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M4Or1B-01: [Invited] Technologies and Topologies for Cryogenic-Based Electric Aircraft

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With the substantial development underway to seek alternatives to diesel and gasoline driven propulsion for various forms of transportation, cryogenic-based platforms are receiving renewed interest for aviation, space, trucking, marine, and railway. A big reason for this is the presence of a cryogen as a fuel source that can be utilized to achieve greater electrical efficiencies in the respective drivetrains. Noteworthy elements of the drivetrain are the motors and the cabling in which superconductivity can be achieved. This talk will focus on the power electronic technologies and the circuit topologies built from those components that can thrive in these cryogenic conditions. Design guidelines will also be provided to ensure that the resulting system is reliable as not all components have sufficient performance to be included in the cryogenic domain and must remain at higher temperatures.

Highly efficient electrically driven avionics have led to a renewed interest in cryogenic propulsion systems with the goal of reducing carbon emission footprint. Although cryogenic converters promise better efficiency and improved power density, successful design is incumbent upon the appropriate switching device selection and simulation-based analyses prior to initial prototyping. In addition to having components, such as power semiconductor devices, suitably packaged to be able to thrive at cryogenic temperatures and over thermal cycles, it is also important to have compact models for these components to analyze circuit topologies prior to prototype and manufacturing. Elsewhere in the conference, a datasheet-driven compact model for a gallium nitride (GaN) Gate Injection Transistor (GIT) implemented in LTSpice has been presented. Key attributes of this model along with a summary of results indicating why this GaN technology is superior for cryogenic applications is described. This description is a broad summary of the extensive component testing, evaluations, and modeling that the UA team has performed over the past 4 years.

In the last portion of the talk, the circuit topologies and design techniques will be described. A baseline case of a non-cryogenic power electronic motor drive will be described initially. This 250 kW and 30 kW/kg drive is the result of a design of a hybrid electric aircraft (Cessna 337) that has recently been demonstrated in flight via the ARPAe-owned and Ampaire-operated flying testbed. As a non-cryogenic application, it forms a frame of reference to appreciate gains available when cryogenic solutions are possible.

Overall system performance can be further improved if the power electronic converters can also work under cryogenic temperatures. The gallium nitride (GaN) high electron mobility transistor (HEMT), which has the best overall performance under cryogenic temperatures among various types of semiconductors, has been adopted to design power converter topologies for various applications within the aircraft. GaN devices do not exhibit carrier freeze-out effects in the way that doped semiconductor devices do. However, due to the current limitation of an individual GaN HEMT, power modules with paralleled GaN HEMTs in each switching position are designed. Physical design is extremely important to ensure that electrical parasitics are balanced, thus achieving equal current sharing among paralleled components that in turn leads to longer lifetime. Based on converter power loss and size models, an optimization-based design method is illustrated for select circuit topologies. The theoretical efficiency performance under different operating conditions is presented. The double-pulse test (DPT) is performed to validate the function of a designed half-bridge power module. The thermal test of the power module is conducted to validate the symmetric layout design for the paralleled devices.

GaN HEMT-based power converters with different power levels (from several Watts to several kiloWatts) are evaluated at cryogenic temperature. Due to the degraded performance of conventional magnetic components, air core magnetics are used in these power converters to improve the converter efficiency. Efficiency improvements at cryogenic temperature are observed for all the GaN HEMTs and air core magnetics-based power converters, which are promising for cryogenic power electronics applications.

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