Fault Tolerant Electric Machine Concept for Aircraft Propulsion with PM Rotor and DC Current Stator Dual-Stage Excitation

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***Abstract*—The development of electrically propelled aircraft requires electric machines that are fault-tolerant, compact, and efficient at multiple operating points. This paper proposes a novel machine topology combining a coreless Halbach PM array axial flux unit and a PM-less synchronous hybrid excited radial flux unit. Both units are coupled on the same shaft to take advantage of the opportunities available in the unique usage profile for aviation. The machines can be used simultaneously for the take off and altitude climbing stage or used individually during the cruising stage. The coreless axial flux PM (CAFPM) motor unit consists of two Halbach array PM rotors, two stators, and an integrated cooling plate to enable high efficiency at maximal current density. The stator DC-excited synchronous (SDCES) motor unit operates using AC 3-phase and DC stator windings employing concentrated non-overlapping toroidal coils with a reluctance consequent-pole rotor. Both units have two stator modules which are independently excited and controlled, allowing for continued propulsion under partial system deterioration. Combining both units takes advantage of the high specific power and efficiency of the CAFPM due to the Halbach array and cooling potential and the fault tolerance of the SDCES, with no potential for demagnetization and separate excitation.**

***Index Terms*—Aircraft propulsion, electric machine, hybrid excitation, permanent magnets, coreless machines, synchronous machines, modularization**

I. Introduction

In the US, the electrification of aircraft propulsion systems is supported by NASA [1] and the US Department of Energy through the ARPA-e ASCEND program [2] due to the potential for emissions mitigation and increased energy efficiency. Typical requirements for electric machines to replace conventional engines, like those discussed in Ansell *et al.*, include ultra-high efficiency, high specific power, and high fault-tolerance all at the multi-MW level, i.e., 1MW per stage at 3,000rpm [3]. Conversion to distributed electric propulsion, like the NASA NH3 concept [4] shown in Fig. 1, can, according to a recent review by Fard *et al.*, improve aerodynamics, increase propulsion efficiency, and allow for decoupled propeller operation [5].

One of the earliest designs for electric aircraft propulsion was an axial flux machine proposed by Eastham *et al.* for its potential for high specific power and high efficiency [6]. Recent examples of axial flux machines for electric aircraft propulsion with more than 25kW/kg and 90% efficiency include those proposed by Saeidabadi *et al.* [7] using cryogenic cooling and advanced materials and Halbach array PMs in Al-Qarni *et al.* [8]. Lawhorn *et al.* [9] previously proposed a coreless axial flux machine for electric aircraft propulsion which may be improved upon through recent findings by Chulaee *et al.* [10] on the mitigation of AC loss mechanisms to maximize electrical loading. It was also shown by the same research group that the integration of Halbach PM array magnetization can greatly amplify airgap flux density by as much as 30% compared to conventional PM arrangements at a similar volume, enabling even greater specific power [11]. A remaining concern with PM machines is the risk of demagnetization, which is reduced by the large reactance and low armature reaction of coreless configurations but nevertheless is still present.

A special machine that employs a robust reluctance-type rotor and uses in the stator both permanent magnets for excitation and a multi-phase AC winding with concentrated toroidal coils has been proposed and studied by the research group in Han *et al.* [12]. Evolved from this modular topology, a variety of machines employing either PM magnets or DC windings in the stator have been further proposed by the research group for traction applications in Badewa *et al.* [13, 14]. These machines benefit from outer rotor design, allowing for a larger airgap diameter and a smaller airgap yielding correspondingly increased average torque/power. In addition, there are no permanent magnets and herein no associated potential for demagnetization. Other examples of hybrid excited machines include those in Paulides *et al.* [15] and Mörée and Leijon [16], which intensify airgap flux density at a smaller machine volume and size than reluctance alternatives.

High current densities necessary for high specific power requires aggressive cooling through advanced materials and thermal management techniques. One example axial-radial flux machine in Zhentao *et al.* [17] maximizes electrical loading with embedded cooling channels and high-performance steel and PMs resistant to demagnetization up to 150°C. Previous examples of integrated designs for cooling range from direct in-slot liquid cooling proposed by Bobba *et al.* [18] to cryogenically cooled copper or aluminum Litz wire in Manolopoulos *et al.* [19].

In this paper, a novel concept is proposed to couple two

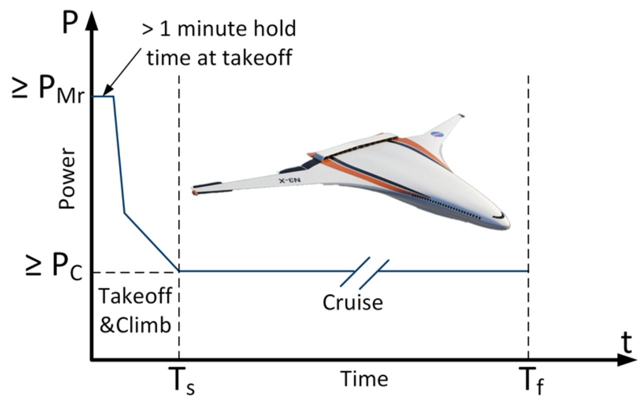

Fig. 1. Example flight profile for airplane operation varying with flight time and an example distributed propulsion blended wing NASA NH3 airplane concept [4]. Two main operating regions are identified: an initial short takeoff and climb at a typical twice to three times the rated power and a long cruising stage at rated power.

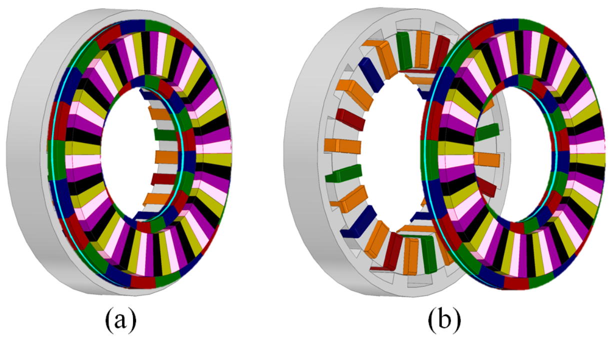

Fig. 2. The proposed dual-stage electric machine for electric aircraft propulsion in (a) compact stacked assembly and (b) exploded views. Both units are mechanically coupled on the same shaft for synchronous operation with one or both stages energized.

stages, i.e., electromagnetic units, on the same shaft to maximize fault tolerance and enable the potential for ultra-efficient and compact electric aircraft propulsion. The proposed concept is described in more detail in the rest of the paper, including rated performance estimated based on electromagnetic FEA methods [20] with the ANSYS Maxwell software [21], and a discussion of potential for fault tolerant operation.

II. Construction and Operation

The proposed design combines two special machine variations, as depicted in Fig. 2, introduced in previous papers by the research group: a coreless axial flux PM (CAFPM) synchronous unit with Halbach array orientation from Chulaee *et al.* [11] and a hybrid stator DC-excited synchronous (SDCES) motor unit with a reluctance outer rotor from Badewa *et al.* [14]. The CAFPM motor unit, with the exploded view from Fig. 3, is an axial flux machine with dual PM Halbach array rotors and coreless stators with integrated cooling. The SDCES motor unit, exploded in Fig. 4, is a radial flux machine with an AC 3-phase and DC stator windings of concentrated non-overlapping toroidal coils and a reluctance single-barrier consequent-pole rotor. Each electromagnetic stage has two modular sections: a set of power converters and stator windings that can operate independently from one another.

In total, multiple MW motors of the type proposed in this paper may be used for the propulsion of a blended wing aircraft as exemplified in Fig. 1. The propulsive power necessary for propelled aircraft flight can be described using an example operation profile, depicted in Fig. 1. Starting with initial take off and climb, maximum power, P_{Mr}, of twice to three times the rated power is needed. Upon reaching the target high altitude at T_s, power is ramped down to the cruising power, P_C, and held on for long term flight, until T_f.

The dual-stage electric machine operation takes advantage of this propulsive power profile by selectively activating the two electromagnetic units depending on the specific requirements. During the take-off stage, all sections are activated on both units to meet the short term very high rated power requirement. In cruise mode, only the CAFPM unit is energized to benefit of its power factor and high efficiency, depending on the manufacturing and cooling. Coupling of these two machines for dual-stage flight operation optimally exploits the specific power, efficiency, and high power factor of the CAFPM and the fault tolerance of the PM-less SDCES.

III. Rated Performance

Effective operation of the airplane flight profile depends on multiple conflicting objectives including ultra-high efficiency, high power density (kW/kg), high fault tolerance and reliability. The high ratio of short and long-term power rating between take-off and cruising flight operation led to the idea of a multi-stage machine focusing on multiple operating points. To ensure the capability of achieving rated performance, both motor units were simulated independently in ANSYS Maxwell FEA.

The stages, i. e. electromagnetic units, and unit modules can be used to make a comparative twin for maintaining normal operation. It should be noted that the combination of radial and axial flux stages may result in a minimum total axial length, when considering the relatively short ends of the concentrated coils and PM disc rotors. Nevertheless, other combinations, such as two radial stages, axially or concentrically stacked, may be employed depending on the preferred implementation of the mechanical assembly and transmission. The following subsections include descriptions of the factors impacting the performance of both stages/units and design selection.

A. Coreless Axial Flux PM (CAFPM) Motor Stage

The CAFPM motor unit uses a stator without ferromagnetic core to drive two PM Halbach array rotors. The Halbach array PM orientation maximizes airgap flux density on the side facing the stator by as much as 30% compared to traditional PMs at a similar volume, greatly increasing power density. The Halbach array's specific characteristics minimize the magnetic field on the side facing away from the airgap such that a

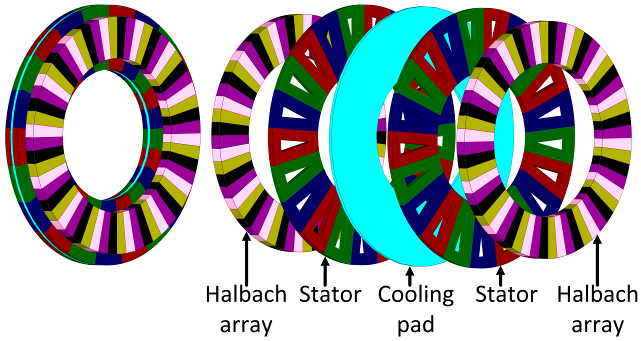

Fig. 3. Assembled and exploded view of the coreless axial flux PM (CAFPM) synchronous motor unit. The twin Halbach array PM rotors contribute a high airgap flux density, and the integrated cooling pad enables high current density.

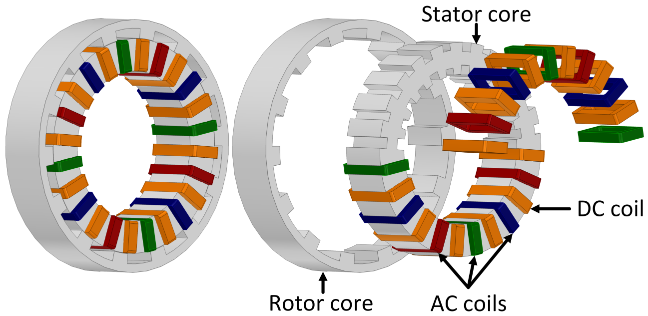

Fig. 4. Exploded view of the stator DC-excited synchronous (SDCES) motor unit. The toroidal windings operate with separate AC (red, green, blue) and DC excitation (orange) to drive the reluctance outer rotor.

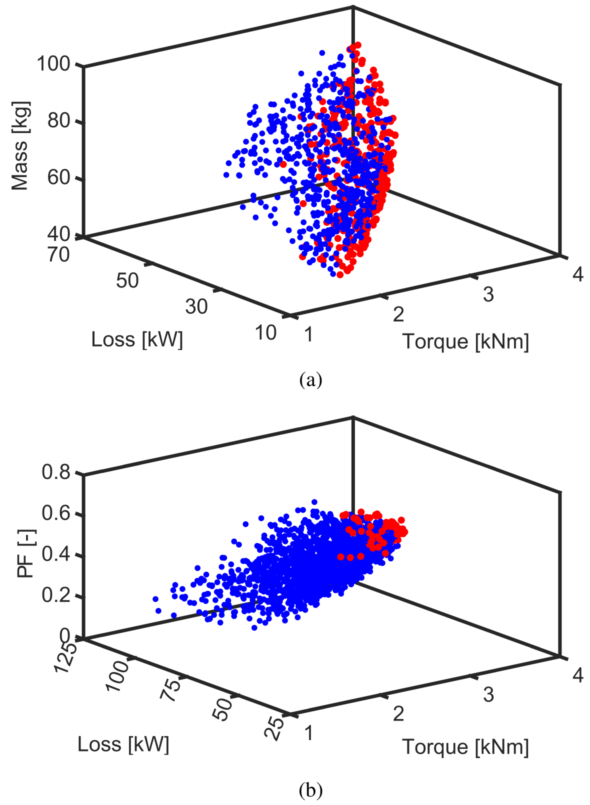

Fig. 5. Example Pareto fronts from ANSYS Maxwell simulation and optimization for (a) the CAFPM motor unit and (b) the SDCES motor unit.

ferromagnetic back iron is not required, and the rotor can be constructed much lighter by employing special composite materials for the support and mechanical transmission structure. Enhanced cooling methods, like the cryostat integrated plate suggested in Fig. 3, may be employed to maximize current density in the stator.

Losses in the CAFPM unit mainly originate from the copper and AC losses in the stator windings following the removal of the stator core and associated losses. The application of Litz wire can mitigate eddy current losses within the machine at high frequency. Similarly, conductor transposition can significantly reduce induced voltage and circulating currents due to coreless exposure to varying air gap flux. For the purpose of this analysis, only the losses in the conductor have been considered on the assumption that these methods were applied to minimize AC losses. Mitigation of these losses enables performance benefits for operation at high specific power and efficiency during the second stage of cruising flight.

A 3D ANSYS Maxwell parametric model was developed for the CAFPM and optimized considering four independent variables with three concurrent objectives of maximizing electromagnetic torque, and minimizing active mass, and total loss. An example Pareto front following the optimization is depicted in Fig. 5(a). A selected design for a power rating of 1.5MW at 5,000rpm has an approximate outer diameter of 500mm, power density of 75kW/liter, power factor close to unity, and electromagnetic efficiency between 96% and 98% depending on material characteristics, manufacturing, and cooling technologies.

B. Stator DC-Excited Synchronous (SDCES) Motor Stage

The SDCES synchronous motor unit uses DC and 3-phase AC supply in the stator to drive a reluctance outer rotor. The combination of DC excited coils and moving reluctance rotor produces a traveling field, which has due to a consequent pole effect, twice the polarity of the number of rotor protrusions. This excitation magnetic field interacts with the AC-winding armature reaction field to produce the synchronous electromagnetic torque. The application of DC excitation rather than PM magnets enables the potential for a high electrical loading without the risk of potential demagnetization.

Coupling for dual-stage operation takes advantage of the PM-less nature of the SDCES by both contributing power during takeoff and climb and providing backup operation during the cruising stage if the CAFPM unit experiences demagnetization or failure. The challenges of the SDCES motor unit include the resistive losses in the stator windings, which are dependent on the slot fill factor, and the mitigation of core losses in the stator. Typical power factor for this machine is higher than 0.70, necessitating larger form factor power electronic converters than the CAFPM modules. In principle, concentrated coils can be integrated into the stator windings

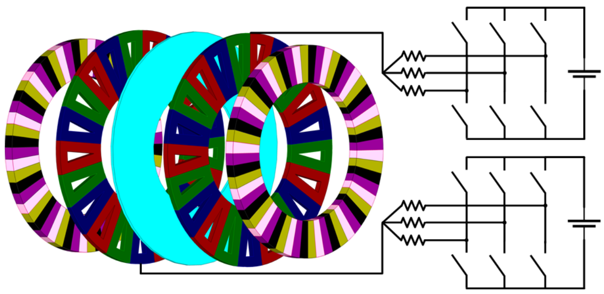

Fig. 6. Example CAFPM stage implementation with two indepedent, coreless stator modules, each with a PE converter.

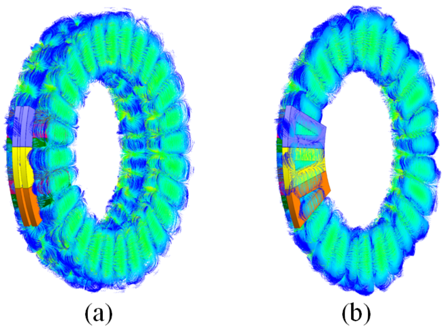

Fig. 7. Electromagnetic field plot for the CAFPM operating on load with (a) both modules active and (b) one rotor module inactivated due to demagnetization and the unit still operating at partial load.

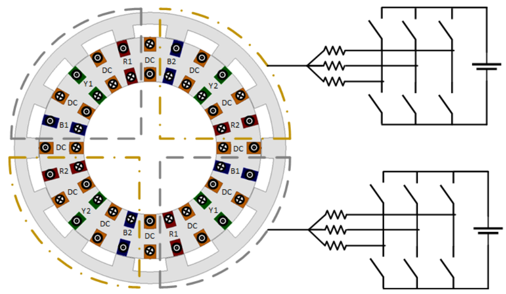

Fig. 8. Example SDCES stage employing two independently powered stator segments, represented by the dashed and dotted dashed lines.

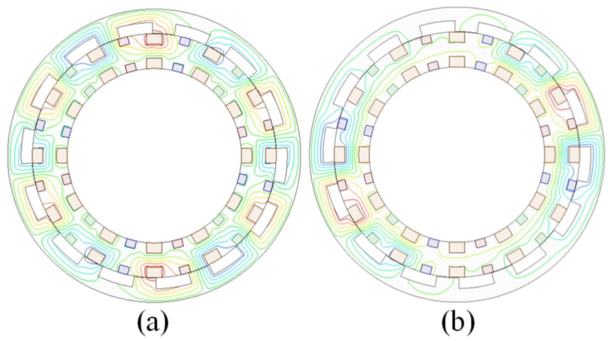

Fig. 9. Magnetic flux lines for the SDCES motor stage with (a) both operational stator modules and (b) one stator module assuming a fault condition. Separately connected PE converters enable fault tolerant partial operation.

with cooling systems such as cryostats to significantly improve performance.

A 2D ANSYS Maxwell model was developed for the SDCES and optimized using nine independent variables towards three concurrent objectives of maximizing electromagnetic torque, maximizing power factor, and minimizing total losses. An example Pareto front for this optimization is presented in Fig. 5(b). A selected design for a power rating of 1.5MW at 5,000rpm has an approximate outer diameter of 500mm, power density of 40kW/liter, power factor close to unity, and electromagnetic efficiency between 96% and 98% depending on material characteristics, manufacturing, and cooling technologies.

IV. Fault Tolerance

Fault tolerant capability is an absolute necessity for electric aircraft propulsion components and systems development to mitigate the risk of catastrophic system failure. Reliability is typically expected with technological maturity, provided there are no inherent limitations, such as, for example, PM demagnetization risk, or excessive number of electric terminal connections. Selective machine segmentation and modularity can also allow for partial operation under fault conditions, as discussed for example in Swanke *et al.* [22]. The proposed two-stage electric machine has been designed for modular construction and partial operation, requiring all four power converters and machine segments to fail before a unit is completely inoperable.

The CAFPM unit power electronic (PE) converters and system modularity are illustrated in Fig. 6 with a PE module dedicated to each stator winding. In the event of a module failure, the alternate stator can still be excited to facilitate partial machine operation. If demagnetization were to occur with one of the two Halbach array PM rotors, derated operation can still continue as the flux distribution, shown for in Fig. 7, has similar patterns with double and single rotors.

The SDCES unit converter modules, shown in Fig. 8, employ segmentation to group diagonally opposed quadrants as indicated by the dashed and dotted dashed lines. Example flux lines are depicted in Fig. 9 for operation with two PE modules and a single operational PE module respectively. The flux line distribution indicates continued operation even after partial system failure with a single PE module.

Further segmentation of the stator into four quadrants both electrically and magnetically can limit the magnetic flux paths and enhance modularity. One of the challenges involved with large system segmentation is ensuring synchronicity with all four converters driving both units in the same direction simultaneously. The two stages/units combined may employ two separate converters each, two of a larger form factor due to the lower power factor specific to the SDCES machine unit.

V. Conclusion

The novel dual-stage electric machine proposed in the paper innovatively combines two different special electromagnetic units that are mechanically coupled. A first stage/unit, which is always energized during aircraft normal operation, employs an axial flux coreless configuration with one stator between two PM Halbach array rotors providing major advantages in terms of ultra-high efficiency and specific power.

The second stage, which is energized only during aircraft take off and under emergency operation, employs a special synchronous machine with a stator containing separate concentrated coils for DC excitation and AC armature windings and an outer rotor with consequent-pole single-barrier reluctance configuration providing major advantages for fault tolerance and eliminating the risk of PM demagnetization. The absence of the magnets in the second stage also eliminates core losses during cruise operation, maximizing system efficiency.

The combination of axial and radial flux units both with concentrated coils and outer rotor(s) is advantageous in minimizing overall axial length and volume for given rated power. The proposed electromagnetic assembly is suitable for mechanical integration, and may benefit by the use of advanced materials, manufacturing technologies, and cooling systems. Further fault tolerance enhancements may be achieved by employing two separate modules of stator winding, controls, and power electronic converters for each of the two stages of the proposed electric machine.

Acknowledgment

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