



ED-320

GUIDANCE DOCUMENT FOR AGING MECHANISMS OF ELECTRICAL INSULATION MATERIALS IN A HIGH ENERGY SYSTEM

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FOREWORD

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CHAPTER 1

RATIONALE

The growing trends of reducing carbon dioxide emissions has led to development of high power and high energy system for electrification in aerospace applications where high voltages are required. Electrical insulation is a key element for safe and reliable operation of a high voltage system. This EUROCAE guidance document is intended to provide comprehensive reference and background information pertaining to aging factors and aging mechanisms of electrical insulation materials used in a high energy system for powering an aircraft.

1.1 LIST OF NOMENCLATURES

AC – alternating current
 CT – current transformer
 DC – direct current
 DF – dissipation factor
 DWV - dielectric withstand voltage
 EIM – electrical insulation materials
 EIS – electrical insulation system
 ETFE - Ethylene tetrafluoroethylene
 EWIS - electrical wiring and interconnection systems
 FEP - fluorinated ethylene propylene
 FR4 - flame retardant epoxy fiberglass laminate
 ft – foot
 GaN - gallium nitride
 GΩ - giga ohms
 HV – high voltage
 IEC - international electrotechnical commission
 IGBT - insulated-gate bipolar transistor
 IR – insulation resistance
 Kft – 1000 feet
 kV – kilovolts
 kΩ - kilo ohms
 LV – low voltage
 MΩ - mega ohms
 PBT - polybutylene terephthalate
 PD – partial discharge
 PDEV – partial discharge extinction voltage
 PDIV – partial discharge inception voltage
 PEA - pulsed electro acoustic
 PEEK - polyether ether ketone
 PFA - perfluoroalkoxy alkanes
 PI - polyimide
 PMG – permanent magnet generator
 PPS - polyphenylene sulfide
 PTFE – polytetrafluoroethylene
 PWM – pulse width modulation
 RF – radio frequency

RPDEV – repetitive PDEV
RPDIV – repetitive PDIV
s – second
SiC – silicon carbide
TEAM – thermal, electrical, ambient and mechanical
TFE – tetrafluoroethylene
TMS - thermal step method
TPE – thermoplastic elastomers
VS-PWM – voltage source pulse width modulated
XLPE – crosslinked polyethylene
Z – impedance

CHAPTER 2

INTRODUCTION

2.1 BACKGROUND

Electrification plays a significant role to reduce greenhouse gas emissions, lower acoustic noise, and deliver fuel burn benefits on future aircrafts. In fact, around 215 types of electric-powered aircraft are currently being developed worldwide, and industry observers say electric airplanes will be commonplace before the end of the next decade. From the more electric aircrafts (MEA) to near zero-emission electrified aircrafts using an electrical propulsion system, the power demand is anticipated to increase from tens of kW to tens of MWs and more. Electrical insulation systems (EIS) for high voltage (HV) and high-power electric components are required to deliver MWs of power while meeting the weight, space and volume constraints. Several categories of high voltage levels above the present 0-270 VDC, to include ± 270 VDC up to 1 kVDC and higher, are discussed in future aircraft designs. For example, SAE AIR 7502 has defined the HV categories for aircraft applications as shown in Table 1.

TABLE 2-1: VOLTAGE LEVEL RANGE DEFINITIONS*

Voltage Level	AC V-RMS (LN)	Nominal, DC VDC	Nominal,
VL-1	Up to 42.4 VAC	Up to 60 VDC	
VL-2	42.4 to 213 VAC	60 to 300 VDC	
VL-3	213 to 425 VAC	300 to 600 VDC	
VL-4	425 to 707 VAC	600 VDC to 1.0 kVDC	
VL-5	707 VAC to 3.6 kVAC	1.0 to 5.1 kVDC	
VL-6	Above 3.6 kVAC	Above 5.1 kVDC	

Where LN = Line-to-Neutral and LL = Line-to-Line.

For multi-phase systems:

- 3-phase system, $LL = \sqrt{3} \cdot LN$
- Multiple channel 3-phase system, adjacent channels might see $2 \cdot LN$ since being 180° out of phase is a possibility.
- 6-phase system, $LL = 2 \cdot LN$

The aging process of EIS in a low voltage (LV) power system (270 VDC or 235 VAC and below) are mainly driven by thermal and mechanical stresses. The apparent electrical failures in LV system is the result of EIS aging under thermal and mechanical loads, sometimes exacerbated by the environmental factors such as ultraviolet radiation and fluids. Many standards have been established for EIS evaluation and qualification in LV power system in aircraft under thermal and mechanical stresses.

There are several publications that discuss the subject of high voltage design for airborne equipment [HI1, HI2, ESC, KUF], however, the degradation mechanisms of electrical insulation materials (EIM) and life prediction in HV components and equipment used in aircraft in general are not well understood. Key factors are the lower air density that may lead to partial discharge (PD) according to Paschen's law, the impact of UV, gamma rays and cosmic radiation at different altitudes that may accelerate PD activity is less known. In addition, lower heat conduction is expected at high altitude due to the lower air density. The lower ambient temperature at higher altitudes coupled with lower heat conduction could result in a higher temperature gradient across the electrical insulation. In addition, resulting higher temperature at the conductors caused by Joule heating leads to a conductivity gradient across the insulation under DC stress, which may cause space charge accumulation and distortion of the electric field at the interface or in the bulk [CHO, FI1, KWU]. The impact of the space charge formation on field

distortion in HV DC system in aircraft is not yet clear. In addition, very limited service experience is available for understanding the deleterious impact of partial discharges (PD) at different altitudes and its interactions with other stress factors such as thermal, mechanical, and environmental on the EIS life in aircraft.

There is a wide range of HV applications of EIS at sea level in industry, and many industrial standards (for example, IEC 60505) have been published for EIS evaluation and qualifications for HV components and equipment. Although these industrial standards may not be directly applicable to aerospace applications, these standards may serve as foundations for us to understand the HV impact on EIS in general.

To meet future aircraft needs, it is imperative to understand the degradation mechanisms and aging processes of HV EIS at flight altitudes in order to design a reliable high voltage power system that is compatible with the airplane's thermal and mechanical environment to meet the stringent fault-free operation requirement.

2.2 SCOPE

The objective of this guidance document is to serve as an introductory (educational) document to cover the potential failure mechanisms related to EIS in high voltage electrical component or HV electrical equipment in aircraft power systems. It has the following contents: 1) an overview of the current understandings of potential failure mechanisms related to EIS for high voltage and high-power application in aircraft; 2) main aging stressors and aging processes of EIS in electrical components used in the aircraft power systems and their common failure modes, and 3) the key indicators to assess the status of electrical insulation degradation and related testing needs.

This document aims to assist HV power system designers in understanding the key considerations for EIS design and testing of HV components in aircraft, as well as the requirements for predicting their designed service life. Detailed testing guideline including testing methods will be provided in ARP7375, and life modelling in ARP7380.

2.3 REFERENCES

2.3.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.3.2 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR6127, "Managing Higher Voltages in Aerospace Electrical Systems", 2017.

AIR7502, "Aircraft Electrical Voltage Level Definitions", 2021.

AS50881 Wiring Aerospace Vehicle

SAE J1654 unshielded HV

2.3.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610 832-9585, www.astm.org.

ASTM D3032 Standard Test Methods for Hookup Wire Insulation

2.3.4 IEC Publications

Available from IEC Central Office, 3 rue, de Varembe, P.O. Box 131, CH-1221 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60505 Evaluation and qualification of electrical insulation systems

IEC 60034-18-1 Rotating electrical machines - Part 18-1: Functional evaluation of insulation systems - General guidelines

IEC 60034-18-41 Rotating electrical machines - Part 18-41: Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters - Qualification and quality control tests

IEC 60034-18-42 Rotating electrical machines - Part 18-42: Partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters - Qualification tests

IEC 60071-2 Insulation co-ordination - Part 2: Application guidelines

IEC 60183 Guidance for the selection of high-voltage A.C. cable systems

IEC 60216-1 Electrical insulating materials - Thermal endurance properties - Part 1: Ageing procedures and evaluation of test results

IEC 60270 High-voltage test techniques - Partial discharge measurements

IEC 60502-2 Power cables with extruded insulation and their accessories for rated voltages from 1 kV ($U_m = 1,2$ kV) up to 30 kV ($U_m = 36$ kV) - Part 2: Cables for rated voltages from 6 kV ($U_m = 7,2$ kV) up to 30 kV ($U_m = 36$ kV)

IEC 60502-4 Power cables with extruded insulation and their accessories for rated voltages from 1 kV ($U_m = 1,2$ kV) up to 30 kV ($U_m = 36$ kV) - Part 4: Test requirements on accessories for cables with rated voltages from 6 kV ($U_m = 7,2$ kV) up to 30 kV ($U_m = 36$ kV)

IEC 60664-1 Insulation coordination for equipment within low-voltage supply systems - Part 1: Principles, requirements and tests

IEC 60664-4 Insulation coordination for equipment within low-voltage systems - Part 4: Considerations of high-frequency voltage stress

IEC 61251 Electrical insulating materials and systems - AC voltage endurance evaluation

IEC 61442 Test methods for accessories for power cables with rated voltages from 6 kV ($U_m = 7,2$ kV) up to 30 kV ($U_m = 36$ kV)

IEC TS 61586 Estimation of the reliability of electrical connectors

2.3.5 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 2678 Insulation resistance and high voltage tests for electrical equipment

2.3.6 NASA Publications

Available from NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, Tel: 757-864-9658, Fax: 757-864-6500, <http://ntrs.nasa.gov/>.

NASA-HDBK-4007 SPACECRAFT HIGH-VOLTAGE PASCHEN AND CORONA DESIGN HANDBOOK, 2020

NASA/TM-20220004926 Urban Air Mobility Electric Motor Winding Insulation Reliability: Challenges in the Design and Qualification of High Reliability Electric Motors and NASA's Research Plan

2.3.7 NEMA Publications

Available from National Electrical Manufacturers Association, 1300 North 17th Street, Suite 900, Arlington, VA 22209, Tel: 703-841-3200, www.nema.org.

NEMA WC 27500 Aerospace and Industrial Electrical Cable

2.3.8 DOT Publications

DOT/FAA/AR-08/2 Aircraft Wiring Degradation Study

2.3.9 IPC publications

Available from IPC, 3000 Lakeside Drive, 309 S, Bannockburn, IL 60015, Tel: 847-615-7100, www.ipc.org.

IPC-A-610 IPC-A-610H, Acceptability of Electronics Assemblies, Rev. H, Oct 7, 2020

IPC-2221 IPC-2221B, Generic Standard on Printed Board Design, Rev. B, Nov 20, 2012

IPC-6012 IPC-6012E, Qualification and Performance Specification for Rigid Printed Boards, Rev. E, Feb 20, 2020

IPC-6013 IPC-6013E, Qualification and Performance Specification for Flexible/Rigid-Flexible Printed Boards, Rev. E, Sep 16, 2021

2.3.10

Related Publications

The following publications are provided for information purposes only and are not a required part of this EUROCAE Guidance Document.

[HI1] HIGH VOLTAGE DESIGN GUIDE: AIRCRAFT, AFWAL-TR-82-2057, Volume IV, January 1983. AD No. A129530.

[HI2] HIGH VOLTAGE DESIGN GUIDE: SPACECRAFT, AFWAL-TR-82-2057 Volume V, January 1983. AD No. A129142.

[ECS] ECSS-E-HB-20-05 A High voltage Engineering and Design Handbook

[KUF] E. Kuffel, W.S Zaengl, J. Kuffel, "High Voltage Engineering: Fundamentals - Second Edition," Newnes, 2001. Sections 5.2, 5.6.

[CHO] W. Choo, et al, "Electric field in polymeric cable due to space charge accumulation under DC and temperature gradient", IEEE Transactions on Dielectrics and Electrical Insulation (Volume: 18, Issue: 2, April 2011).

[FI1] D. Fabiani, et. al, "HVDC Cable Design and Space Charge Accumulation. Part 3: Effect of Temperature Gradient", IEEE Electrical Insulation Magazine (Volume: 24, Issue: 2, March-April 2008).

[KWU] Kai Wu, et, al, "Space charge behavior under temperature gradient and its effects on material aging", 2017 1st International Conference on Electrical Materials and Power Equipment (ICEMPE).

[HUD] C. Hudon, et. al, "Testing of Low-voltage Motor Turn Insulation Intended for Pulse-width Modulated Applications", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 7 No. 6, December 2000.

[MEN] M. Meneghini, et. al, "Reliability issues in GaN-based light-emitting diodes: Effect of dc and PWM stress" Microelectronics Reliability, Volume 52, Issue 8, August 2012, Pages 1621-1626.

[FLO] Barbara Florkowska, "The influence of PWM stresses on degradation processes in electrical insulation systems", 2010 Electrical Insulation and Dielectric Phenomena (CEIDP).

[FAB] D. Fabiani, et. el, "Aging Acceleration of Insulating Materials for Electrical Machine Windings Supplied by PWM in the Presence and in the Absence of Partial Discharges," Proceedings of the 2001 IEEE 7th International Conference on Solid Dielectrics, 2001. ICSD '01.

[MO1] G. Montanari, et al, "Type of Supply Waveform, Partial Discharge Behavior and Life of Rotating Machine Insulation Systems", IPMHVC 2018.

[GUA] F. Guastavino, et al, "Life tests on twisted pairs subjected to PWM-like voltages," 2004 International Conference on Solid Dielectrics.

[WY1] W. Yin, "Failure mechanism of winding insulations in inverter-fed motors", IEEE Electrical Insulation Magazine, Volume: 13, Issue: 6, Nov.-Dec. 1997.

[MEY] D. R. Meyer, A. Cavallini, L. Lusuardi, D. Barater, G. Pietrini, A. Soldati, "Influence of impulse voltage repetition frequency on RPDIV in partial vacuum", IEEE Trans. Dielectric. Electr. Insul., vol. 25, no. 3, pp. 873-882, Jun. 2018.

[RUM] A. Rumi, J. G. Marinelli, P. Seri, M. Kohler, A. Cavallini "Performance of Corona Resistant Insulation for Aerospace", 2021 IEEE Electrical Insulation Conference (EIC), pp. 22-25, June 2021.

[GRO] David Gross, "Aircraft Generator Design and Analysis", Honors Theses, University of Dayton, April 2018.

[ARA] F. Arastu, X. Yi, M. Garg, K. Haran, J. Lyding, "Magnet Wire for Venus Exploration", AIAA Scitech 2019 Forum, 2019.

- [GCS] G.C. Stone, I. Culbert, A.A. Boulter, H. Dhirani, "Electrical Insulation for Rotating Machines - Design, Evaluation, Aging, Testing and Repair," IEEE Press/Wiley, 2014.
- [GRI] F. Grilli et al, "Superconducting motors for aircraft propulsion: the Advanced Superconducting Motor Experimental Demonstrator project" 32nd International Symposium on Superconductivity (ISS2019), <https://doi.org/10.1088/1742-6596/1590/1/012051>.
- [BAL] T Balachandran et al "A fully superconducting air-core machine for aircraft propulsion" 2020 IOP Conf. Ser.: Mater. Sci. Eng. 756 012030.
- [WY2] W. Yin, et al, "End Winding Protections Improvements Helping to Downsize dV/dt Filter For Medium Voltage Machine Fed by NPP Multi-levels VSI Drive" 2018 IEEE 2nd International Conference on Dielectrics (ICD).
- [FAN] L. Fang, I. Cotton, Z. J. Wang, R. Freer, "Insulation performance evaluation of high temperature wire candidates for aerospace electrical machine winding application", 2013 IEEE Electrical Insulation Conference (EIC), pp. 253-256, 2013.
- [RAM] R. Ramin, G.C. Montanari and Q. Yang, "Designing the Insulation System for Motors in Electrified Aircraft: Optimization, Partial Discharge Issues and Use of Advanced Materials" Materials, 2021, 14, 7555.
- [TEC] <https://techcrunch.com/2021/09/07/wright-tests-its-2-megawatt-electric-engines-for-passenger-planes/#:~:text=Wright's%20engine%20is%20a%20,out%20there%2C%E2%80%9D%20said%20Engler>
- [FLI] <https://www.flightglobal.com/systems-and-interiors/ge-reveals-major-achievements-in-hybrid-electric-propulsion/125203.article>
- [AER] <https://www.aerospacetestinginternational.com/news/electric-hybrid/rolls-royces-electric-propulsion-system-reaches-1mw-in-testing.html>
- [SOO] B. Sood, "Printed Circuit Board Inspection and Quality Control- PCB Failure Causes and Cures," NASA ID 20180005658, Aug 2018.
- [ZHA] C. C. Zhang, Y. F. Li, M. Y. Hu, F. L. Ma, H. Zhao and B. Z. Han, "Conductivity properties of XLPE insulation used for HVDC cable after accelerated thermal ageing," 2018 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), 2018, pp. 500-503, <https://doi.org/10.1109/ICPADM.2018.8401037>.
- [KHA] R. Khazaka, M. Locatelli and S. Diaham, "Conductivity spectroscopy and conduction current measurements of polyimide thin films during high temperature aging," 2011 - 14th International Symposium on Electrets, 2011, pp. 107-108, <https://doi.org/10.1109/ISE.2011.6085005>.
- [ZUL] A. Zulkifli, "Polymer dielectric materials", in Dielectric Material, IntechOpen, Ed. M.A. Silaghi, Chap. 1, 2012.
- [KEM] Y. Kemari, G. Teyssède, A. Mekhaldi and M. Tegar, "Dielectric Properties and β -Relaxation in Cross-linked Polyethylene: Effect of Thermal Aging," 2020 IEEE 3rd International Conference on Dielectrics (ICD), 2020, pp. 73-76, <https://doi.org/10.1109/ICD46958.2020.9341896>.
- [HAS] Yuka Hasegawa et al, "Estimation of thermal expansion coefficients of polymeric insulating films from temperature dependence of dielectric permittivity," 2014 Jpn. J. Appl. Phys. 53 071501.
- [SAV1] S. Savin, S. Ait-Amar and D. Roger, "Cable aging influence on motor diagnostic system," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 4, pp. 1340-1346, August 2013, <https://doi.org/10.1109/TDEI.2013.6571454>.
- [SAV2] S. Savin, S. Ait-Amar, D. Roger and G. Vélú, "May the capacitance of power cables be an aging indicator?," 2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2011, pp. 60-63, <https://doi.org/10.1109/CEIDP.2011.6232596>.
- [MAD1] V. Madonna, P. Giangrande, W. Zhao, Y. Wang, H. Zhang and M. Galea, "Insulation Capacitance as Diagnostic Marker for Thermally Aged, Low Voltage Electrical Machines," 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), 2019, pp. 1-5, <https://doi.org/10.1109/ICEMS.2019.8921657>.

- [MAD2] V. Madonna, P. Giangrande, L. Lusuardi, A. Cavallini and M. Galea, "Impact of thermal overload on the insulation aging in short duty cycle motors for aerospace," *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, 2018, pp. 1-6, <https://doi.org/10.1109/ESARS-ITEC.2018.8607539>.
- [WAN] X. Wang et al., "Effect of Thermal Cycling on the Thermal and Mechanical Properties of Dielectric Materials," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 10, no. 7, pp. 1166-1174, July 2020, <https://doi.org/10.1109/TCPMT.2020.2998492>.
- [FAR] M. Farahani, E. Gockenbach, H. Borsi, K. Schäfer and M. Kaufhold, "Behavior of machine insulation systems subjected to accelerated thermal aging test," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 17, no. 5, pp. 1364-1372, October 2010, <https://doi.org/10.1109/TDEI.2010.5595537>.
- [DIN] R. Ding and N. Bowler, "Influence of accelerated aging on dielectric properties of extruded Nylon 6 film," *2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2013, pp. 152-155, <https://doi.org/10.1109/CEIDP.2013.6747095>.
- [LIL1] Li Li, N. Bowler, S. H. Yoon and M. R. Kessler, "Dielectric Properties of PTFE Wiring Insulation as a Function of Thermal Exposure," *2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2008, pp. 95-98, <https://doi.org/10.1109/CEIDP.2008.4772850>.
- [LIL2] L. Li, N. Bowler, S. H. Yoon and M. R. Kessler, "Dielectric properties of ETFE wiring insulation as a function of thermal exposure," *2009 IEEE Conference on Electrical Insulation and Dielectric Phenomena*, 2009, pp. 63-66, <https://doi.org/10.1109/CEIDP.2009.5377783>.
- [LIL3] L. Li, N. Bowler, P. R. Hondred and M. R. Kessler, "Dielectric response of polyimide to thermal and saline degradation," *2010 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2010, pp. 1-4, <https://doi.org/10.1109/CEIDP.2010.5724011>.
- [IOS] V. Iosif, S. Duchesne and D. Roger, "Voltage stress predetermination for long-life design of windings for electric actuators in aircrafts," *2015 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2015, pp. 318-321, <https://doi.org/10.1109/CEIDP.2015.7352159>.
- [DIA] E. N. Diaw, S. L. Roy, G. Teyssède and E. Aubert, "Electric Field and Current Conduction Modelling in Bi-layers Insulations HVDC Aeronautic Cables," *2020 IEEE 3rd International Conference on Dielectrics (ICD)*, 2020, pp. 505-508, <https://doi.org/10.1109/ICD46958.2020.9341847>.
- [PIN] S. Pin, G. Belijar, L. Fetouhi, L. Somer, C. Van de Steen and L. Albert, "Ageing study in aircraft electromechanical chain: systems modeling for property evolution monitoring," *2020 IEEE Electrical Insulation Conference (EIC)*, 2020, pp. 79-84, <https://doi.org/10.1109/EIC47619.2020.9158659>.
- [FET] L. Fetouhi, J. Martinez-Vega and B. Petitgas, "Electric conductivity, aging and chemical degradation of polyesterimide resins used in the impregnation of rotating machines," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 1, pp. 294-305, Feb. 2018, <https://doi.org/10.1109/TDEI.2018.006823>.
- [SIL] E. Sili, J. P. Cambronne, N. Naude and R. Khazaka, "Polyimide lifetime under partial discharge aging: effects of temperature, pressure and humidity," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 2, pp. 435-442, April 2013, <https://doi.org/10.1109/TDEI.2013.6508745>.
- [CAN] N. Can, F. Aras, V. A. Alekperov and A. Altındal, "Investigation on aging mechanism of polyester under combined stresses," in *IEEE Electrical Insulation Magazine*, vol. 32, no. 4, pp. 38-42, July-August 2016, <https://doi.org/10.1109/MEI.2016.7528988>.
- [GAR] 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," *2015 IEEE Electrical Insulation Conference (EIC)*, 2015, pp. 430-433, <https://doi.org/10.1109/ICACACT.2014.7223588>.

- [LUS] L. Lusuardi, A. Rumi, A. Cavallini, D. Barater and S. Nuzzo, "Partial Discharge Phenomena in Electrical Machines for the More Electrical Aircraft. Part II: Impact of Reduced Pressures and Wide Bandgap Devices," in *IEEE Access*, vol. 9, pp. 27485-27495, 2021, <https://doi.org/10.1109/ACCESS.2021.3058089>.
- [SHA] T. Shahsavarian *et al.*, "High Temperature Insulation Materials for DC Cable Insulation—Part II: Partial Discharge Behavior at Elevated Altitudes," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 1, pp. 231-239, February 2021, <https://doi.org/10.1109/TDEI.2020.009166>.
- [KAR] M. Karadjian, N. Imbert, C. Munier, M. Kirkpatrick and E. Odic, "Partial Discharge Detection in an Aeronautical Power Cable," *2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, 2018, pp. 1-9.
- [HAS2] A. Hascoat, « Étude et modélisation du vieillissement sous contraintes électrothermiques de l'isolant pour câble de transport d'énergie haute tension à courant continu », *Thèse de doctorat Université de Montpellier*, 2016.
- [YAH1] H. Yahyaoui, J. Castellon, S. Agnel, A. Hascoat, W. Frelin, C. Moreau, P. Hondaa, D. Le Roux, V. Eriksson and C-J. Andersson, "Behavior of XLPE for HVDC Cables under Thermo-Electrical Stress: Experimental Study and Ageing Kinetics Proposal", *Energies* 2021, 14, 7344. <https://doi.org/10.3390/en14217344>, 2021.
- [YAH2] H. Yahyaoui, P. Notingher, S. Agnel, C. Perrier and Y. Kieffel, "Electrical properties of polytetrafluoroethylene with mineral fillers under high DC electric field," 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP), 2017, pp. 712-715, <https://doi.org/10.1109/CEIDP.2017.8257580>.
- [CAS] J. Castellon, P. Notingher, S. Agnel, J-F. Brame, P. Mirebeau, J. Mattalana, "Electric Field And Space Charge Measurements in Thick Power Cable Insulation", *Electrical Insulation Magazine*, pp 30-42, Vol 25, N°3, 2009.
- [BOY] L. Boyer, P. Mirebeau, K. Vershnin, A. Tzimas, J. Castellon, P. Notingher, "Follow up of space charge distributions in HVDC cable during a Pre-Qualification test using the Pulse ElectroAcoustic technique and the Thermal Step Method," *10th International Conference on Insulated Power Cables, Jicable 2019, paper A8-5, CD rom proceedings, Versailles*, 2019.
- [IMP] M. V. Imperatore, L. S. Fifield, D. Fabiani and N. Bowler, "Dielectric spectroscopy on thermally aged, intact, poly-vinyl chloride/ethylene propylene rubber (PVC/EPR) multipolar cables," 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP), 2017, pp. 173-176, <https://doi.org/10.1109/CEIDP.2017.8257522>.
- [VER] L. Verardi, D. Fabiani, G. C. Montanari and V. Plaček, "Electrical aging markers for low-voltage cable insulation wiring of nuclear power plants," 2012 IEEE 10th International Conference on the Properties and Applications of Dielectric Materials, 2012, pp. 1-4, <https://doi.org/10.1109/ICPADM.2012.6318966>.
- [SUR] S. V. Suraci, D. Fabiani, L. Mazzocchetti, V. Maceratesi and S. Merighi, "Investigation on Thermal Degradation Phenomena on Low Density Polyethylene (LDPE) through Dielectric Spectroscopy," 2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 2018, pp. 434-437, <https://doi.org/10.1109/CEIDP.2018.8544734>.
- [SHA] D. Bar-Shalom, "Altitude Effects on Heat Transfer Processes in Aircraft Electronic Equipment Cooling", Master of Science 02/89, MIT.
- [PIET] G. Pietrini, D. Barater, G. Franceschini, P. Mancinelli, and A. Cavallini, "An open problem for more electrical aircraft (MEA): how insulation systems of actuators can be qualified ?" in *Proc. IEEE Energy Conver. Congress and Expo. (ECCE)*, Milwaukee, USA, 2016, pp. 1-8.).
- [BOR] M. Borghei, M. Ghassemi, "Insulation Materials and Systems for More and All-Electric Aircraft: A Review Identifying Challenges and Future Research Needs", *IEEE Trans on Transportation Electrification*, vol.7, Issue 3, Sept. 2021
- [DIL] L. Dilillo, F. Wrobem, JM. Galliere, F. Saigné "Neutron Detection through an SRAM-Based Test Bench" *International Workshop On Advances in Sensors and Interfaces: IWASI 2009*, DOI : 10.1109/IWASI.2009.5184769