Virginia Polytechnic Institute and State University (Virginia Tech)

Final Technical Report

High Power Density Cost-Effective MVDC Aircraft Cable

DE-AR0001465

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| **Award:** | DE-AR0001465 |
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| **Lead Recipient:** | Virginia Tech |
| **Project Team Members** | Dr. Mona Ghassemi and Dr. Jane Lehr |
| **Project Title:** | High Power Density Cost-Effective MVDC Aircraft Cable |
| **Program Director:** | Dr. Isik Kizilyalli |
| **Principal Investigator:** | Dr. Mona Ghassemi |
| **Contract Administrator:** | Wendy Jay |
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## Public Executive Summary

To make the power density of electric aircraft closer to conventional aircraft, an electric power system (EPS) with high power delivery and low system mass is necessary. As an essential component of aircraft EPS, cables are necessary to transmit power from one node to another. Virginia Tech will design high-power density, cost-effective ±5 kV cables for twin-aisle all-electric aircraft. Innovations include conductors with increased current-carrying capacity and a multilayer, multifunctional insulation system made of exceptionally high thermal conductivity materials. Designed for DC voltage, the new insulator will allow fewer partial discharge events and provide improved electromagnetic interference protection.

## Acknowledgements

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## Accomplishments and Objectives

This award allowed Virginia Tech to demonstrate a number of key objectives. The focus of the project was on optimally designing high-power density, cost-effective ±5 kV, 1 kA cables capable of working at an altitude/pressure of 12.2 km/18.8 kPa for twin-aisle all-electric aircraft.

The actual performance against the stated milestones is summarized here:

**Table 1. Key Milestones and Deliverables**

| Tasks | Milestones and Deliverables |
|---|---|
| **Task 1: Phase 1. Conceptual Design – EPS**<br>1.1 Develop a DC Load Flow Model<br>1.2 Optimal EPS Architecture | Q1: Completion DC load flow model for the EPS of a twin-aisle, wide-body AEA with a largest mismatch of <1 W for load flow convergence.<br>**Actual Performance:** (11/01/2021) This task (1.1) was completed (100%) on 9/30/2021.<br><br>Q2: Envisaged EPS architectures compared to determine optimal EPS architecture in terms of specific power transfer (kW/(kg.$m^3$)), reliability, power loss, and cost. To this end, an objective function will be defined as a weighted combination of the four mentioned parameters. Then for a few envisaged architectures, their objective functions will be compared to obtain the optimal architecture.<br>**Actual Performance:** (11/01/2021) This task (1.2) was completed (100%) on 11/01/2021. |

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| **Task 2: Phase 1. Conceptual Design — Electromagnetic Interference, Compatibility, and Shield Layer Design**<br><br>2.1 Electromagnetic Interference, Compatibility, and Shield Layer Design | Q1: Completion of design and development of lightweight graphene-based materials for the shield layer of the cable with a thickness from 0.3 nm to 2 mm with a density of 3 mg/cm$^3$. Electromagnetic shielding performance, evaluated through radiated EMI/EMC testing, and mechanical loading strength compared with SOA shielding layers.<br>**Actual Performance:** (05/01/2022) This task (2.1) was completed (100%) on 05/01/2022. |
| **Task 3: Phase 1. Conceptual Design — Partial Discharge Testing**<br><br>3.1 PD Modeling under DC<br><br>3.2 Temperature Effect on PD Behavior under DC<br><br>3.3 Setup Preparation for PD Tests | Q1: Completion of models to analyze the physics of PDs and characterize them in DC at low pressures. Results validated with experimental tests and presented to program director.<br>**Actual Performance:** (08/01/2022) This task (3.1) was completed (100%) on 08/01/2022.<br><br>Q2: Completion of study on the effect of temperature and temperature gradients across the insulation in 25-100°C range through modeling/simulation and experimental investigation. Simulations validated with experimental tests and presented to program director.<br>**Actual Performance:** (08/01/2022) This task (3.2) was completed (100%) on 08/01/2022.<br><br>Q3: Completion of design and test setup preparations for PD tests on the cable under dc for a) atmospheric pressure conditions, b) low-pressure conditions, c) pressure change simulating take-off and landing conditions. Design and test setup presented to program director.<br>**Actual Performance:** (08/01/2022) This task (3.3) was completed (100%) on 08/01/2022. |
| **Task 4: Phase 1. Conceptual Design — Cable Design**<br><br>4.1 Cable Design — Core Conductor and Insulation System Model<br><br>4.2 Cable Design — Optimal Design<br><br>4.3 Conceptual Design — Cable Connectors | Q1: Completion of a coupled Multiphysics model including three physical effects: 1) computational fluid dynamics, 2) heat transfer in solids, and 3) electric for the cable design. Results compared results with benchmarking case studies from literature.<br>**Actual Performance:** (08/01/2022) This task (4.1) was completed (100%) on 08/01/2022.<br><br>Q2: Completion of optimal design for the ±5 kV, 10 MW cable via the model developed in M5.1. Determination of the arrangement, type/material, and thickness of different MMEI insulation layers to reach: the maximum dielectric breakdown voltage, maximum ampacity, minimum overall thickness of the MMEI system, and the minimum overall weight of the MMEI |

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| | system. The optimal design considers operation under atmospheric pressure, low-pressure (18.8 kPa), and pressure change simulating take-off and landing conditions, all in a harsh environment. Two types of core conductors (standard and E3X) for each TransPowr® AAC/TW bare overhead conductor and the designed graphene-based shield layer designed and developed in M3.1 are considered in the optimization. Constraints for the optimal cable design include (i) $E_{max} \leq 0.8E_{bd}$ ($E_{max}$: maximum electric field of each layer, $E_{bd}$: breakdown strength of each layer) for all insulation layers in the MMEI system, (ii) under a pressure of 18.8 kPa, the steady-state temperature of a) the core < 75°C for AAC/TW conductors or < 90°C for AAAC/TW conductors, b) each layer < thermal limit of that layer, and c) reach convergence in simulations for heat transfer from the core to ambient with natural cooling, (iii) compare the parameter $M = I_A/(d.w)$, where $I_A$ is ampacity, $d$ is the outer diameter, and $w$ is weight, between our optimal design and a conventional design with Cu for the core conductor and a single layer for the insulation system.<br>**Actual Performance:** (08/01/2022) This task (4.2) was completed (100%) on 08/01/2022.<br><br>Q3: Completion of conceptional design for both the joint and the termination for the cable designed in M5.2 to ensure compatible connectors can be built for the cable. 3D FEM electrothermal models for connectors will be developed in COMSOL Multiphysics to calculate both the electric field and temperature distributions and to achieve optimal designs for connectors. Under the pressure of 18.8 kPa, the steady-state temperature in all parts of connector < thermal limit of the material used for each part. Details of conceptual design thermal limits presented in the quarterly report and the quarterly review and accepted by the Program Director.<br>**Actual Performance:** (08/01/2022) This task (4.3) was completed (100%) on 08/01/2022. |

## Project Activities

In this project, for the first time, several aircraft MVDC power cables are designed to meet environmental aviation challenges, including arc and arc tracking, partial discharge (PD), and thermal management, while maintaining high-power-density and low-system-mass requirements for envisaged wide-body all-electric aircraft. The designed cable systems are analyzed thermally and electrically. Thermal and electrical analysis of the cables was conducted using a coupled electric, thermal, and fluid flow dynamic model. The model included all possible heat transfer approaches, including conduction, convection, and radiation.

## Project Outputs

### *A. Journal Articles*

1. M. Ghassemi, A. Barzkar, and M. Saghafi "All-electric NASA N3-X aircraft electric power systems," *IEEE Trans. Transportation Electrification*, vol. 8, no. 4, pp. 4091-4104, Dec. 2022.
2. A. Azizi, M. Ghassemi, and J. Lehr, "Heat transfer challenges for MVDC power cables used in wide body all electric aircraft under low pressures," *IEEE Access*, vol. 10, pp. 111811-111819, Oct. 2022.
3. A. Azizi and M. Ghassemi, "Design of high power density MVDC cables for wide body all electric aircraft," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 30, no. 5, pp. 2315-2324, Otc. 2023.
4. A. Azizi and M. Ghassemi, "A FEM coupled electrical, thermal, and computational fluid dynamic model and a theoretical model for calculation of maximum permissible current in envisaged wide-body all-electric aircraft bipolar MVDC power cables," *IET High Voltage*, submitted and under review.
5. A. Saha, A. Azizi, and M. Ghassemi, "Optimal designs of bipolar MVDC aircraft cables for conventional, cuboid, and coaxial geometries," *IEEE Dielectrics and Electrical Insulation*, submitted and under review.

### *B. Conference Papers*

1. M. Ghassemi and A. Barzkar, "Power flow solvers for medium voltage direct current (MVDC) microgrids," *The 6th IEEE Workshop on the Electronic Grid (eGrid 2021)*, Virtual, November 8-10, 2021.
2. M. Ghassemi and A. Barzkar, "DC load flow models for the electric power system of wide body all electric aircraft," *IEEE Aerospace Conference*, Big Sky, MT, USA, March 5-12, 2022.
3. M. Ghassemi and M. Saghafi, "Optimal electric power system architectures for wide body all electric aircraft," *IEEE Aerospace Conference*, Big Sky, MT, USA, March 5-12, 2022.
4. M. Saghafi, M. Ghassemi, J. Lehr, M. Borghei, B. Kordi, and D. Oliver, "A finite element analysis model for internal partial discharges under DC voltage," *IEEE Power Modulator and High Voltage Conference (IPMHVC)*, Knoxville, TN, USA, pp. 8-11, June 19-23, 2022.
5. A. Azizi, M. Ghassemi, and J. Lehr, "Influence of low pressure on thermal limit of MVDC power cables used in all electric aircraft," *IEEE Power Modulator and High Voltage Conference (IPMHVC)*, Knoxville, TN, USA, pp. 88-91, June 19-23, 2022.
6. A. Azizi, M. Ghassemi, and J. M. Lehr, "Design of a cable system for a high-power density MVDC aircraft electric power system," *IEEE Conference Electrical Insulation Dielectric Phenomena (CEIDP)*, Denver, CO, USA, pp. 151-154, Oct. 30-Nov. 2, 2022.
7. A. Samimi Motlagh, J. Lehr, M. Ghassemi, "Heat transfer simulations for MVDC power cable under low pressures," *IEEE International Conference on Plasma Science (ICOPS)*, Santa Fe, New Mexico, USA, May 21-25, 2023.
8. A. Saha, A. Azizi, and M. Ghassemi, "An optimal bipolar MVDC coaxial power cable design for envisaged all electric wide body aircraft," *IEEE Conference Electrical Insulation Dielectric Phenomena (CEIDP)*, East Rutherford, NJ, USA, Oct. 15-19, 2023.
9. A. Azizi, A. Saha, and M. Ghassemi, "A cuboid geometry design for MVDC power cables for using in future all electric wide body aircraft," *IEEE Conference Electrical Insulation Dielectric Phenomena (CEIDP)*, East Rutherford, NJ, USA, Oct. 15-19, 2023.

### *C. Status Reports*
None.

### *D. Media Reports*
None.

### *E. Invention Disclosures*
None.

### *F. Patent Applications/Issued Patents*
None.

### *G. Licensed Technologies*
None.

### *H. Networks/Collaborations Fostered*
None.

### *I. Websites Featuring Project Work Results*
None.

### *J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)*
None.

### *K. Awards, Prizes, and Recognition*
None.

## Follow-On Funding
None.