

Inner-Rotor Thermal Coupling as a Design Constraint in Multistage Axial-Flux Permanent-Magnet Machines with Directly Cooled Stators: A Research Framework

Istiack Mohammad

Founder and Chief Technology Officer, Orbitronix Technologies, United Kingdom

Correspondence: contact@orbitronix.tech

Working paper · October 2026 · Preprint, not peer reviewed

Abstract

Electric propulsion systems for vertical take-off aircraft and podded marine drives must deliver high torque within a tightly constrained outer diameter. Axial-flux permanent-magnet machines meet this requirement well, and stacking several stages on a common shaft is the established way to raise torque without increasing diameter. Direct liquid cooling of the stator windings has matured in parallel and now permits current densities well beyond those of jacket-cooled designs. However, studies that optimise the number of stages have so far treated the problem electromagnetically, and the thermal consequences of stacking have been explicitly left outside their scope. This working paper identifies a component that exists only in stacked machines: the inner rotor. It has no coolant path of its own and is bounded on both sides by stators that, although cooled, operate at elevated temperature. The paper describes the resulting heat-transfer problem, outlines an analytical framework that yields a size-independent screening criterion relating permissible magnet loss to gap heat transfer and stator temperature, and states a hypothesis on how inner-rotor thermal coupling alters the optimum stage count. A validation programme based on three-dimensional finite-element analysis and a two-stage prototype is proposed.

Keywords: axial-flux machine, multistage, direct oil cooling, permanent-magnet temperature, thermal management, electric propulsion

1. Introduction

Axial-flux permanent-magnet (AFPM) machines offer higher torque and power per unit mass than comparable radial-flux machines in many applications. Their disc geometry accommodates high pole numbers and short end windings, which suits direct-drive operation [1], [2]. These properties have made AFPM machines a leading candidate for electric propulsion, where every kilogram of motor mass and every millimetre of frontal diameter carries a system-level penalty.

When the required torque exceeds what a single disc pair can deliver within the available diameter, designers stack stages axially: several stators and rotors share one shaft, and their torques add. Multistage, or multi-disc, AFPM machines have been proposed for ship propulsion [3], aeronautical applications [4] and direct-drive wind generation [5], [6]. In each case the motivation is the same. Torque scales strongly with diameter, so when diameter is fixed, axial stacking is the remaining design freedom.

Thermal management has advanced in parallel. Segmented-stator machines of the yokeless and segmented armature type allow coolant to flow directly over the windings [7]. Experimentally validated thermo-fluid models now predict the temperature and flow distribution in such oil-cooled stators [8], and constructions that place cooling channels between coil sides or integrate heat-conducting elements into the coils have raised permissible current density considerably [9], [10]. As a result, the winding is no longer necessarily the component that limits continuous rating.

This working paper argues that combining these two developments, axial stacking and direct stator cooling, creates a thermal constraint that neither line of research has addressed. It describes the problem physically, outlines the analytical framework developed to study it, and states a testable hypothesis together with a validation plan.

2. Background and Research Gap

The most complete published study of stage count is the optimisation of ironless multistage AFPM generators for offshore wind by Zhang et al. [6]. They compared single-, two- and three-stage machines across a range of outer diameters and found that additional stages raise torque density when diameter is constrained, at the cost of efficiency. Their study, however, states explicitly that structural and thermal analyses were outside its scope, and that providing a proper cooling arrangement could affect the conclusions. Stage count has therefore been optimised without the thermal side of the problem.

Recent work on multistage and modular machines for aircraft and marine propulsion has developed fast analytical and surrogate-based design tools for coreless machines with Halbach-array rotors [11], [12]. Configurations that combine Halbach arrays on the outer rotors with conventional magnet arrays on the middle rotors have also been reported [13]. These contributions are electromagnetic in focus. The thermal studies of directly cooled stators [8], [9], [10], for their part, examine a single stator in isolation.

What is missing is a treatment of the stacked machine as a coupled thermal system, in which the cooling of the stators and the temperature of the rotors interact through the number of stages. This paper addresses that gap.

3. Physical Description of the Problem

Consider a machine with N stators and $N + 1$ rotors on a common shaft. In the arrangement studied here, every stator is cooled directly by a dielectric fluid in contact with the windings. The two end rotors carry Halbach arrays oriented towards the adjacent stator, which removes the need for rotor back iron. The inner rotors carry axially magnetised magnets, so that flux passes through them from one stator to the next.

The two kinds of rotor differ sharply in how they lose heat. An end rotor faces a stator on one side and the end cover of the housing on the other. It can therefore reject heat to the housing as well as across its air gap. An inner rotor has no such option. Both of its faces look onto stators, so its only thermal paths are across two narrow air gaps to stator surfaces, and radially through its carrier to the shaft and on to the bearings.

The stators bounding an inner rotor are cooled, but they are not cold. Their surfaces run at a temperature set by the winding losses and the effectiveness of the coolant, which is typically well above that of the coolant itself. An inner rotor therefore cannot run cooler than its neighbouring stators unless heat is removed through the shaft path. Its own losses, principally eddy currents induced in the magnets by slot and winding harmonics, raise it further above that level. A single-stage machine contains no inner rotor, so this coupling appears only once stages are stacked.

This has a direct design consequence. If the permissible temperature of the magnets is lower than that of the winding insulation, the inner rotors, rather than the windings, may set the continuous rating of a stacked machine. Improving stator cooling then has two effects. It lowers winding temperature directly, and it lowers the boundary temperature of the inner rotors, so the stator and rotor thermal problems cannot be designed separately.

4. Proposed Analytical Framework

To study this problem at the concept stage, a lumped steady-state thermal model of the rotor stack has been developed and coupled to an analytical model of the directly cooled stators. The model resolves the end rotors and inner rotors separately. It includes heat transfer across each air gap, conduction through the rotor carriers to the shaft and bearings, and the dependence of winding loss on temperature, which is solved self-consistently.

From this model a closed-form screening criterion has been derived. It relates the permissible magnet loss density on an inner rotor to the gap heat transfer, the air-gap length and the margin between the stator temperature and the allowable magnet temperature. The criterion does not depend on machine size, so it can be applied early in design, before the geometry is fixed. It also gives finite-element studies a clear target: the magnet loss that the rotor thermal design can tolerate.

The magnitude of the magnet eddy loss itself depends on the winding harmonics, the magnet segmentation and the operating frequency. It requires three-dimensional electromagnetic analysis. In the present framework it is therefore treated as an explicit unknown parameter rather than assumed, and conclusions are expressed as a function of it.

The framework has been applied to a stage-count study for a representative direct-drive propulsion requirement, with the electromagnetic design held consistent across stage counts so that the comparison isolates the effect of stacking. Detailed results will be reported in a subsequent full paper once the model has been verified against published experimental data.

5. Hypothesis

Under an outer-diameter constraint, adding stages is necessary to meet the torque requirement, but each stage beyond the minimum adds active and structural mass. In addition, every stacked design contains inner rotors that are thermally bounded by hot stators. The hypothesis of this work is therefore as follows.

Inner-rotor thermal coupling introduces a permanent-magnet temperature limit that is absent from single-stage machines. This limit reduces the allowable current density and torque density of stacked designs by an amount governed by the inner-rotor magnet loss density, the air-gap heat transfer and the thermal conductance of the rotor carrier. Rotor thermal management can partly recover this penalty and so changes the optimum design.

This hypothesis is testable. It predicts that the binding constraint moves from the winding to the inner-rotor magnets as stages are added. It also predicts that the size of the penalty correlates with the magnet loss density and with the carrier conductance in the way described by the screening criterion.

6. Planned Validation

The research is organised as a progression of increasing fidelity.

First, the analytical model will be verified against published experimental and numerical data from other groups, covering air-gap field and torque, winding temperature under direct cooling, and measured heat transfer coefficients in oil-cooled stators. The errors will be reported.

Second, three-dimensional electromagnetic finite-element analysis will establish the eddy loss in the inner-rotor magnets under realistic slot and winding harmonics, including the effect of magnet segmentation.

Third, coupled electromagnetic and thermal analysis, together with a detailed treatment of heat transfer in the rotating air gap, will test the screening criterion and the predicted shift of the binding constraint.

Finally, a two-stage prototype will be built and tested with telemetry of rotor temperature, so that the analytical model, the finite-element predictions and the measurements can be compared directly. Surrogate models trained on the finite-element results will then support a multi-objective optimisation of stage count that includes the thermal constraints.

7. Expected Contribution and Limitations

The expected contribution is a design method for multistage AFPM machines in which stage count, stator cooling and rotor thermal management are treated as one coupled problem. It comprises a screening criterion usable at the concept stage, a characterisation of when the inner rotors become the rating-limiting component, and validated guidance on how rotor thermal design changes the optimum number of stages.

This working paper is a research framework and does not yet report verified results. The central uncertainty is the magnitude of the inner-rotor magnet loss, which can only be established numerically and experimentally. The air-gap heat transfer in a rotating stack and the thermal behaviour of the stator tooth tips also require detailed analysis. These questions define the next stages of the work.

Declaration of AI Assistance

The author used an AI assistant (Claude, Anthropic) for literature searching, checking calculations and drafting the manuscript text. The author defined the research problem and architecture, directed the analysis, reviewed and edited the text, and takes full responsibility for its content.

References

- [1] F. Nishanth, J. Van Verdegheem and E. L. Severson, "A review of axial flux permanent magnet machine technology," *IEEE Transactions on Industry Applications*, vol. 59, no. 4, pp. 3920–3933, 2023, doi: 10.1109/TIA.2023.3258933.
- [2] J. F. Gieras, R.-J. Wang and M. J. Kamper, *Axial Flux Permanent Magnet Brushless Machines*, 2nd ed. Springer, 2008.
- [3] F. Caricchi, F. Crescimbeni and O. Honorati, "Modular axial-flux permanent-magnet motor for ship propulsion drives," *IEEE Transactions on Energy Conversion*, vol. 14, no. 3, pp. 673–679, 1999, doi: 10.1109/60.790934.
- [4] F. Dumas, P. Enrici and D. Matt, "Design and comparison of two multi-disc permanent magnet motors for aeronautical application," in *Proc. International Conference on Electrical Machines (ICEM)*, 2012, pp. 647–652, doi: 10.1109/ICEIMach.2012.6349938.
- [5] A. S. McDonald, M. Benatmane and M. A. Mueller, "A multi-stage axial flux permanent magnet machine for direct drive wind turbines," in *Proc. IET Renewable Power Generation Conference*, 2011, doi: 10.1049/cp.2011.0105.
- [6] Z. Zhang, R. Nilssen, S. M. Mueen, A. Nysveen and A. Al-Durra, "Design optimization of ironless multi-stage axial-flux permanent magnet generators for offshore wind turbines," *Engineering Optimization*, vol. 49, no. 5, pp. 815–827, 2017, doi: 10.1080/0305215X.2016.1208191.
- [7] T. J. Woolmer and M. D. McCulloch, "Analysis of the yokeless and segmented armature machine," in *Proc. IEEE International Electric Machines and Drives Conference (IEMDC)*, 2007, pp. 704–708, doi: 10.1109/IEMDC.2007.382753.
- [8] R. Camilleri, D. A. Howey and M. D. McCulloch, "Predicting the temperature and flow distribution in a direct oil-cooled electrical machine with segmented stator," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 1, pp. 82–91, 2016, doi: 10.1109/TIE.2015.2465902.
- [9] R. Camilleri and M. D. McCulloch, "Integrating a heat sink into concentrated wound coils to improve the current density of an axial flux, direct liquid cooled electrical machine with segmented stator," *Energies*, vol. 14, no. 12, 3619, 2021, doi: 10.3390/en14123619.
- [10] S. A. Semidey and J. R. Mayor, "Experimentation of an electric machine technology demonstrator incorporating direct winding heat exchangers," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 10, pp. 5771–5778, 2014, doi: 10.1109/TIE.2014.2303779.
- [11] M. Vatani, Y. Chulaee, J. F. Eastham and D. M. Ionel, "Analytical and FE modeling for the design of coreless axial flux machines with Halbach array and surface PM rotors," in *Proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, 2024.
- [12] M. Vatani, D. R. Stewart, P. Asef and D. M. Ionel, "Optimal design of coreless axial flux PM machines using a hybrid machine learning and differential evolution method," in *Proc. IEEE International Electric Machines and Drives Conference (IEMDC)*, 2025.
- [13] A. Habib, H. S. Che, N. Abd Rahim, M. Tousizadeh and E. Sulaiman, "A fully coreless multi-stator multi-rotor (MSMR) AFPM generator with combination of conventional and Halbach magnet arrays," *Alexandria Engineering Journal*, vol. 59, no. 2, pp. 589–600, 2020, doi: 10.1016/j.aej.2020.01.039.