Fault Tolerant Dual Coreless Stator with Dual PM Rotor Axial Flux Synchronous Motors for Electric Aircraft Propulsion

Matin Vatani
SPARK Lab, Pigman Eng. College
University of Kentucky
Lexington, KY, USA
matin.vatani@uky.edu

Spencer Goode-Kulchar
SPARK Lab, Pigman Eng. College
University of Kentucky
Lexington, KY, USA
spencer.goode-kulchar@uky.edu

Dan M. Ionel
SPARK Lab, Pigman Eng. College
University of Kentucky
Lexington, KY, USA
dan.ionel@ieee.org

***Abstract*—This paper presents a novel coreless stator axial-flux permanent-magnet (CAFPM) machine with enhanced fault-tolerant capability, targeting high-reliability electric aircraft propulsion (EAP) applications. The proposed topology comprises a double-sided permanent-magnet rotor and two stators with different winding patterns, i.e., pole/coil combinations. This configuration enables electromagnetic and electrical decoupling between the stators, thereby significantly improving fault tolerance and effectively doubling fault resilience compared to conventional topologies. In addition to motor operation, the proposed machine can operate as a generator, providing two independent three-phase outputs from a single integrated structure, thereby further enhancing system flexibility and reliability. As a result, the proposed topology enables the functional integration of two separate electric machines into a single compact structure, leading to reduced overall volume, lower structural complexity, and increased specific power density. The analytical electromagnetic model is developed to describe the operating principles of the proposed concept, including torque production and winding interactions, and is supported by detailed three-dimensional finite element analysis (FEA) for accurate validation. The results demonstrate a substantial improvement in fault-tolerance capability, along with significant mitigation of permanent-magnet eddy-current losses resulting from the modified field distribution and reduced harmonic interactions. These characteristics highlight the strong potential of the proposed CAFPM topology for high-performance, lightweight, and reliable electric propulsion.**

***Index Terms*—Aircraft propulsion, axial flux, coreless machines, decoupled stators, eddy current, electric machine, fault-tolerant, modularization, permanent magnet loss.**

I. Introduction

Axial-flux permanent magnet machines are capable of producing high torque in a compact form factor, offering the possibility of greater specific power density (kW/kg) than traditional radial-flux machines [1, 2]. Although they are not as widely deployed as radial-flux designs, this combination of high torque and a smaller size makes AFPM machines strong candidates for electric aircraft propulsion. Illustrative developments include AFPM motor integrated with a magnetic gear [3] and YASA-type AFPM motor powering Rolls-Royce's Spirit of Innovation [4].

A particular subclass, the coreless AFPM (CAFPM) machine, removes all ferromagnetic material from the stator. This configuration shift enables even higher specific power density and improved efficiency [5]. Without a stator core, several benefits emerge: core losses are eliminated, higher operating frequencies and speeds become feasible, and the resulting increase in allowable speed can reduce overall motor dimensions [6]. Thermal management also becomes more effective because the stator windings are directly accessible for forced cooling, allowing higher current loading and further reducing machine size. In addition, removing the core simplifies fabrication by eliminating lamination processes and reducing the need for magnet segmentation [7].

Coreless stator AFPM machines have been proposed and studied for aerospace applications due to their potential for achieving high specific power density. Examples can be found in studies conducted more than two decades ago on stratospheric unmanned solar-powered aircraft [8], as well as in more recent NASA research [9]. Another example includes commercial products developed by LaunchPoint Electric Propulsion Solutions, which are used as alternators in drone systems [10, 11].

In applications requiring high reliability, such as electric aircraft propulsion, multiple approaches can be employed to enhance fault tolerance, including the use of multiple independent modules [12, 13]. This aspect requires particular attention in coreless stator machines, as these configurations typically exhibit lower phase inductance and, consequently, higher phase currents under short-circuit fault conditions [14]. The pancake-shaped structure of axial flux machines enables the stacking of multiple units, rather than relying on a single machine, as demonstrated in [15].

This paper introduces a novel approach to enhance the fault-tolerance capability of CAFPM machines by developing independent stator modules. The progression from a base CAFPM topology to a multi-stator, multi-stage motor configuration is presented, along with the associated challenges of this new topology. A new method is proposed to decouple the stator modules, resulting in a twofold improvement in fault tolerance. The underlying theory of the proposed method is described, and its effectiveness is validated through 3D FEA.

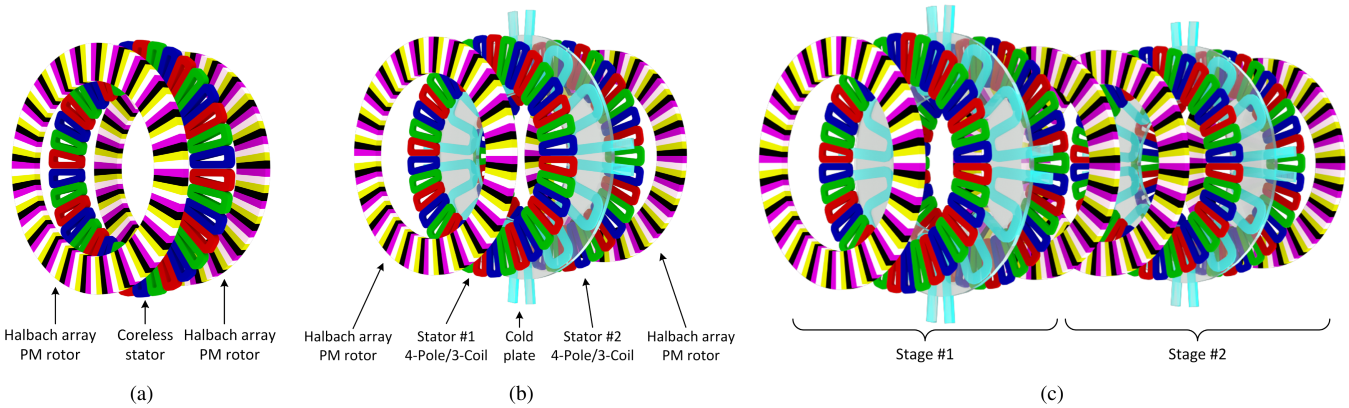

Figure 1. Exploded views of coreless-stator AFPM motors with double-sided Halbach-array PM rotors in a 4-pole/3-coil configuration, showing (a) the fundamental design, (b) a two-layer coreless stator with direct cooling, and (c) a dual-stage architecture with a two-layer stator and one cold plate per stage.

This research is a continuation of prior works conducted under NASA initiatives to enhance the performance of large commercial aircraft through a broad academic–industrial collaborative framework. The effort focuses on developing advanced technologies for a regional blended-wing-body aircraft concept featuring distributed hybrid hydrogen-electric propulsion [16]. The primary specifications for the electric motors considered in this study are presented in [17, 18].

II. Coreless AFPM Motor Topology for Electric Aircraft Propulsion

This section introduces the base topology of the coreless stator AFPM machine for electric aircraft propulsion (EAP), followed by a topology with enhanced fault tolerance, which is a critical design criterion for this application. The baseline configuration, shown in Fig. 1(a), is a double-sided rotor, coreless-stator AFPM machine, in which the rotor employs a Halbach array with four permanent magnets per pole-pair wavelength, and the stator adopts a three-coil configuration paired with a four-pole rotor. An immersed-cooling strategy can be applied to this topology, in which the coreless stator is directly submerged in a liquid-cooling enclosure.

While this approach can provide highly effective thermal management due to direct contact between the coolant and the windings, it introduces two major challenges. The presence of the cooling enclosure significantly increases the magnet-to-magnet (M2M) gap length, leading to an exponential reduction in the effective air-gap flux density. This reduction necessitates higher current loading to maintain the required torque, which in turn increases copper losses and demands a larger cooling enclosure. Additionally, because windings from different phases are simultaneously exposed to the coolant, the likelihood of inter-phase short circuits is substantially increased, posing serious reliability and fault-tolerance concerns.

To improve reliability and enhance motor performance, the topology shown in Fig. 1(b) was proposed. In this configuration, the stator is axially divided into two electrically isolated stators, which can be driven by either a single inverter or two independent inverters to increase redundancy and fault tolerance. A cold plate with a serpentine flow channel is designed and embedded between the two stators. To minimize the cold-plate volume and improve overall motor efficiency, liquid hydrogen at cryogenic temperatures is used as the coolant. This topology not only addresses the limitations of the baseline configuration but also significantly enhances fault-tolerant capability and overall motor performance.

The final configuration is a two-stage motor topology, shown in Fig. 1(c), which employs two identical CAFPM machines based on the topology in Fig. 1(b). The two stages are magnetically and electrically isolated and are mechanically coupled through a common shaft. This configuration further enhances redundancy and fault tolerance, as the motor can continue to operate at exactly half of the rated load in the event of a fault in one stage.

III. Typical Pole/Coil Combinations in Coreless Stator AFPM Machines

In the topology shown in Fig. 1(b), although the two stators can be electrically isolated by supplying them through independent inverters, magnetic coupling between the stators still exists. Consequently, a fault occurring in one stator can adversely affect the operation of the other stator. Ideally, the two stators should also be magnetically isolated so that, in the presence of a fault in one stator, the other stator can continue operating independently, allowing the motor to deliver half of the rated torque. This capability would effectively double the system's fault tolerance, which is particularly advantageous when combined with two-stage motor topologies.

The major contribution of this paper is the proposal of a method to mitigate this magnetic coupling. To this end, this section introduces a new approach that employs different winding patterns, i.e., pole/coil (slot-equivalent) combinations for the two stators. It is demonstrated that, by appropriately selecting these pole/coil combinations, the mutual magnetic coupling between the stators can be reduced to approximately

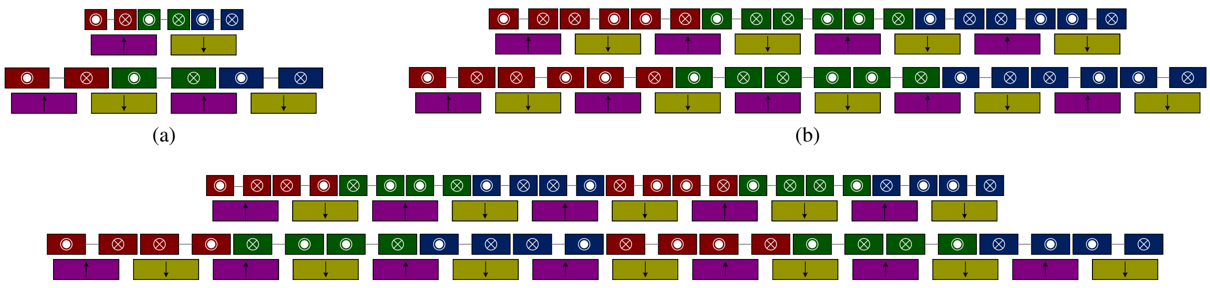

Figure 2. Pole/coil combinations in CAFPM machines: (a) 3-coil with 2- and 4-pole, (b) 9-coil with 8- and 10-pole, and (c) 12-coil with 10- and 14-pole.

Table I
TYPICAL POLE/COIL COMBINATIONS IN CORELESS AFPM MACHINES.

Poles (P)	Coils (N_c)	Coil Grp. No.	Phase shift (elec. deg.)	Periodicity frac. coeff. (K_M)
2	3	1	120°	$\overline{P}/2$
4	3	1	240°	$\overline{P}/4$
10	12	2	120°	$\overline{P}/10$
14	12	2	240°	$\overline{P}/14$
8	9	3	120°	$\overline{P}/8$
10	9	3	240°	$\overline{P}/10$

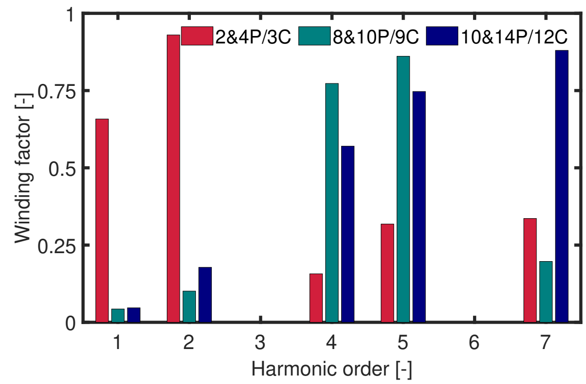

Figure 3. Winding factor harmonics of typical pole/coil combinations in coreless-stator AFPM machines, with pure sinusoidal current injection.

zero. This section presents the underlying electromagnetic theory by analyzing the winding harmonic content for various pole/coil combinations in CAFPM machines. The corresponding topology and simulation results are presented in the following section.

The typical pole/coil combinations employed in CAFPM machines, represented using an equivalent 2-D modeling, are illustrated in Fig. 2, and their corresponding electromagnetic specifications are summarized in Table I. The harmonic magnetic field produced by the stator windings can be characterized through the calculation of the winding factor. In CAFPM machines, the winding factor can be calculated as [19]:

$$K_W = K_T \cdot K_p \cdot K_g, \tag{1}$$

where K_T is the distribution factor, K_p is the pitch factor, and K_g is the coil group factor, which can be calculated as:

$$K_T = \frac{2N_c}{K\pi\nu} \sin\left(\frac{K\pi\nu}{2N_c}\right), \tag{2}$$

$$K_p = \sin\left(\frac{\nu\pi\,(2-K)}{2N_c}\right), \tag{3}$$

where N_c denotes the number of coils within the smallest circumferential periodicity, as listed in Table I, K is the ratio of the coil pitch to the coil width, and ν is the harmonic order.

The coil group factor depends on the number of coils per phase per periodicity. For the three-coil configuration, the coil group factor is unity, for the 12-coil configuration, it is calculated as:

$$K_g^{N_c=12} = \sin\left(\frac{\pi\nu}{12}\right), \tag{4}$$

and for the nine-coil configuration, it is given by:

$$K_g^{N_c=9} = \frac{1}{3}\left(2\cos\left(\frac{2\pi\nu}{9}\right) - 1\right). \tag{5}$$

IV. FAULT TOLERANT CORELESS AFPM MACHINE WITH DUAL DOUBLE-LAYER STATORS

The fundamental harmonic corresponds to the 1st order for the 2/3 combination, the 2nd order for 4/3, the 5th order for 10/12, the 7th order for 14/12, the 4th order for 8/9, and the 5th order for 10/9. Therefore, by selecting stators with different fundamental harmonic orders, the magnetic coupling between the stators can be significantly reduced. Examples of the winding harmonic spectra for all considered combinations at a representative value of $K = 0.6$ are shown in Fig. 3.

The CAFPM machine introduced in Section II employs 48 poles; consequently, the pole/coil combinations must be selected to be compatible with this pole count while minimizing cross magnetic coupling between the stators. Based on this criterion, the 4/3 and 8/9 pole/coil combinations were selected. The resulting topology is illustrated in Fig. 4. It should be noted that the torque contributions of the two stators differ, as the 4/3 configuration produces higher torque due to its higher winding factor. If identical back-EMF contributions from both

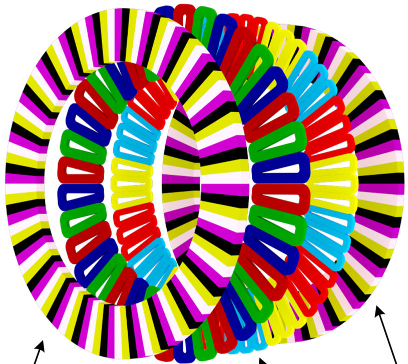

Figure 4. Dual-stator coreless AFPM motor, where one stator employs a 4-pole/3-coil configuration, and the other employs an 8-pole/9-coil configuration. The rotor features identical 48-pole Halbach arrays on both sides.

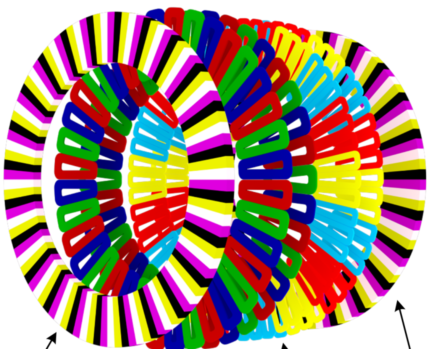

Figure 5. Dual-stator coreless AFPM machine with stators employing 4-pole/3-coil and 8-pole/9-coil configurations, both incorporating the proposed two-layer offset windings, while the rotor remains unchanged.

stators are desired, the number of turns of the 8/9 stator must be adjusted. The electromagnetic torque can be obtained by summing the torque contributions by each stator, leading to:

$$T = K_M N_c N_t I_p \left(\frac{K_{w1,1} + K_{w1,2}}{4} \right) K_D D_o^2 (1 - \lambda) B_1, \quad (6)$$

where K_M is the periodicity coefficient determined by the pole/coil configuration (see Table I); P and N_c are the pole and coil numbers, respectively; $\overline{P}$ is the total number of poles over 360° mechanical; N_t is the number of turns per coil; I_p is the peak phase current; $K_{w1,1}$ and $K_{w1,2}$ are the fundamental winding factors for the 4/3 and 8/9 combinations, respectively; K_D accounts for the effective diameter; D_o is the outer diameter; λ is the inner-to-outer diameter ratio; and B_1 is the fundamental flux density. As indicated by (6), the torque exhibits a quadratic dependence on the outer diameter. It is worth noting that the winding factor, K_w, inherently includes a diameter-dependent term, as discussed in [19].

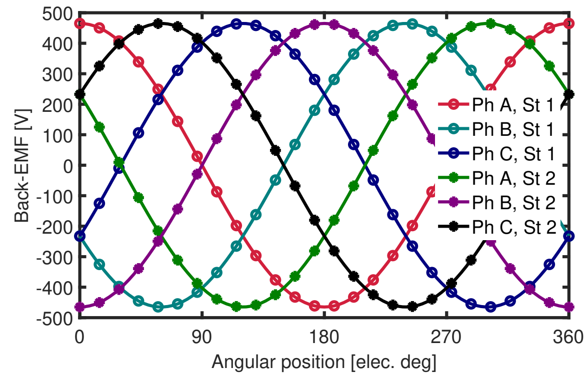

Figure 6. Per-phase back-EMF of the proposed motor topology, with the number of turns adjusted to achieve an identical voltage level.

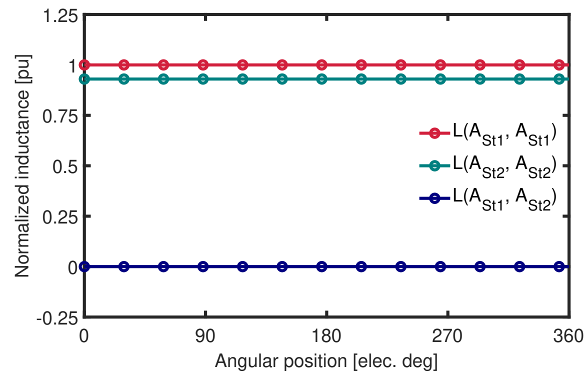

Figure 7. Self-inductance of each stator and the mutual inductance between the two stators, normalized to the self-inductance of stator #1.

As shown in Fig. 3, a non-negligible fifth-harmonic component is still present for the selected pole/coil combinations, which creates magnetic coupling between the stators. For the 8/9 pole/coil combination, the fifth harmonic can be effectively suppressed by adopting a two-layer offset winding configuration. In this arrangement, the amplitude of the winding factor for the offset two-layer stator is modified by a factor of [20]:

$$K_\theta = \left| \cos\left(\frac{\theta_0 \nu}{P} \right) \right|, \quad (7)$$

where θ_0 is the offset angle in electrical degrees, ν is the harmonic order, and P is the pole number within the smallest circumferential periodicity, as listed in Table I. To eliminate the fifth harmonic associated with the 8/9 combination, the two winding layers must be offset by 144 electrical degrees, which corresponds to 6 mechanical degrees.

The suppression of this non-torque-producing harmonic not only reduces magnetic coupling between the stators but also mitigates eddy-current losses induced in the PMs. To further reduce magnet eddy-current losses caused by the first harmonic of the 4/3 pole/coil combination, a two-layer offset winding was also employed for this stator. In this case, the second layer is offset by 360 electrical degrees, corresponding to 7.5 mechanical degrees.

The final CAFPM topology, featuring reduced cross-coupling between the stators and mitigated magnet eddy-current losses, is illustrated in Fig. 5. The induced back-EMF of the proposed motor topology is shown in Fig. 6, where the number of conductors per phase has been adjusted such that both stators achieve identical voltage levels. The self and mutual inductances of the stators, normalized with respect to the self-inductance of the 4/3 stator, are presented in Fig. 7. It can be observed that the mutual inductance between stator #1 (4/3) and stator #2 (8/9) is approximately zero, indicating that the two stators are effectively decoupled.

V. Conclusion

This paper reviewed the conventional CAFPM motor topology for electric aircraft propulsion, which employs a double-sided rotor and two identical stators, primarily to accommodate an interleaved cooling structure. Although this conventional configuration enhances reliability by supplying the stators through two independent inverters, magnetic coupling between the stators still remains. To address this challenge, a new CAFPM topology was proposed that preserves the dual-stator concept while employing stators with different pole/coil combinations. In addition, a two-layer offset winding configuration was implemented for both stators to further suppress magnetic coupling and substantially reduce PM eddy-current losses. The electromagnetic basis of the proposed approach was established through analytical winding-factor formulations and harmonic analyses of typical pole/coil combinations in CAFPM machines. The effectiveness of the proposed topology was validated through 3D FEA, which showed the mutual inductance between the two stators to be approximately zero, confirming effective magnetic decoupling.

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