Fault-Tolerant Topologies with Halbach Array and PM-Free Multi-Stage Multi-Module Electric Machines for Electric Aircraft Propulsion

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***Abstract*—Electrically propelled aircraft require electric machines which are compact and efficient at largely different operating conditions and with maximal fault tolerance. This paper studies the fault tolerance of machine topologies with two electromagnetic stages mechanically coupled on the same shaft. A coreless axial flux PM (CAFPM) motor stage consists of two Halbach array PM rotors and two stators with integrated cooling to enable high efficiency at high current density. A second stator DC-excited synchronous (SDCES) motor stage operates using AC 3-phase and DC stator windings employing concentrated non-overlapping toroidal coils with a reluctance consequent-pole rotor. The combination of two stages can take advantage of the ultra-efficient, lightweight, and fault-tolerant aspects for one electric machine with multiple independent sections or modules per stage. Systematic analysis is performed assuming modular construction and derated operation is simulated for both stages with finite element analysis (FEA). Markov chain reliability analysis is employed to illustrate system survivability, considering multiple combinations of single-point faults that enable cruising power operation for a large hydrogen-fueled blended wing aircraft with distributed electric propulsion.**

***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 (EAPS) 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 efficiency. Requirements for machines in distributed EAPS, like those reviewed in Wang *et al.* [3], depend on conflicting objectives including high specific power density (kW/kg) and high fault-tolerance all at the multi-MW level with ultra-high efficiency. Specialty machines are under development to meet objectives for more than 12kW/kg and 93% efficiency at a reference power of 250kW and 5,000rpm with reliable and fault-tolerant operation, which are typical of ARPA-e ASCEND supported projects [4], [5]. Previously proposed electric machines for EAPS include those with dual-rotor Halbach array PMs [6] and outer rotor machines with special windings [7].

Design for reliability at the device-level has led to developments such as demagnetization analysis for machines in aerospace applications [8] and studies on fault-tolerance for power electronic (PE) drives in electric propulsion [9]. Demagnetization of PMSM machines is a major concern for electric propulsion and can be caused by electromagnetic, thermal, and mechanical stress as reviewed in [10]. Typical faults associated with PE converters include loss of power switch modules due to inherent material failure, overheating, over-current, loss of DC capacitor, short-circuit and ground faults as documented in [11] and [12], necessitating device and phase redundancies. Fault-tolerant analysis for electric machines has been proposed prior in, for example, [13] and [14], to evaluate total failure probability with a combination of module single point faults with Markov chain analysis or fault trees respectively.

Recently, multiple electric machines of the YASA-type were mechanically coupled on the same shaft and used to achieve the record for the fastest all-electric aircraft [15]. Our extended research group has developed two machines, which when combined have the potential to meet the conflicting objectives for electric aviation propulsion. A previously proposed coreless axial flux machine for electric aircraft propulsion [16] was further developed in [17] with mitigation of AC loss mechanisms to maximize electrical loading. The airgap flux density can also be amplified greatly by as much as 30% with Halbach PM array magnetization compared to conventional arrangements at a similar volume [18]. A special machine with a robust reluctance-type rotor and a stator employing DC winding excitation and a multi-phase AC winding with concentrated toroidal coils was proposed in [19]. The toroidal DC windings can support high electrical loading, enabling high power density without the risk for demagnetization.

In this paper, two dual-stage multi-module machine configurations are proposed for EAPS combining high specific power of coreless axial flux topologies with Halbach arrays and a topology with only electromagnetic excitation in the stator. Multiple single-type faults are simulated for modules in both stages using experimentally validated 2D and 3D electromagnetic finite element analysis (FEA) [20]. A method for assessing system redundancy is developed, employing Markov chain analysis to configurations of a dual-stage electric machine with satisfactory cruising flight survivability.

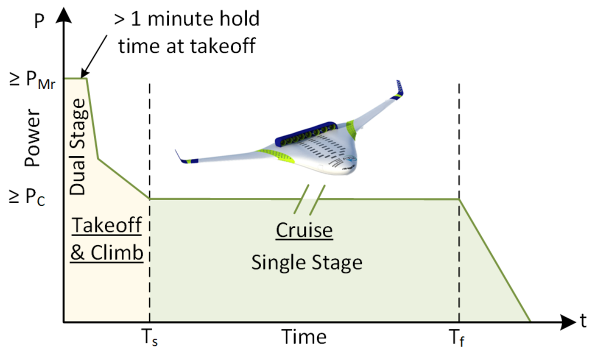

Fig. 1. Example distributed propulsion blended wing aircraft and flight profile with two main operating regions: a short takeoff and climb at approximately twice the rated power, which is required for the much longer cruising stage.

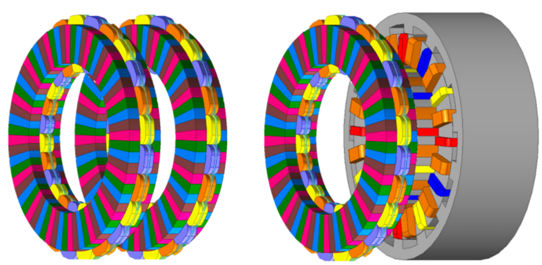

Fig. 2. The proposed electric machine unit concepts with two stages including (a) dual CAFPM stages and (b) combined SDCES and CAFPM stages. Both stages are mechanically coupled on the same shaft for synchronous operation.

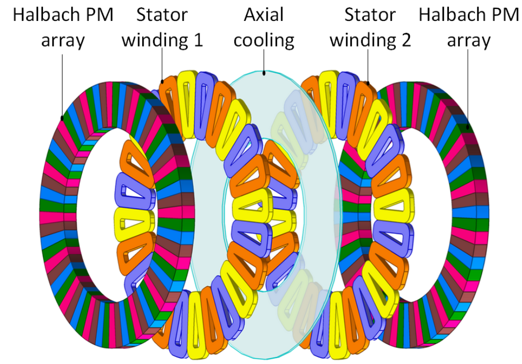

Fig. 3. Exploded view of the coreless axial flux permanent magnet (CAFPM) motor stage. The rotors have dual 90° Halbach PM arrays with each color signifying a different direction of magnetization.

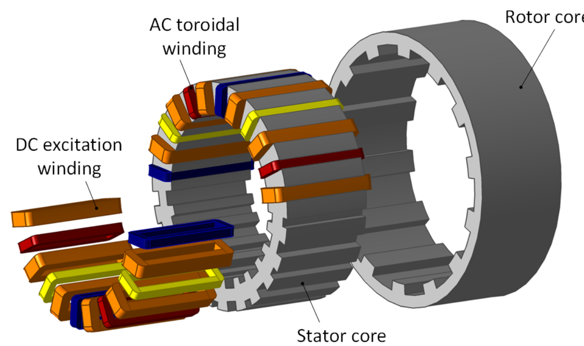

Fig. 4. Exploded view of the stator DC-excited synchronous (SDCES) motor stage. The toroidal coils operate with separate AC (red, yellow, blue) 3 phase and DC excitation (orange) windings to drive the reluctance outer rotor.

II. Dual Stage Combined Axial and Radial Electric Machines

The propulsive power required for a distributed aircraft has two unique flight stages, depicted in Fig. 1, which would benefit from a innovative dual-stage machine, such as that proposed and shown in Fig. 2, which can selectively operate for high efficiency and fault tolerance. The first stage consists of initial takeoff and climb to cruising altitude for which a maximum power, P_{Mr}, of approximately two times the rated power is required. The second stage occurs once the target cruising altitude is reached at T_s and power is reduced to half of the peak power or rated cruising power, P_C, until T_f is reached. In one design of the aircraft, like the one shown in Fig. 1, there are 8 motor units each with a peak power of 2MW for distributed blended wing electric propulsion. The proposed motor units each employ two machine stages coupled on the same shaft to operate the highest efficiency machine within both stages and the second machine to aid in initial takeoff.

The coreless axial flux PM (CAFPM) stage, depicted in Fig. 3, is a synchronous machine with two 90° Halbach array PM rotors developed prior in Vatani *et al.* [21] for maximum specific power and efficiency. A ferromagnetic back iron is not included as the Halbach array uniquely minimizes the magnetic field on the side facing away from the airgap. Additionally, the Halbach array maximizes airgap flux density by as much as 30% compared to a standard PM orientation at a comparable volume. The design proposed has a rated power of 1MW at 4,000rpm at near unity power factor with specific power density in excess of 30kW/kg and efficiency ranging from 96 to 99%, depending on the cooling system and mechanical configuration.

The hybrid stator DC-excited synchronous (SDCES) motor stage from Badewa *et al.* [19] operates using DC and 3-phase AC stator windings with concentrated non-overlapping toroidal coils for maximum fault tolerance. The SDCES motor stage is a radial flux machine with a reluctance single-barrier consequent- pole outer rotor as depicted in Fig. 4. By utilizing a field produced by DC excitation rather than PMs, the demagnetization risk at high electrical loading is eliminated. The design proposed has a rated power of 1MW at 4,000rpm with an outer diameter of 500mm and may be implemented with advanced cooling systems based on water and oil for power densities around 10kW/kg and typical efficiency of approximately 95%. Power factors range around and above 0.7 depending on the priority of objectives for design selection.

The explored configurations for a 2MW rated unit may be two back-to-back coreless axial flux stages with Halbach arrays or a combination of CAFPM and SDCES stages for increased survivability in environments prone to demagnetization, previously proposed by the authors in [22]. Assuming

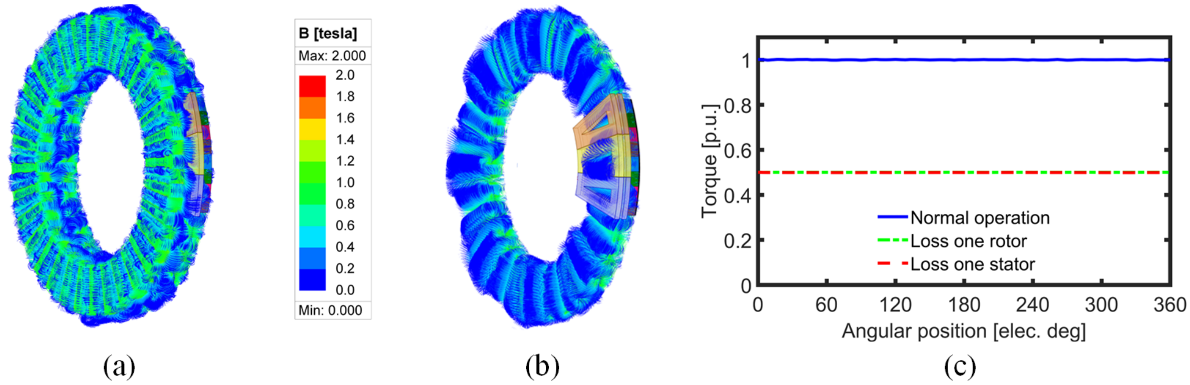

Fig. 5. Magnetic field plots for the CAFPM motor stage operating on load with rated current (a) both stator modules active and (b) one rotor demagnetized. (c) Normalized torque waveforms for normal and fault operation with an open-circuit stator or rotor demagnetization considering ideal sinewave current regulation.

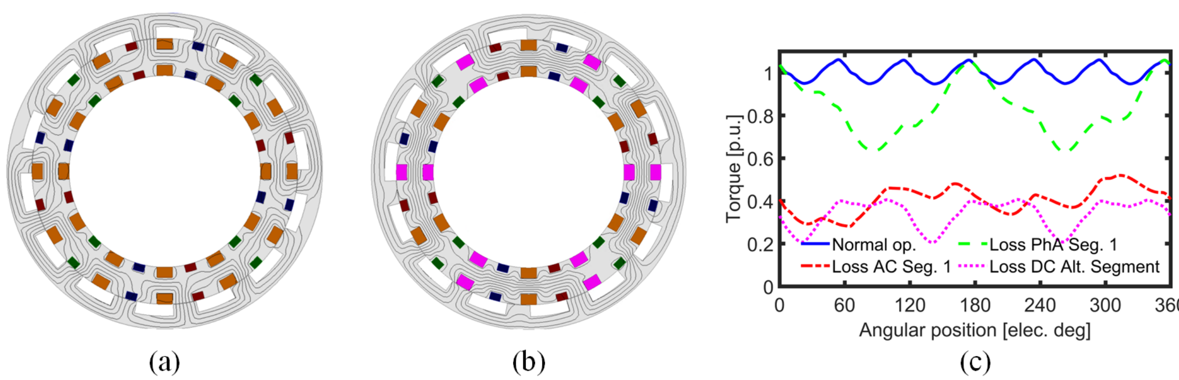

Fig. 6. Magnetic flux lines for the SDCES stage with (a) both fully operational stator modules and (b) with one of two DC excitation stator modules in an open-circuit fault condition. (c) Normalized torque waveforms with normal and fault operation with open-circuit faults for various stator modules.

suitable cooling, the combination of the two stages can take advantage of the ultra-efficient, lightweight, and fault-tolerant aspects of both for one electric machine unit with independent modules/sections.

III. Fault Analysis and Survivability Considerations

Fault tolerant capability is a major requirement for EAPS 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 may allow for partial operation under fault conditions. The proposed two-stage electric machine has been designed for modularity and partial operation, requiring all power converters and machine modules to fail before a unit is completely inoperable. Multiple studies were performed using ANSYS Maxwell 2D and 3D FEA [23] to evaluate performance considering potential single-type failures.

Modularity in the CAFPM stage can be implemented electrically with multiple sections of AC stator windings, each with independently excited and controlled drives. In the event of an open-circuit failure of one stator, the additional stators can be excited for partial operation. Dual channel operation for twice the rated current can also produce approximately rated torque due to direct proportionality between torque and electric or magnetic load. Example magnetic field plots with double and single rotor operation, following demagnetization, are shown in Fig. 5 (a) and (b). Both of these fault states were simulated using time domain finite element analysis with the normalized torque with respect to rotation shown in Fig.5(c). The resulting torque is approximately half in either case and with very low torque ripple assuming a pure sine wave three-phase excitation.

The SDCES stage can be sectioned diagonally to group opposite quadrants of AC coils or alternating DC coils with separate converter connections or converters. The magnetic fields for normal operation and the loss of half of the alternating DC coil excitation are illustrated in Fig. 6(a) and (b) with a significant change in flux density throughout the machine. Within the SDCES stage, less than half of the torque can be achieved in derated operation as depicted in Fig. 6(c). Dual channel operation with twice the rated current would produce approximately three quarters of the rated torque. Although fault tolerant in principle, the SDCES has substantial torque ripple during faults in the simulated modular configurations.

Two machine combinations were considered for systems-level reliability analysis following the results of single-point failure modularity simulations. The first, a combination of the

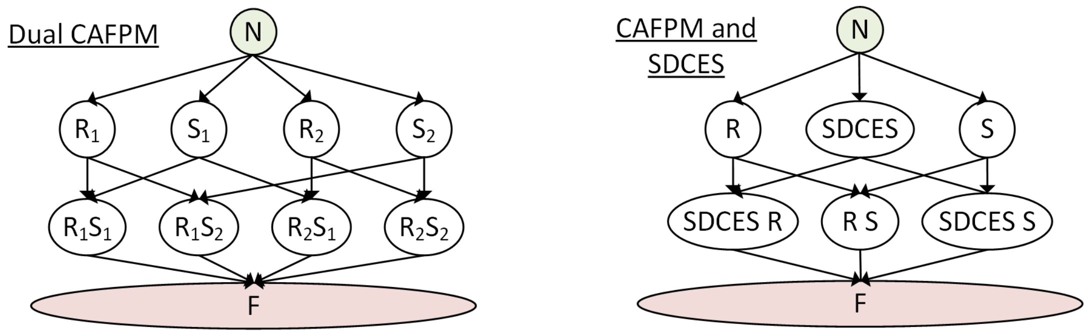

Fig. 7. Example Markov models for reliability considering machines with: the two back-to-back CAFPM stages and the combined CAFPM and SDCES stages (see also Fig. 2).

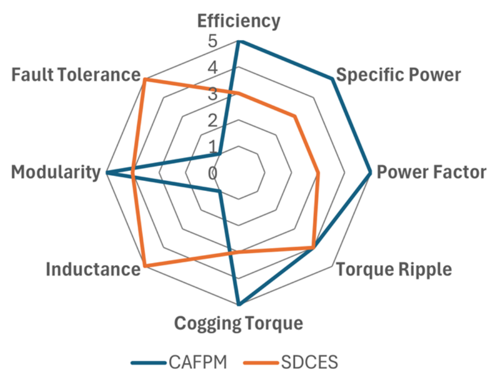

Fig. 8. Spider plot for the CAFPM and SDCES motor stage characteristics, illustrating the complementarity of their advantages.

CAFPM stages, would couple two back-to-back for maximum specific power. The Halbach array magnetization allows for continued operation partial load if there is partial demagnetization in a single rotor of both stages. To alleviate the concern of permanent Halbach array demagnetization as studied, for example, in in [24], the second proposed motor configuration combines CAFPM and SDCES stages for continuous operation of the CAFPM and of the SDCES during lift-off. The third in principle combination, two SDCES stages, is not studied mainly due to the low specific power and efficiency compared to the other configurations.

IV. Markov Chain Modeling and Discussions

Markov chain analysis can be used to determine the failure sensitivity of systems with the assumption that the likelihood of failure is independent of other systems. The transition between operating states is defined by a failure rate per 10^6 hours, λ, where the component failure probability is assumed to follow $F(t) = 1 - e^{-\lambda t}$. The likelihood of a single point failure as a result of multiple components can be assessed, for example, with parts count method (PCM), a technique described in MIL-HDBK-217F [25], a handbook on reliability prediction of electronic equipment. Failure rate for individual components vary within a range depending on the environment and are combined to approximate the composite failure rate.

The failed state, F, requires aggregate module failure such that cruising power cannot be met, which is assumed to be half of the peak power in this study. By extending this assumption to the electric motor, we can compare the probability of failure, defined as output power less than half of rated power from the proposed dual-stage machines. With our proposed modular motor and drive, the combination of electromagnetic stages requires at least a combination of two decoupled faults before catastrophic failure, with some failures minimally impacting expected performance.

Two example Markov models are shown in Fig. 7 for the dual CAFPM and CAFPM/SDCES machines assuming R is one CAFPM rotor, S is one CAFPM stator, SDCES is the SDCES machine. Each state has associated failure rates for that machine module and repair rates exist from each state to healthy. The dual CAFPM model assumes dual rotor and dual stator configuration in both stages such that operation can continue if a module is lost in each stage, or one stage has lost both modules. The CAFPM/SDCES model follows the FEA results such that the SDCES is implemented as backup if the CAFPM rotors are demagnetized or otherwise inoperable. Due to the increased capability to operate with segmentation and reduced terminal connections, the dual CAFPM model has less likelihood for failure and more survivable states unless in an environment prone to demagnetization.

A high-level comparison of both electromagnetic stages is depicted in Fig. 8. The CAFPM stage benefits from high efficiency, specific mass, and power factor with low torque ripple and cogging torque. The coreless winding of the CAFPM does result in an ultra-low phase inductance which can cause high ripple current and losses unless mitigated through solutions such as wide bandgap devices and special converters. The surface-mounted permanent magnets also have the potential for demagnetization, reducing machine fault tolerance depending on the environment. The SDCES stage has no concern about inductance or demagnetization with only electric excitation. Challenges of the SDCES stage, apart from the lower specific power, include the resistive losses in the stator windings, mitigation of core losses in the stator, and a lower power factor than the CAFPM, requiring a larger drive system. The SDCES stage does not have cogging torque with all windings at open-circuit but does have some with DC excitation acting as the equivalent magnets. While both machines are modular, the performance of the CAFPM stage, unless in an environment with a high probability of demagnetization, suggests better single-point fault-tolerant capability.

V. Conclusion

The proposed dual-stage multi-module electric machines are advantageous because they deliver both high efficiency and best-fault tolerance for the unique flight profile of aircraft propulsion. Both machines contain two electromagnetic stages: one with back-to-back coreless axial flux machines with dual Halbach array PM rotors and one with a coreless machine of the described type and radial flux machine with a reluctance rotor and AC and DC excitation in the stator. The combination addresses the conflicting objectives of ultra-high efficiency, specific power, and reliability with modular construction for fault-tolerant operation.

Derated operation was simulated using electromagnetic FEA for potential single-point faults to evaluate partial torque output considering stage modularity, assuming independent excitation and control of motor modules. Markov chain theory was applied to unit survivability with different combinations of electromagnetic stage modules. Cruising aircraft operation is possible in multiple partial failure states with machines combining the high specific power coreless axial flux stage with Halbach array rotors and the demagnetization-resistant radial flux stage with only stator electromagnetic excitation.

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