Design of a High Power Density, High Efficiency, Low THD 250kW Converter for Electric Aircraft

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A high efficiency, high power density, low distortion 250kW motor controller is being developed at NASA Glenn Research Center. Future electric aircraft require motor controllers which achieve the needed key performance parameters required to show benefit in increasing overall aircraft efficiency. Through a combination of carefully considered electrical topological choices and through the use of recent advancements in power switches and magnetic materials, a converter is designed which meets these requirements. A multilevel and interleaved converter architecture is chosen to meet the voltage, current, and THD requirements. The enclosure and thermal designs meet their weight targets and enable high altitude operation.

I. Nomenclature

GRC = Glenn Research Center
HEMM = High Efficiency Megawatt Motor
NEAT = NASA Electric Aircraft Testbed
SiC = Silicon Carbide
THD = Total Harmonic Distortion

II. Introduction

Much research has been conducted in recent years for enabling single aisle class electrified aircraft. Research has shown turboelectric aircraft power system architectures can provide an overall benefit compared with conventional aircraft, given that key performance parameters are met in the electric drive system. These include obtaining specific

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power above 9 kW/kg and efficiency in the upper 90% range [1], [2]. Accordingly, much research is being conducted into designing electric aircraft drive system components that meet these criteria. For instance, engineers at NASA Glenn Research Center (GRC) have accomplished an electric aircraft motor controller capable of 98% efficiency and a power density of 11 kW/kg. These advancements were made possible due to advancements in wide bandgap power switches, as well as advanced thermal and mechanical integration [3].

The topic of this paper is a 250kW converter design that advances research in this area. There are several requirement-driving goals for this converter. One is that the design should scale to meet the performance goals of [4]. This includes the capability to drive the NASA GRC High Efficiency Megawatt Motor (HEMM). Because of the HEMM's superconducting rotor design, loss induced from the stator current to the rotor components must be minimized. This aspect of the HEMM's design necessitates a strict output ripple requirement on the converter. This challenge is exacerbated by the HEMM's low inductance design, as well as the additional challenges that come with high voltage and high current operation. Original requirements were placed on the converter's output current THD in order to minimize rotor loss. Later analysis has revealed that THD is not an accurate proxy metric for rotor loss [5]. For the purposes of this paper the original THD requirements will be considered.

The other major design goal for this converter is to enhance the testing capabilities of the NASA Electric Aircraft Testbed (NEAT) at NASA GRC-ATF (formerly Plum Brook Station). NEAT is a reconfigurable MW-level testing platform for evaluating electric aircraft topologies and technology [6]. In order to facilitate future testing at this facility, it is desirable for the converter to be capable of operating at a high bus voltages, 1 kV or higher. Additionally, the converter should feature a flexible and easily reconfigurable control system, although the avionics and controller are not featured in this paper.

The following sections of the paper will outline the electrical, magnetic, mechanical, and thermal design choices that enable the converter to achieve its design requirements. Through a combination of new materials, optimized topological choices, and a thorough mechanical/thermal design, significant progress has been made in meeting the key performance parameters.

III. Electrical Architecture

The electrical architecture of the converter is shown in Fig. 1. The two key features of this design are the multilevel and interleaved architectures. The main advantage of the multilevel architecture is its ability to allow for high voltage operation using lower voltage rated switches. Current trends in the commercial silicon carbide MOSFET market provide for an abundance of switches with voltage ratings in the 1.2 to 1.7 kV range. Although aerospace standards are not yet settled for this class of electric power drive, projecting from current requirements shows that a 1.7 kV switch would only just meet standard over-voltage requirements for 1 kV operation. A series architecture is an advantageous method for meeting voltage margin requirements for higher bus voltage applications. An additional benefit of the multilevel design is the additional voltage level, which provides a reduction in THD.

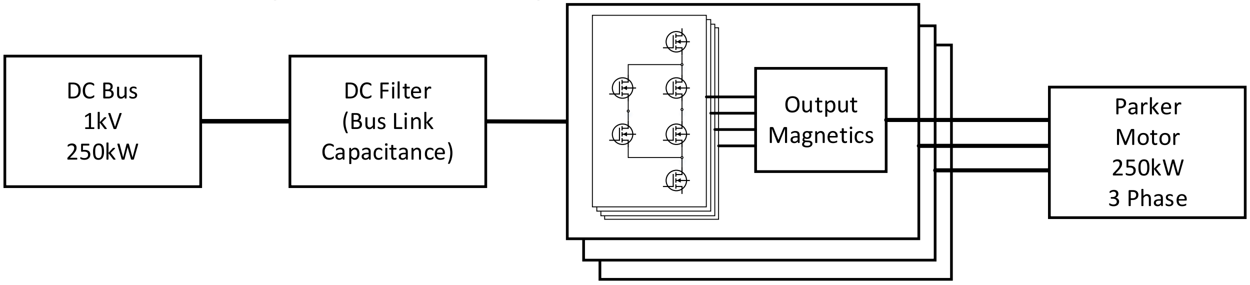


Fig. 1 Electrical architecture of the converter. Key design choices include the multilevel and interleaved capabilities.

The main advantage of the interleaving architecture is its THD reduction capability. An increased number of interleaves decreases output current ripple. An additional advantage of this architecture is the enhanced current sharing capability gained through the use of parallel MOSFET channels, which results in significant conduction loss reduction. Additionally, similar to the voltage benefit given by a multilevel design, an interleaved design allows for the high-current converter to be constructed from lower current rated switches. The phase voltage and current waveforms generated by this topology are shown in Fig. 2. The added voltage levels generated by the multilevel and interleaved topology are clearly seen in the phase voltage waveform in Fig. 2 (a). These added levels produce the low THD (2.57%) current waveform seen in Fig. 2 (b).

(a)

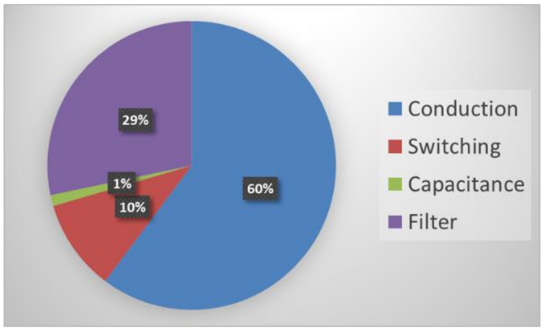
(b)

Fig. 2 Electrical waveforms generated by the multilevel, interleaved design. Shown are the (a) terminal voltage and (b) phase current.

These architecture choices are complimented with the performance enhancements gained through the use of state of the art commercially available silicon carbide switches. By combining these design choices, efficiency and power density targets can be achieved. Fig. 3 shows the anticipated loss breakdown of the converter, including losses attributed to the power electronics and the interleaving output filter. An efficiency greater than 99% is anticipated.

Source	**Loss (W)**	
Conduction	1277	
Switching	217	
Capacitance	26	
Filter	600	**Efficiency**
SUM	**2120**	**99.15%**

(a)



(b)

Fig. 3 Projected efficiency (a) table and (b) pie chart.

IV. Magnetics

Another key enabling technology for the converter design is the magnetics. Circulating current is unavoidable in an interleaved configuration. The interleaving architecture is therefore made possible because of inductive output filters which control the amplitude of the circulating current. Filters with larger inductance proportionally result in lesser circulating current amplitude, and accordingly greater efficiency increases and less device stress.

The magnetics design is a critical aspect of the converter, as the amount of inductance and current magnitude required could result in a high-mass, high-loss design. This converter takes advantage of proprietary magnetic material developed at NASA GRC. Amorphous magnetic material is fabricated in-house and formed into inductors usable in converter designs. Examples of such inductors are shown in Fig. 4, which are prototypes meant for a two-interleave converter. When excited by a three-level converter, they produce the waveforms seen in Fig. 5.

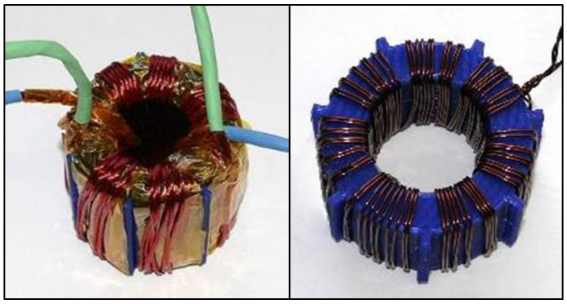
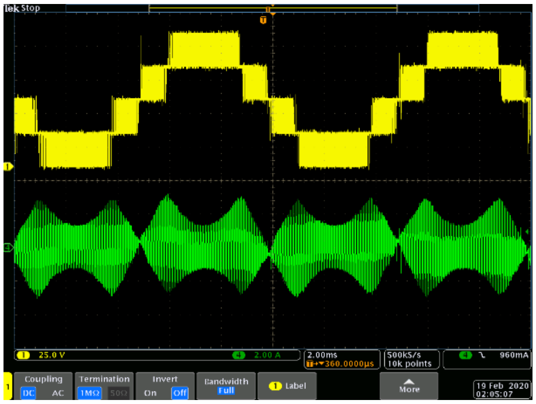


Fig. 4 Two-interleave prototype magnetic structures.

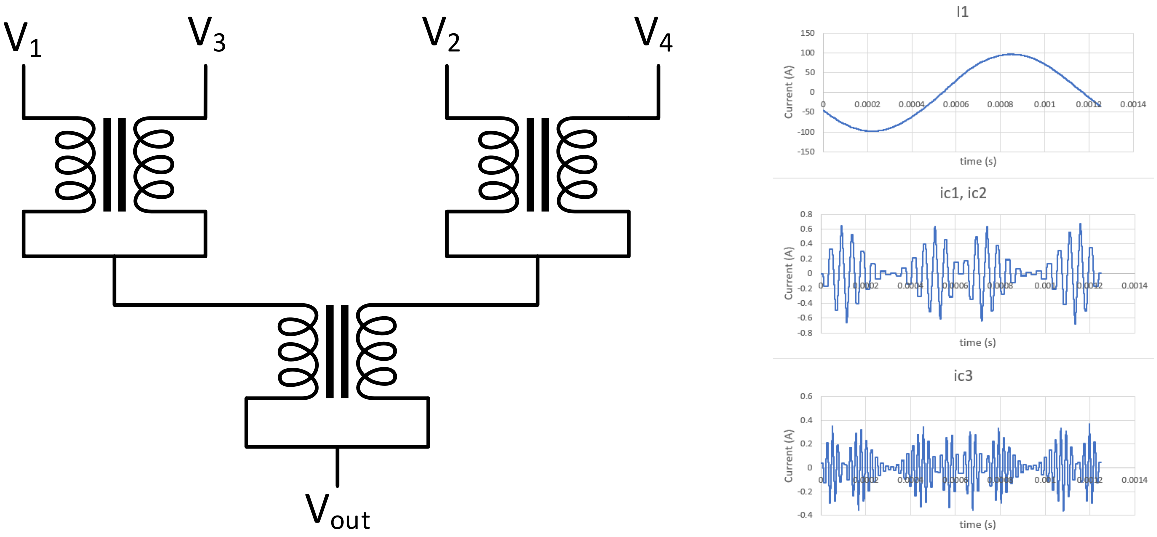


Coupling DC AC
Termination 1MΩ 50Ω
Invert On Off
Bandwidth Full

Fig. 5 Waveforms from the two-interleave prototype. The top trace is the voltage on the filter output, corresponding to the phase voltage. The bottom trace is the circulating current developed in the filter.

For this 250kW build, a four-interleave structure is planned. Testing a four-interleave configuration is advantageous from a technology development perspective because of the added challenge produced by the asymmetry of the structure. Symmetric monolithic two- and three-interleave cores are possible to build, but for four-interleaves and greater the flux through the structure cannot be perfectly symmetrical [7].

The structure and simulated electrical waveforms of the four-interleave filter are shown in Fig. 6. A whiffletree configuration is used, seen schematically in Fig. 6 (a). This configuration exhibits optimal mass, a significant reason for which being it requires the fewest number of 2-winding cores for a four-interleave configuration [8]. The magnetizing current plots for each core can be seen in Fig. 6 (b). The peak amplitude of these waveforms is a major driving factor for the mass of these filters. The peak amplitude is a function of bus voltage, filter inductance, and modulation index.



(a) (b)

Fig. 6 Interleaving filter (a) schematic and (b) output current (top), magnetizing current in cores A and B (middle), and magnetizing current in core C (bottom).

Finally, a thermal analysis of a prototype output filter configuration is shown in Fig. 7. The cores are made of a custom alloy which can withstand high temperature operation. This simplifies the thermal considerations for the configuration considerably.

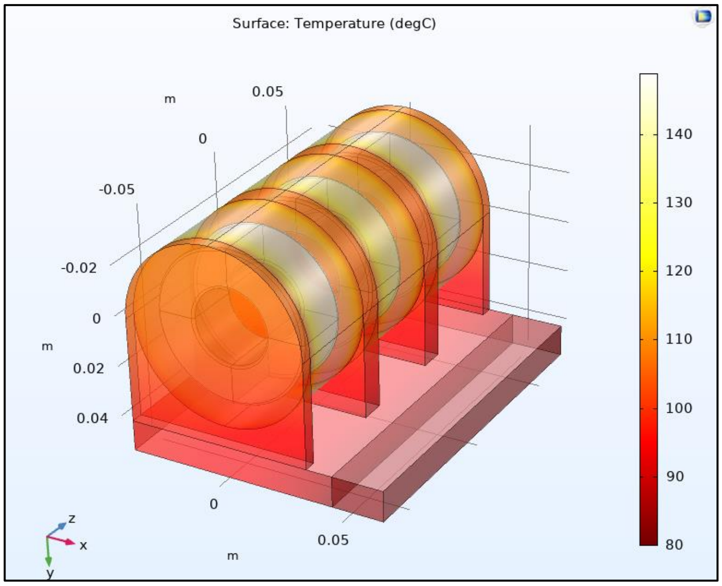
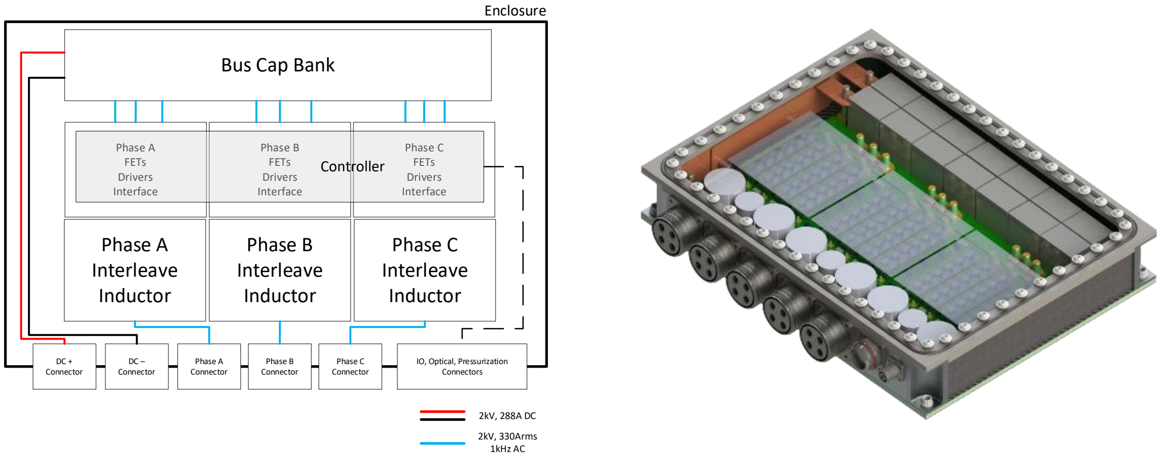


Fig. 7 Thermal analysis of the prototype magnetics and housing.

V. Mechanical and Thermal Integration

A critical component enabling the converter’s high power density is the enclosure design, preliminary renderings of which are shown in Fig. 8. In order to maintain a low mass design, carbon fiber is used for the structure as much as possible. An additional requirement placed on the design is the ability for the enclosure to withstand 40kft altitude operation. To meet the altitude requirement the enclosure is designed for hermetic sealing, enabling the electrical components to operate at their rated 1 atm conditions. This is advantageous because it avoids problems such as Paschen curve effects and placing a pressure differential on sealed capacitors.



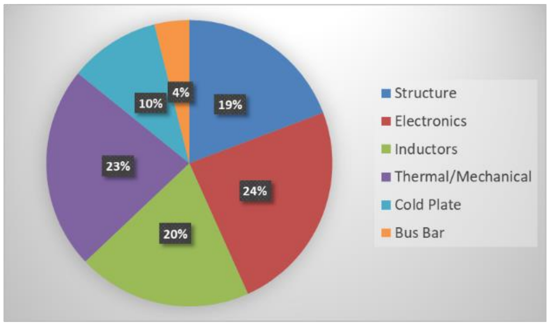
(a) (b)

Fig. 8 Drawings detailing enclosure design. Pictured are the (a) diagram of packaging and approximate component placement, and (b) CAD rendering of enclosure.

The enclosure is capable of withstanding the pressure differential at altitude while simultaneously being lightweight enough to meet mass requirements. The mass breakdown of the preliminary enclosure design and its contents is shown in Fig. 9. Although some subcomponents of this preliminary design exceed their mass targets, higher mass components are preferred for this initial revision for testing and robustness purposes. Future revisions of the converter design will take advantage of the results from this first iteration to intelligently reduce mass where possible. Additionally, a preliminary structural analysis was completed for this design, a portion of the results of which are shown in Fig. 10. The results conclude that the design is capable of sustaining the pressure differential developed at full altitude (40kft).

Component	Mass [kg]	Percent [%]
Structure	4.9	19
Electronics	6.1	24
Inductors	5.0	20
Thermal/Support	5.8	23
Cold Plate	2.6	10
Bus Bar	1.0	4
SUM	**25.4**	**100**

(a)



(b)

Fig. 9 Mass breakdown of preliminary converter design, (a) table and (b) pie chart.

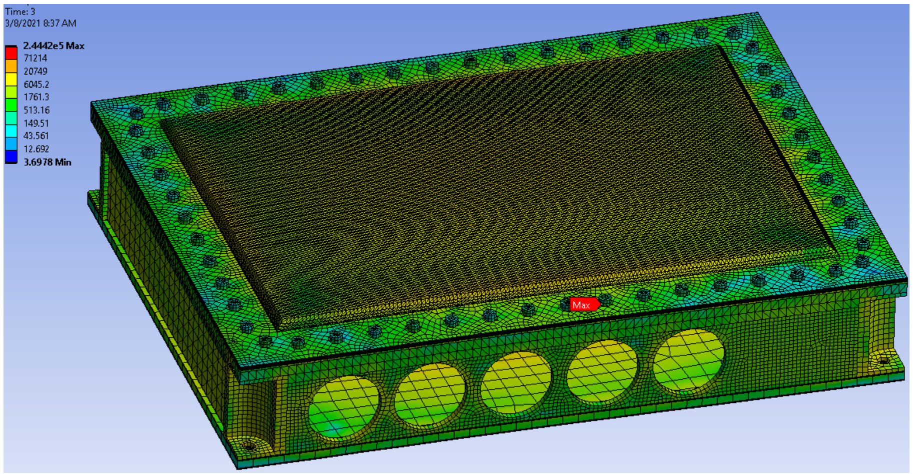


Fig. 10 Results from the enclosure structural analysis at altitude.

The thermal design takes advantage of a cold plate, on which the high-power electrical components are mounted. Since the converter will be incorporated into NEAT, facility cooling is utilized. Minimal internal convection is assumed due to the hermetically sealed design. A preliminary thermal analysis was completed, the results of which are shown in Fig. 11. This analysis shows all components have positive margin.

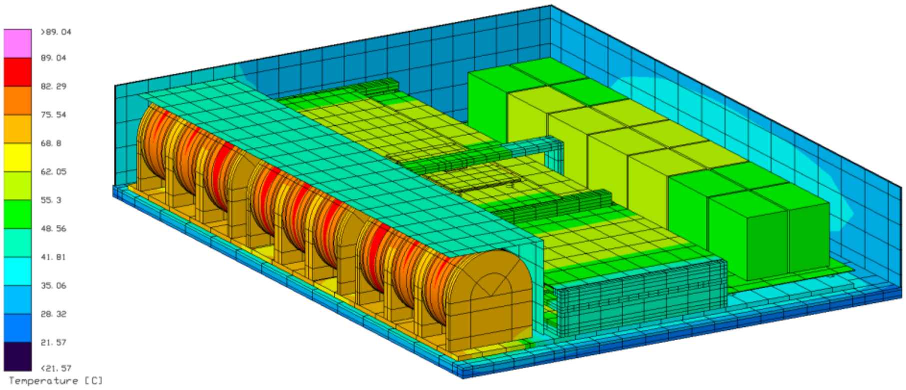


Fig. 11 Preliminary thermal analysis.

VI. Conclusion

This paper presents the progress made into the development of a 250kW high efficiency, flight weight, low harmonic distortion converter. An electrical power stage design was presented which meets its performance metrics through the use of a multilevel and interleaved topology. The interleave output filters were presented in detail, showing the optimized filter design and preliminary simulation and packaging results. The preliminary enclosure design was presented, showing the packaging efforts, as well as analysis of the structural integrity of the design. The preliminary thermal design was presented, showing analysis confirming positive margin throughout the design.

The benefits of this design are twofold. One, the converter will enhance the testing capabilities at the NEAT facility at NASA GRC-ATF. The multilevel power electronics architecture allows for 1kV bus operation using readily available 1.2kV SiC MOSFETs. Although not addressed in this paper, the avionics and controls for these converters are designed to simplify the coordination of multiple units to drive larger systems, such as the future 1.4MW HEMM.

The second major benefit of this design is the advancements made towards meeting the performance metrics required to close the 1.4MW design. For the hybrid electric aircraft to close at the system level, the converter should not exceed its allotted loss and mass targets. For converter/HEMM compatibility, the converter must produce a sufficiently clean waveform with which to drive the HEMM. This issue is discussed in greater detail in [5]. The electrical, magnetic, mechanical, and thermal design accomplishments presented in this paper align with these system-level goals. Future work will include adapting the converter design to accommodate the findings of [5], as well as progressing the design towards higher power testing.

Acknowledgments

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