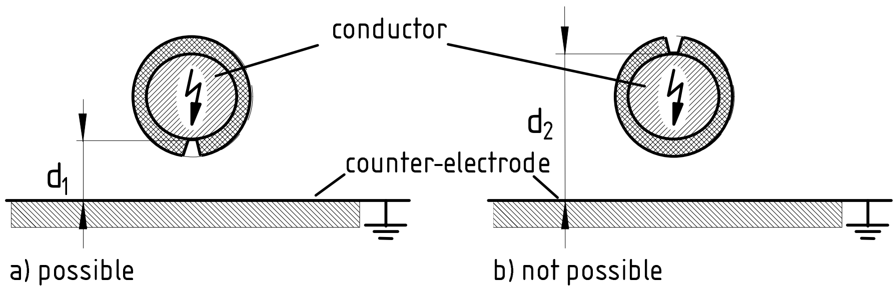

Figure 2: Possible error configurations, represented as measurable (a) and non-measurable (b) error events, when using [DIN-96].

A non-ignitable test gas with a reduced breakdown voltage also allows the emulation of a "critical atmosphere", which arises, e.g., during normal service conditions in a closed fuel tank, when the reduction of the fuel level produces areas of explosive air/fuel mixtures.

With the help of proper measuring tools, e.g. a "clip-on measuring device", a section check of the installed wire bundle can be made, so that at least the visual check executed at present could be completed meaningfully by an objective measuring procedure.

3 EXPERIMENTAL RESULTS AND DISCUSSION

In Chapter 2 some procedures are introduced to indicate weak insulation with the aim to get an objective instrumentation to measure aged wiring problems. In the following some experimental test results are presented for reflection measurement and for a measurement under a test gas atmosphere.

3.1 Time Domain Reflection Measurements

For the investigation of the reflection characteristics a simplified experimental test setup is used. The pulse generator (Agilent 33250A, 80 MHz) is connected over a tee-coupling to the oscilloscope and to the test specimen. The test impulse û is fed as a square-wave pulse with t_p = 8 ns (rise time t_r = 5 ns, amplitude û = 5 V). The period duration amounts to 9 µs. The test specimen consists of a 36 ft (11 m) twin cord, 2·0.75 mm^2 (surge impedance $Z_W \approx 210\ \Omega$). The setup realizes a simplified two-conductor arrangement with defined geometrical dimensions over the entire length (Figure 3). A low resistance short Z_F (0.5 ... 250 Ω) is connected halfway.

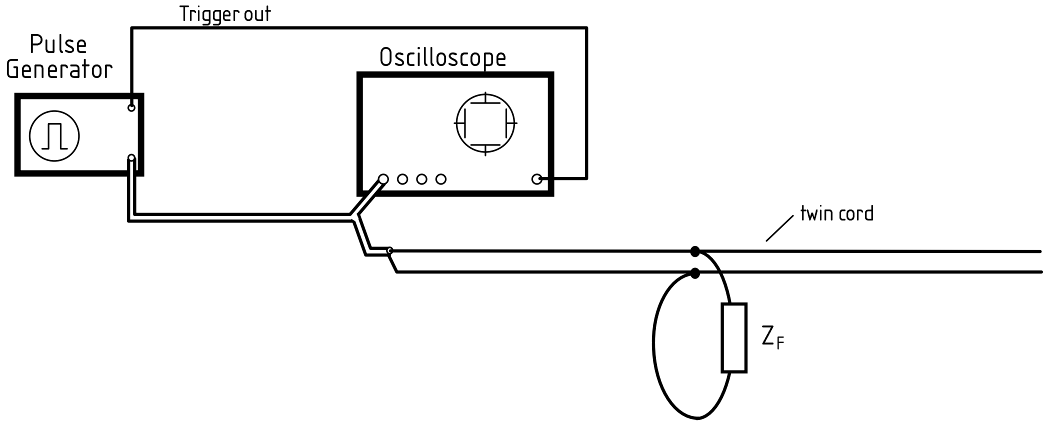

Figure 3: Principle test setup for the measurement of the reflection characteristics of a low resistance short Z_F.

With the test setup it is checked, how the reflected amplitude changes as a function of the low resistance short. The test specimen operates as an open wire at the end. Figure 4 shows the experimental results:

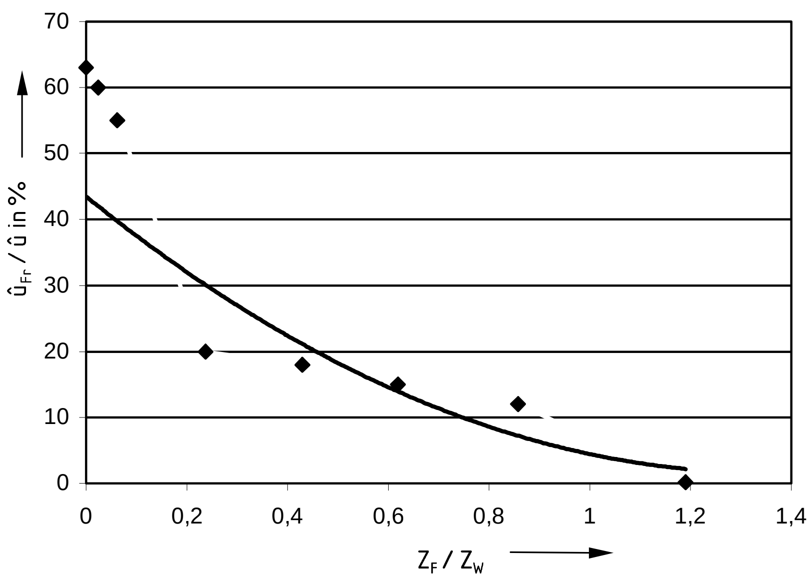

Figure 4: Reflected voltage signal u_{Fr} vs. fault resistance Z_F;
$\hat{u}_{Fr} / \hat{u} = f(Z_F, Z_W)$; $Z_W \approx 210\ \Omega$.

It is shown that a clear reflection is achieved only in the case of a low resistance short. The more the fault resistance moves close to the value of the surge impedance Z_W, the more an exact error analysis is difficult. Nevertheless, low resistance shorts are within the area of a few Ω and represent high danger potential, since they can result from electrical short-circuits. Due to a fault arc the electrical conductor is short circuited by decomposition products of the insulation [HAN-00]. By this, the load current can commutate on this parallel current path. If the fault current flows on, a continuous "glowing" on the fault location occurs. Thereby, the thermal power ($Z_F I^2$), leads to a continued glowing. Furthermore, the fault current remains limited by Z_F at the fault location. Therefore, a detection by conventional circuit breakers is hardly possible [STA-94].

3.2 Gas Discharge Measurements

The test set up used, allows different arrangements between a wire / wire and a wire / metal sheet configuration, as shown in Figure 5. The tested wire consists of a hybrid insulation of PTFE/PI/PTFE (AWG 20), a typical aircraft wire, with a length of 4 in (0.1 m). The performed test parameters are:

Table 1: Test Parameters for gas discharge measurements on an AWG 20 wire.

Atmosphere	Pressure / bar	Distance *d* / mm	Configuration
Helium (He) Nitrogen (N_2)	0.2 .. 1	0,5; 1; 3; 5	wire / wire wire / sheet

The pre-damage is made by removing the insulation material over the half circumference of the wire for a length of 0.5 mm. The distance *d* between the pre-damaged wire and the counter electrode (wire or metal sheet) varies from 0.5 ... 5 mm. The used high-voltage generator is a bipolar operation amplifier. The generator is capable of a maximum voltage of 4 kV DC / 3 kV AC. The output current is limited to a maximum of 20 mA. This limit takes effect if the object under test gets to a low resistance. If a flash over occurs the installed arc detector enables an immediate set of the output voltage to zero.

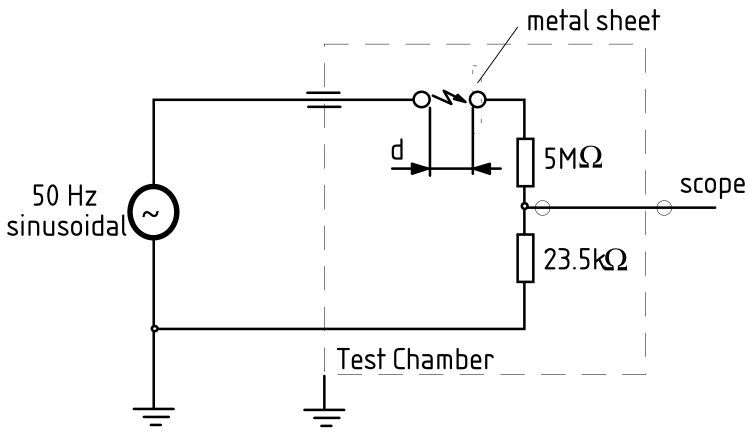

Figure 5: Principle setup for the measurement of gas discharge effects on different damage faults.

For quasi-homogeneous arrangements and constant temperature the breakdown voltage U_d is directly proportional to the product of pressure p and electrode gap d. The function $U_d = f(pd)$ has for all gases a typical shape with a pronounced minimum, e.g., for air this is in the range of $p \cdot d = 7.3 \cdot 10^{-3}$ bar·mm, where the breakdown voltage is roughly $U_{dmin} = 350$ V [BEY-86]. For the analysis of the test results the same illustration was selected. The partial irregular shape may be explained on the one hand with the inhomogenous experimental assembly. On the other hand it is possible, that pollution of the gap between the electrodes, e.g., proportions of decomposed insulation, may influence the height of the breakdown voltage.

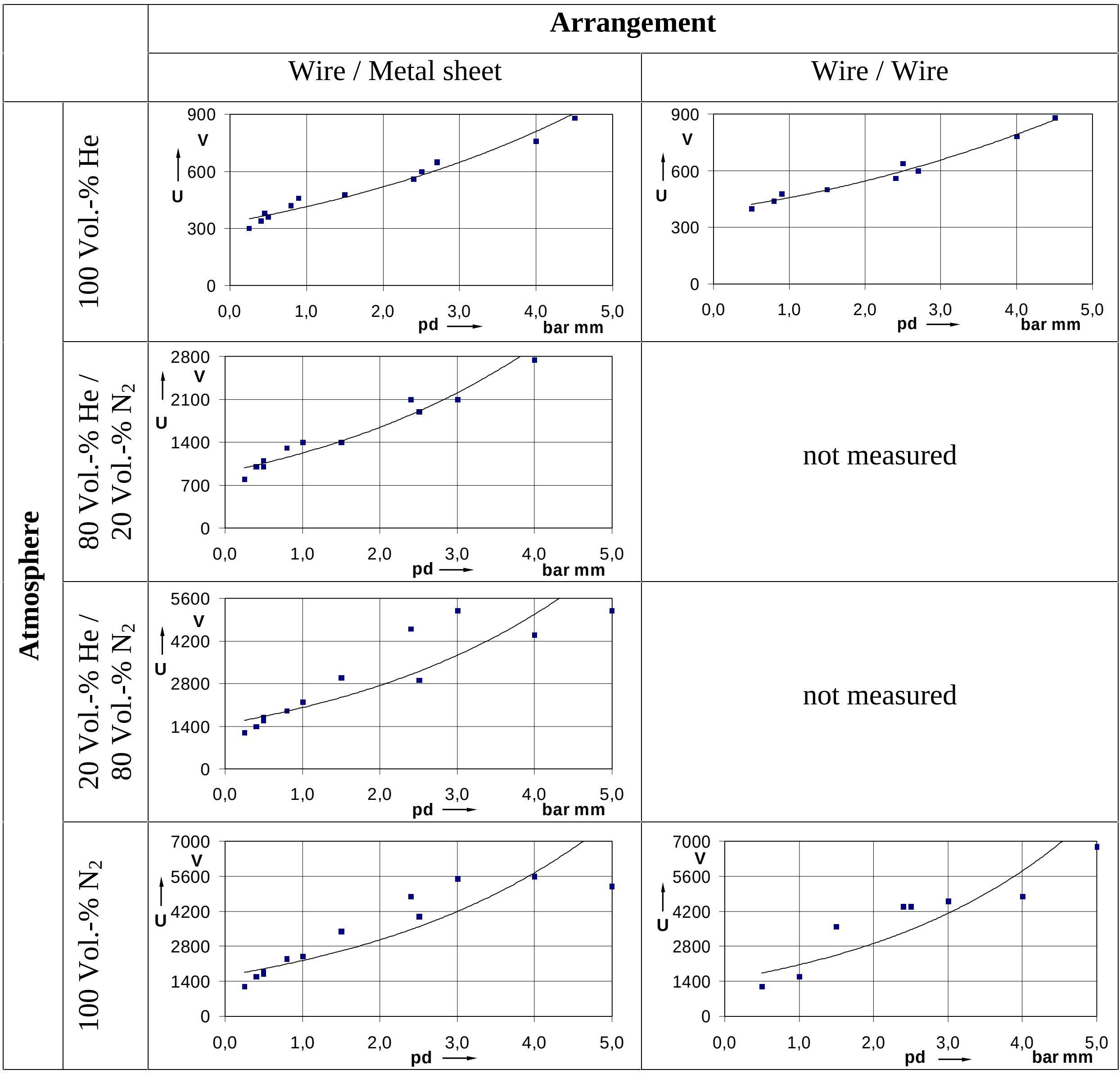

Figure 4: Breakdown Voltage vs. product of pressure *p* and electrode gap *d* (Paschen´s law) of the examined arrangements for different gases.

It is shown that the amplitude for the breakdown voltage depends on the kind of gas mixture. At p·d = 1.5 bar·mm an electrical breakdown can be initiated already at voltages smaller than 500 V. Thereby, the testing voltage necessary for a fault detection is explicit smaller compared to investigations without an additional gas atmosphere. Together with low-energy discharge guaranteed by the voltage generator a non-destructive fault detection is possible.

CONCLUSION

Despite high attention during wire installation and in-service maintenance, wire bundles can damaged. Thus, a residual risk of possible fault arcs can not be excluded. In order to find weak insulation points within the insulation, this paper discusses three different testing methods. With the High Insulation Resistance Measurement aging effects on the insulation can be measured. The additional knowledge of so-called "typical zones" of an airplane may lead to a very efficient testing method.

Damages caused by electrical shorts can always be divided in three categories: Metallic short-circuit, open circuit (high impedance) and low resistant short. Such faults, indicated by a proper circuit breaker device, can be determined with a TDR measurement. The analysis of the reflected signal enables both, a specification of the failure itself and a fault location, which enables an elimination of the damage.

Critical insulation errors, which are not detectable by a conventional voltage strength test can be determined by the application of a non-ignitable test gas. Together with a low-energy voltage generator a non-destructive insulation check is possible.

All evaluated testing methods seem applicable within an automated test run. With special measuring systems (combination of a measuring device and a test point matrix) several wires can be tested during one test sequence. However, in each individual case special concern should be put on the design of the test point matrix. This enables the performance of economic test sequences, which can be executed, e.g., during maintenance checks at the electrical system of the airplane. A well-performed testing can guarantee a high safety level in the future.

4 REFERENCES

[AST-98] ASTM D 3032-97: *Standard Test Methods for Hookup Wire Insulation.* American Society for Testing and Materials, March 1998

[AVI-01] Aviation Today – Special Reports: *Swissair Flight 111 Tragedy, Wiring and Other Related Stories*. (www.aviationtoday.com/reports/wiring1.html)

[BEY-86] M. Beyer, W. Boeck, K. Möller, W. Zaengl: *High Voltage Technology*. 1. Edition, Berlin, Tokyo, New York: Publisher: Springer 1986 (in german)

[CAH-89] P. Cahill, L. H. Dailey: *Wet-Wire Arc Tracking of Aircraft Wire Insulations.* Electrical Manufacturing, Vol. 3 No. 3, Mai 1989, S. 39...43

[CAR-98] Y. Carlton: *Fly-By-Wire Dual-Dual Flight Control Actuation System*. Proc. of Aerospace Power Systems Conference P-322, Society of Automotive Engineers (SAE), Warrendale, PA, USA, April 1998, S. 43-54

[DOR-01] M. A. Dornheim: *New Rules and Hardware for Wiring soon to emerge.* Aviation Week & Space Technology, April 2001, pp. 92...98

[DIN-96] DIN EN 2283: *Aerospace series – Testing of aircraft wiring*. German version EN 2283:March 1996

[FUR-01] C. Furse, R. Haupt: *Down to the Wire.* IEEE Spectrum, February 2001, pp. 35...39

[GOU-01] B. Gould: *New Test Methodology for Orbiter Wiring.* Boeing Investigation Report, January 2001

[HAN-00] J. Hanson: *Fault arc effects in wire bundles for space application*. PhD-Thesis Darmstadt University of Technology, June 2000 (in German)

[REP-00] C. Smith: *Transport Aircraft Intrusive Inspection Project.* Final Report, prepared by the Intrusive Inspection Working Group, December 2000

[STA-94] M. Stavnes, A. Hammoud, R. Bercaw: *Operational Environments for Electrical Power Wiring on NASA Space Systems.* NASA Technical Memorandum 106655, NASA Lewis Research Center, Cleveland, USA, 1994