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Optimal Design of Axial Flux Synchronous Machines with Coreless PCB Stator and Surface-mounted or Halbach Array PM Rotors Considering Performance and Cost Objectives

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ABSTRACT This study systematically compares and examines two types of coreless printed circuit board (PCB) stator axial-flux permanent magnet (AFPM) machines for optimally designed cost-sensitive heating, ventilation, and air conditioning (HVAC) applications, differing in rotor configuration. The rotor topologies include conventional surface-mounted permanent magnet (PM) and Halbach array configurations. Analytical and finite element analysis (FEA) methods are employed to assess the air-gap flux density and torque capabilities of each rotor type within the same envelope. Both machines are then optimized using a combination of differential evolution and computationally efficient 3D FEA for the same rating and compared in terms of cost, weight, and efficiency. Optimization findings reveal that a Halbach array rotor coreless AFPM, with performance comparable to its surface PM counterpart, is lighter in mass yet significantly more expensive. A discussion is presented on AC loss mitigation in PCB stators, along with design considerations for coreless AFPM machines, including the effect of magnet-to-magnet gap on torque production and the role of the rotor back iron for the surface PM rotor and the non-magnetic supporting plate in the Halbach array rotor. Given the importance of cost sensitivity in the HVAC industry and based on a comprehensive analysis of production and operating costs, supported by validated analytical and FEA calculations, a prototype with a surface-mounted PM rotor was fabricated and experimentally tested.

INDEX TERMS Axial-flux, coreless machines, AFPM machines, permanent-magnet machines, Halbach-array, PCB stator, FEA, eddy current.

I. INTRODUCTION

PERMANENT magnet synchronous machines (PMSMs) are a pivotal component in modern electromechanical systems, known for their high efficiency, robust performance, and compact design [1], [2]. The axial flux PMSM type, known as AFPMSMs, has the potential for a compact, lightweight structure and increased power density, making them ideal for applications with stringent volume and weight constraints, such as electric vehicles, aerospace, and renewable energy systems [3]. Removing the iron core from the stator additionally allows for a significant reduction in power

losses and cogging torque, resulting in smoother operation and potentially increased energy efficiency [4].

The integration of printed circuit boards (PCBs) as stators presents an opportunity for further volume, weight, and cost reductions in coreless AFPM machines [5]–[7]. Stators made from PCBs have gained popularity due to their potential for reliable and highly repeatable fabrication, modular design, and lightweight nature [8], [9]. The high level of flexibility in PCB coil geometry with minimal impact on manufacturing setup enables design and optimization to mitigate stator losses [10].

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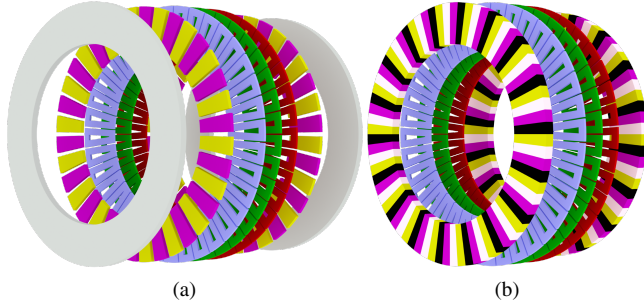


FIGURE 1. Exploded view of the studied dual-rotor 36-pole three-phase and PCB stator coreless AFPM machines with (a) surface-mount and (b) Halbach array PM rotors.

Axial flux PM machines typically use a surface-mounted PM rotor consisting of an alternating polarity arrangement of PMs and a back iron, which acts as a return flux path. Halbach array magnetization is an alternative PM rotor configuration which produces a strong magnetic field on one side and a near zero field on the other [11]. This type of rotor has been rising in popularity for electrified aviation due to its capability for high specific power [12]. Halbach array rotors in electric aircraft propulsion systems have been utilized in multiple projects funded by NASA and the Department of Energy (DoE), [13]–[15], and in private company projects such as LaunchPoint Electric Propulsion Solutions, Inc. [16].

Alternative applications, such as electric machines for aircraft propulsion, place high specific power density and reliability as a much higher priority than machine cost. For applications such as HVAC, while Halbach array rotors may reduce mass for comparable performance, there is a gap in the literature on how their use affects costs. This paper thoroughly examines the cost and performance implications of using Halbach array rotors compared with traditional surface PM rotors with back iron.

In this paper, which extends previous work in [17], design and optimization have been performed using 2/3D FEA on coreless axial flux permanent magnet machines with dual conventional surface PM and Halbach array PM rotors alongside a systematic investigation of torque and power capabilities. The results from analytical equations and FEA models used for the parametric studies and optimizations were verified with a coreless AFPM machine prototype. Optimization results indicate a non-linear trade-off between machine cost and performance alongside the potential application of multiple stators in a dual rotor configuration of Halbach array PMs.

The paper also addresses a gap in the literature regarding the electromagnetic performance and cost comparison of electric machines employing these two rotor configurations. Although the comparison was conducted for coreless-stator axial flux machines, the methodology and key findings are broadly applicable to conventional PMSMs. A comprehensive techno-economic assessment was presented that evaluates the trade-offs between electromagnetic performance improvements and associated cost increases. Both active ma-

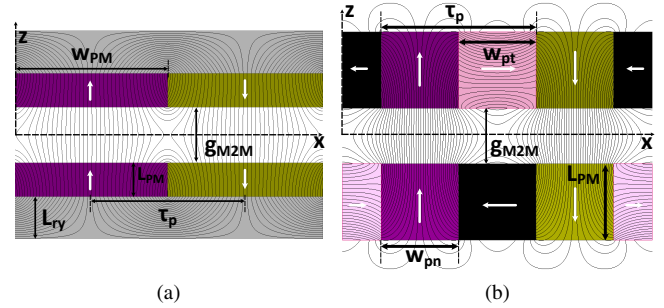


FIGURE 2. The unrolled 2D FEA models and flux lines of the double-sided coreless AFPM machine with (a) conventional surface-mounted PMs and (b) Halbach array rotors.

terial costs and manufacturing costs were considered. Based on the results, recommendations were provided for selecting the most suitable rotor configuration according to specific application requirements and design priorities.

The structure of this paper is as follows: Section II details the explored topologies and methods of FEA and analytical modeling employed for systematic comparison of performance. Section III details the problem formulation and optimization objectives of the coreless AFPM designs, including the cost and Joule loss for both topologies. Section IV discusses the results of the multi-objective optimization with an analysis of Pareto fronts for cost and performance. Section V details considerations specific to machines with PCB coreless stators and Halbach array PMs.

II. MOTOR TOPOLOGIES AND COMPUTATIONAL MODELS

A. MOTOR TOPOLOGIES

This study explores two types of coreless stator AFPM machines with different external dual-rotor designs, including surface PM and Halbach array PM rotors. In the surface PM rotor, permanent magnets are magnetized axially and attached to the back iron, whereas the Halbach array rotor consists of PMs with alternating tangential and normal magnetization, with the absence of the back iron. These configurations are illustrated in the exploded views depicted in Figs. 1(a) and 1(b).

In the Halbach array rotor, each pole is magnetized by two PMs, one with normal and the other with tangential magnetization directions. This arrangement is repeated with opposing magnetization directions around the circumference to form a Halbach array rotor with four magnets per wavelength. Segmentation of PMs is not considered since coreless machines typically exhibit low armature reactions and minimal eddy current losses in the PMs.

There is no concern about core saturation in the coreless AFPM machine with the Halbach rotor because no ferromagnetic core is present. In the surface PM variant, rotor back iron saturation can occur, depending on factors such as the number of poles, pole span, and axial length of the PMs.

The stator configuration remains the same for both machines, featuring a three-layer winding arrangement with

coils positioned in an overlapping manner. Each phase contains a number of coils matching the number of poles, and the current injected into two consecutive coils has an 180 electrical degrees phase shift. To ensure cost-effectiveness in the designated application, the stator employs PCB material. By employing PCB stators, open circuit AC losses, including eddy and circulating current losses, can be effectively mitigated through the design of the planar copper traces.

B. ANALYTICAL AND FINITE ELEMENT MODELING

Axial flux PM machines present three-dimensional problems, necessitating 3D analytical or numerical modeling to account for curvature and edge effects. A proposed 2D modeling approach in [18] involves slicing the machine at the average radius to create a cylindrical surface, then unrolling it to generate an equivalent 2D model. To investigate air-gap flux densities, 2D cross-section models at the average diameter of an example design of the proposed machines with surface-mounted PM and Halbach array rotors were created. These models were utilized for both analytical calculations and 2D FEA in Ansys Electronics Desktop software [19].

Example flux lines are shown for the designs with the surface PM rotor, Fig. 2(a), and the Halbach array rotor, Fig. 2(b). Significant neutralization of flux on one side of the magnets enables the removal of the rotor-back iron within the Halbach rotor variant, such that a comparable axial length can be maintained by increasing the magnet axial length.

For the primary example design, the overall axial length of both configurations was set equal to one another, with the surface PM rotor including the back iron ($L_{PM} + L_{ry}$). The width of one pole in the surface-mounted PM rotor, w_{PM} , is equal pole pitch to be comparable with the pole width in the Halbach rotors, $w_{pm} + w_{pt}$. As a result, these two designs are comparable in terms of volume and mass. It should be noted that the selected strong neodymium magnet has a mass density comparable to that of the back iron electrical steel.

For the double-sided surface PM structure shown in Fig. 2(a), based on [20], the normal component of air-gap flux density in the axial direction can be expressed as:

$$B_{z_{SPM}} = \sum_{i=0}^{\infty} B_{n_{SPM}} \cosh\left(\frac{n\pi z}{\tau_p}\right) \cos\left(\frac{n\pi(2x - \tau_p)}{2\tau_p}\right) \quad (1)$$

$$B_{n_{SPM}} = 4B_r \cdot \frac{\sin(n\pi w_{pm}/2\tau_p)}{n\pi} \cdot \frac{\sinh(n\pi L_{pm}/\tau_p)}{\sinh(n\pi(L_{PM} + g_{M2M}/2)/\tau_p)} \quad (2)$$

where $n = 1 + 2i$ with i being the harmonic orders, B_r is the remanence of the PMs, w_{pm} is the PM width at average rotor diameter, L_{pm} is the PM length, g_{M2M} is the magnet-to-magnet gap length, and τ_p is the pole pitch at average diameter. Pole pitch can be calculated from $\tau_p = \frac{\pi D_{avg}}{p}$, where D_{avg} and p are the average diameter and pole number.

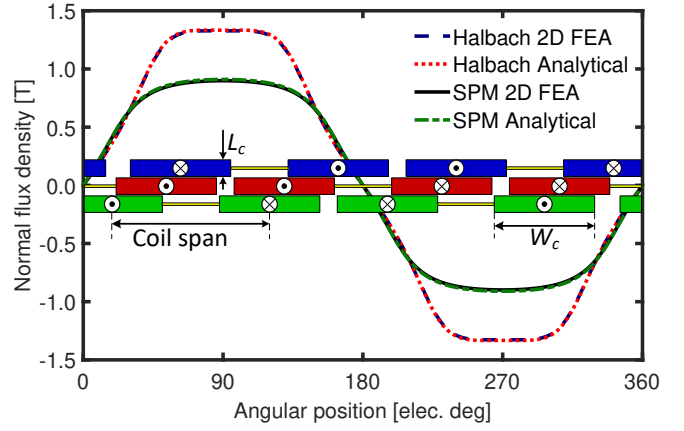


FIGURE 3. Flux density waveforms at the middle of the M2M gap for the surface-mount and Halbach array PM rotor configurations with PM remanence of 1.415 T at room temperature, calculated using 2D analytical and FEA methods. The rectangles represent cross-sections of stator conductors, with the red phase aligned with the position of maximum torque production.

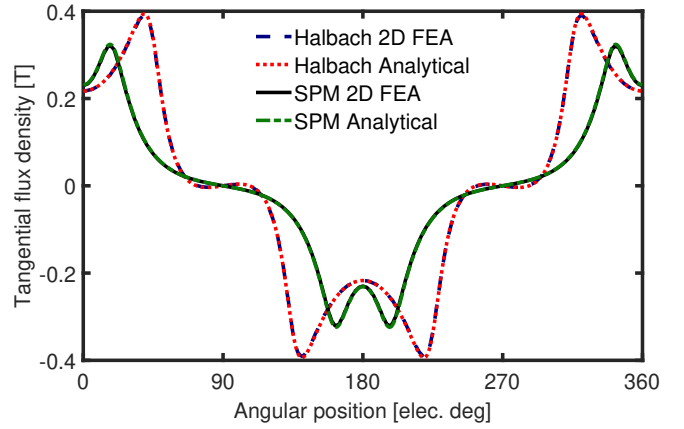


FIGURE 4. The tangential component of air-gap flux density, B_t , calculated over the stator surface with both rotors with the 2D FEA unrolled model and analytically.

A similar equation can be derived from Maxwell's equations for the Halbach array rotor as [20]:

$$B_{z_{Hal}} = \sum_{i=0}^{\infty} B_{n_{Hal}} \cosh\left(\frac{n\pi z}{\tau_p}\right) \sin\left(\frac{n\pi x}{\tau_p}\right) \quad (3)$$

$$B_{n_{Hal}} = 2B_r \cdot \frac{\sin(\epsilon n\pi/m)}{n\pi/m} \cdot \left[1 - \exp\left(\frac{-n\pi L_{pm}}{\tau_p}\right)\right] \exp\left(\frac{-n\pi g_{M2M}}{2\tau_p}\right) \quad (4)$$

where ϵ usually set to one, $n = 1 + mi$, and m is the number of PMs per wavelength.

According to (1) and (3), the normal component of air-gap flux density, B_z , that contributes to torque production varies in the axial direction proportionally to a hyperbolic sinusoid. It

reaches its minimum in the middle of the air-gap and increases towards the PMs in both directions.

The normal component of the air-gap flux density waveforms in the middle of air-gap, $z = 0$, for both surface PM and Halbach array configurations relative to an angular electrical degree within one pole pair, is illustrated in Fig. 3. The position of the stator coils relative to the air-gap flux density is displayed, where the angular position of the middle phase aligns with the maximum torque production for that phase. In this design, the PCB thickness per phase is 1 mm, and the mechanical clearance between the rotor and stator is 1 mm for each side, such that the total magnetic air-gap, magnet-to-magnet (M2M) distance, is 5 mm.

Implementing the Halbach array resulted in an approximately 45% enhancement in the peak value of normal flux density while maintaining the same rotor envelope and mass. However, this augmentation does not guarantee higher torque in the same coil side ratio. The optimal performance for the Halbach array rotor variant may be observed for the wider coil sides, indicating the significance of coil design in coreless AFPM machines.

In coreless machines, the exposure of conductors to varying magnetic fields leads to the induction of eddy current losses in the stator. The normal and tangential components of flux density induce eddy currents in the width and axial length of the conductor, respectively [21]. The tangential component of flux density for surface PM and Halbach rotors over two pole pitches is computed using 2D analytical and FEA approaches and compared as shown in Fig. 4. The variation and magnitude of tangential flux density for the Halbach array are greater than those for the surface PM, potentially resulting in higher eddy current losses.

The torque produced in coreless AFPM machines can be calculated by solving the Lorentz force equation, which is typically represented as [22]:

$$\mathbf{F} = \int_v \mathbf{J} \times \mathbf{B} dv, \quad (5)$$

where $\mathbf{B}$ can be calculated through (1) to (4), and $\mathbf{J}$ represents the current density in the conductor, which is calculated by:

$$\mathbf{J} = \frac{N_t I_p k_w}{\tau_c}. \quad (6)$$

where the number of turns per coil is represented as N_t , I_p is the peak phase current, k_w represents the total winding factor, and τ_c denotes the coil pitch. The winding factor, which is expressed as the product of the distribution, pitch, and group factors, can be calculated from:

$$K_d = \frac{K_D D_o}{W_{cs} \nu} \sin \left(\frac{W_{cs} \nu}{K_D D_o} \right), \quad (7)$$

$$K_p = \sin \left(\frac{\nu \pi (2K_D - \lambda)}{2K_D N_c} \right), \quad (8)$$

$$K_g = 1 - \cos(\pi \nu), \quad (9)$$

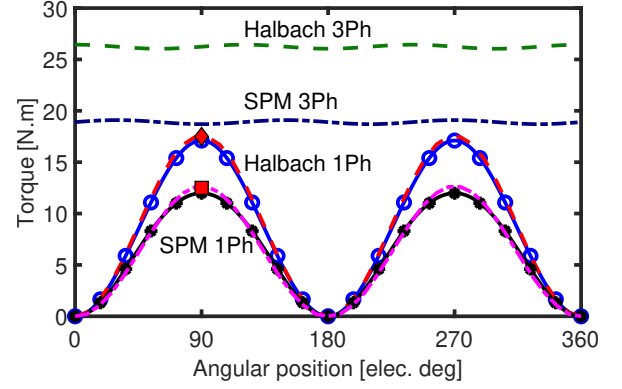


FIGURE 5. Torque waveforms for the conventional and Halbach array variants in single and three phases, calculated analytically and with 3D FEA, which had higher estimates of resulting torque. The maximum torque values, marked in red-filled squares and diamonds, can be used to calculate three-phase torque with a two-point fast solution.

where K_D is a factor that takes into account the diameter at which the calculation is performed and can be obtained from:

$$K_D = \overline{K_D} + (1 - \overline{K_D}) \lambda, \quad (10)$$

where $\overline{K_D}$ is the normalized diameter ratio to outer diameter (e.g., $\overline{K_D} = 0.5$ at the average diameter), W_{cs} represents the coil-side width, ν corresponds to the harmonic order of the winding factor, λ is the inner-to-outer diameter ratio, and N_c is the number of coils within the minimum electromagnetic periodicity, which is equal to 2 for the considered three-layer winding configuration.

By substituting (1) through (4) and (6) into (5) and considering matching boundary conditions, the average torque at the average diameter can be calculated as:

$$T_{avg} = \frac{\sin(w_{cs}/K_D D_o)}{2w_{cs}} K_M K_{P_1} K_{g_1} N_c N_t I_p (1 - \lambda) B_{z_1} K_D^2 D_o^3, \quad (11)$$

where K_M denotes the periodicity boundary condition coefficient, corresponding to the number of repetitions of the fundamental periodic segment, equal to $P/2$ for the motor topologies under study; K_{P_1} represents the fundamental pitch factor; K_{g_1} is the fundamental coil group factor; N_t is the number of turns per coil; I_p is the peak phase current; and B_{z_1} is the fundamental component of the normal flux density, which can be derived for conventional SPM and Halbach rotors from (2) and (4), respectively. The distribution factor is directly incorporated into the formulation. The instantaneous torque can be derived as:

$$T = \frac{1}{6} K_M N_c N_t I_p K_D D_o^2 (1 - \lambda) \sum_{j=0}^2 \sum_{\nu=1}^{\infty} \sum_{i=0}^{\infty} \sin \left(\frac{\pi x}{\tau_p} + j \frac{2\pi}{3} \right) K_w B_z, \quad (12)$$

where j corresponds to the number of phases.

Models were developed with 3D FEA for both variants to precisely assess torque and validate the developed 2D analytical model. Torque calculations were performed considering ideally sine wave regulated current, and the results are shown in Fig. 5. In single and three-phase torque calculations, the output torque from the Halbach array rotor was 30% higher than that from the conventional surface-mounted PMs with the same mass, volume, current density, and temperature rise.

III. PROBLEM FORMULATION FOR 3D FE-BASED OPTIMIZATION

This section focuses on the problem formulation and sensitivity analysis for the design optimization of coreless AFPM machines with surface PM and Halbach array rotors for HVAC systems. The target design aims for 19 Nm of torque at 2,100 rpm with a rotor outer diameter of 300 mm. The rated values are selected for a typical HVAC application.

A. OPTIMIZATION OBJECTIVES

Given that cost competitiveness and efficiency are paramount criteria for both manufacturers and customers of HVAC systems, the optimization objectives prioritize total loss and cost. The two cost functions are determined to minimize the total loss, F_l , and active material cost, F_c . The electromagnetic loss component considered in the optimization process is the Joule loss, and the cost is defined as [2]:

$$F_c = 65 \cdot m_{PM} + 8 \cdot m_{Cu} + m_c, \quad (13)$$

where m_{PM} , m_{Cu} , and m_c denote the masses of PM, copper, and rotor back iron.

Because the harmonic magnitude of the resultant flux density from the stator excitation is significantly low within a coreless stator, the impact of armature reaction is nearly nonexistent in a coreless machine unless it operates under extremely heavy loads. As a result, the losses due to core and PM eddy currents in the rotor are negligible and were not considered in the optimization process.

Eddy and circulating losses in the stator were not considered in the optimization process for two main reasons. Firstly, the configuration of the PCB stator, including parameters such as trace width, height, and number of layers, must vary depending on the design, necessitating a trade-off due to manufacturing limitations. Secondly, integrating a PCB stator with realistic trace dimensions and a multilayer structure into 3D FEA and solving it numerous times during optimization would incur high computational costs. Following the selection of the optimal design from the optimization, the PCB stator is tailored to minimize losses specific to the chosen model. Further strategies to mitigate stator losses are elaborated on in the discussion section.

The cost is calculated based on the mass of the active components' materials, with electrical steel serving as the reference unit. The cost ratios for other materials, incorporated as coefficients in equation (13), are standard values applicable to high-volume production, as outlined in [2].

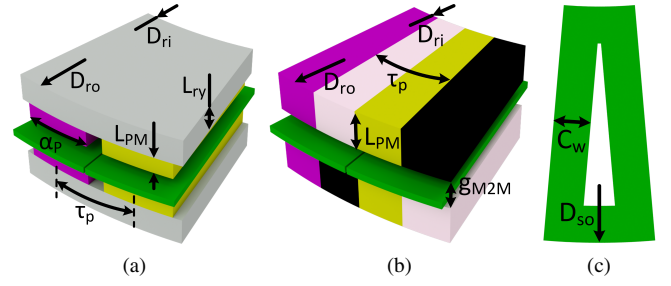


FIGURE 6. Cross-sections of the studied coreless AFPM machine with (a) conventional surface-mounted PMs, (b) Halbach array rotors, and (c) the macro coil representation for one coil of the PCB stator with labeled geometric design parameters.

TABLE 1. Independent Optimization Variables and Corresponding Limits for Coreless AFPM Machines with SPM and Halbach Rotors.

Var.	Description	Surface PM		Halbach	
		Min.	Max.	Min.	Max.
K_{dr}	Rotor diameter ratio = $\frac{D_{ro}-D_{ri}}{D_{ro}}$	0.15	0.35	0.15	0.35
K_{PM}	PM axial length ratio = $\frac{L_{PM}}{\tau_p}$	0.12	0.32	0.15	0.50
K_g	Magnet-to-magnet gap ratio = $\frac{g_{M2M}}{\tau_p}$	0.14	0.40	0.14	0.75
K_{cw}	Coil side width ratio = $\frac{4C_w}{\tau_p D_{ri}}$	0.77	1.00	0.77	1.00
K_{oh}	Overhang ratio = $\frac{D_{ro}-D_{ri}}{2C_w}$	0.00	1.00	0.00	1.00
K_m	PM coverage ratio = $\frac{\alpha_p}{\tau_p}$	0.80	1.00	N/A	N/A
K_{ry}	Back iron axial length ratio = $\frac{L_{ry}}{\tau_p}$	0.25	0.75	N/A	N/A

B. PARAMETRIC 3D AND COMPUTATIONALLY EFFICIENT FEA MODELS

Parametric 3D FEA models were developed for both coreless AFPM machines featuring a surface PM and a Halbach array rotor. Implementing matching boundary conditions over one pole pitch, $\frac{2\pi}{p}$, and axial symmetry boundary conditions for half of the machines in the axial direction allowed for a significant reduction in computational burden.

The geometric design variables for the optimization are depicted in Fig. 6, where there are seven design variables for surface PM and five for Halbach array rotors. The ranges of these variables can be found in Table 1, predominantly normalized according to the pole pitch. The rotor's outer diameter (D_{ro}) was established at 300 mm, the mechanical clearance between the stator and rotor was fixed at 1mm, and the copper fill factor was set to 0.22 to align with current multi-layer PCB technology.

The pole number of 36 was chosen because previous studies, such as [23], have shown that it effectively minimizes stator eddy current loss by enabling fine transposition of conductors. This approach makes the PCB technology comparable to Litz wire counterparts. The benefits of utilizing high pole numbers in coreless AFPM machines have been extensively discussed by various authors in multiple papers, such as [15].

Based on (12), the torque produced in coreless machines is the sum of the torque contributions from each phase. This

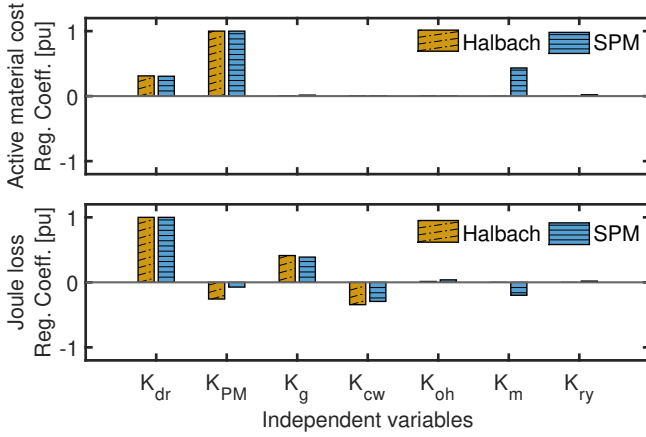


FIGURE 7. The impact of optimization variables on active material cost and Joule loss, represented by per-unit regression coefficients.

facilitates modeling only one phase in the parametric 3D FEA model. Additionally, the total torque was determined using a computationally efficient FEA (CE-FEA) technique. The CE-FEA approach involves solving at two points in the transient solution and computing the torque [24].

To ensure that all design candidates meet the required torque, a two-pass analysis procedure is adopted. In the first pass, each design is evaluated using a predefined current density. In the second pass, the current density is adjusted during post-processing to achieve the torque. Owing to the absence of magnetic core saturation in the stator, the torque scales linearly with the current density. Consequently, the torque can be scaled without additional FEA simulations.

C. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to examine how optimization variables affect the objectives of both machines. Regression coefficients were computed by conducting a full factorial design of experiments (DoE) for each machine. These coefficients, associated with the response surfaces, illustrate how changes in the design parameters within their allowable ranges impact the performance metrics.

The regression coefficients are normalized to the variable with the greatest influence within each group of metrics. Negative coefficients signify that the response decreases in absolute value with an increase in the corresponding factor, while positive coefficients indicate an increase in the response. The magnitude of the regression coefficients reflects the extent of the factor's influence, with larger coefficients indicating greater influence. The impact of optimization variables on active material cost and joule loss is depicted in Fig. 7.

Regarding the design variables that have the greatest influence on active material cost, the dominant contribution comes from the PM mass. Therefore, variables that directly affect PM dimensions, such as K_{dr} , K_{PM} , and K_m , have a more pronounced impact on the overall cost.

In contrast, variables that primarily influence the coil ge-

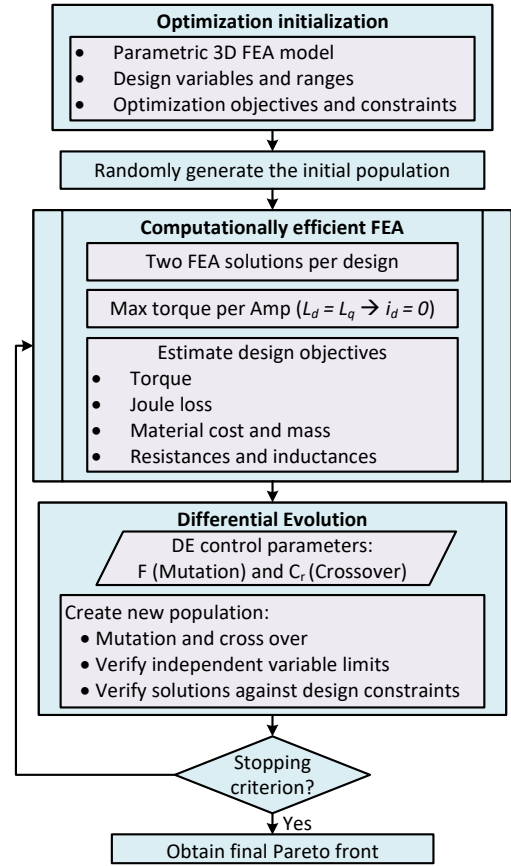


FIGURE 8. Flowchart of the 3D FEA-based multi-objective differential evolution optimization framework.

ometry, including K_g , K_{cw} , K_{oh} , and K_{ry} , have a stronger effect on the Joule losses. Since these two objectives are inherently conflicting and their sensitivities to the design variables differ, carefully selecting appropriate bounds for the design variables is essential. This not only improves the efficiency of the optimization process but also facilitates convergence toward optimal design solutions.

The PM axial length has different effects on the design objectives of surface-mounted and Halbach-array PM machines. While an increase in axial length leads to a similar rate of cost increase in both topologies, thicker PMs contribute more significantly to the reduction of Joule losses in the Halbach configuration. This behavior stems from the inherently higher air-gap flux density produced by the Halbach array, which allows the required current loading to achieve the target torque to be lower than in the surface-mounted configuration, thereby reducing Joule losses.

IV. OPTIMIZATION RESULTS AND SELECTION OF RECOMMENDED DESIGNS

The sensitivity analysis highlights how the design variables individually affect the machines' performance. To determine how these variables interact and affect the ultimate optimal design, tailored to specific objectives and constraints, a thor-

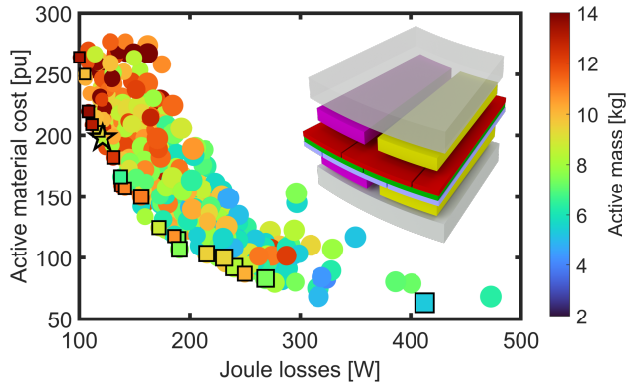


FIGURE 9. All designs with current densities lower than 20 A/mm^2 evaluated using 3D FEA for coreless AFPM machine with surface PM rotor. Squares denote the Pareto optimal designs, and the star indicates the design selected for prototyping. The size of the points correlates with the current density.

TABLE 2. Calculated Results for the Recommended Optimal Surface-mount PM Rotor Coreless AFPM Machine.

Parameter	Analytical	3D FEA	Unit
Torque	18.4	19.0	N.m
Torque constant	2.1	2.2	N.m/A
Phase resistance	0.61	0.55	Ω
Phase inductance	-	28.2	μH
Joule losses	131.8	125.4	W
Efficiency	96.7	96.9	%

ough examination of the design optimization process and outcomes is necessary.

To accurately identify the Pareto-optimal design set, a 3D FEA-based multi-objective differential evolution (MODE) optimization algorithm was employed. The flowchart of the optimization framework is shown in Fig. 8. The population size of each generation is set to 50, which is notably larger than the number of independent variables [2]. The cost function for the optimization problem incorporates the previously discussed performance metrics and aims to minimize both the normalized active material cost and power losses.

The DE parameters were selected based on established recommendations in the differential evolution literature and on previous electric-machine optimization studies employing CE-FEA coupled with DE, such as [25]. The mutation scaling factor was set to $F = 0.5$, which lies within the commonly recommended range of $0.4 \leq F \leq 1.0$ and provides a balance between global exploration and convergence stability [26]. The crossover probability was set to $CR = 0.5$, such that each design variable had an equal probability of being inherited from either the parent or mutant vector.

The selected values provide a balanced trade-off between preserving the favorable characteristics of existing solutions and maintaining sufficient diversity to explore the design space. Similar DE-based optimization frameworks have been

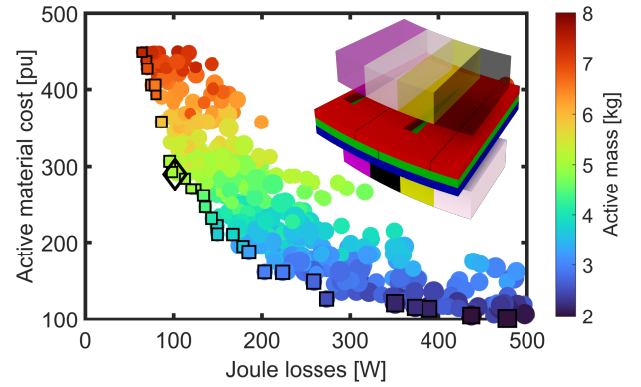


FIGURE 10. All designs with current densities of lower than 20 A/mm^2 evaluated using 3D FEA for the coreless AFPM machine with dual Halbach rotors. Squares denote the Pareto optimal designs, and the diamond indicates the recommended optimal design. The size of the points correlates with the current density.

TABLE 3. Calculated Results for the Recommended Optimal Halbach Array Coreless AFPM Machine at the Rated Condition.

Parameter	Analytical	3D FEA	Unit
Torque	18.6	19.0	N.m
Torque constant	2.3	2.4	N.m/A
Phase resistance	0.59	0.57	Ω
Phase inductance	-	22.2	μH
Joule losses	110.6	107.7	W
Efficiency	97.3	97.1	%

successfully employed in large-scale electric-machine optimization studies involving thousands of candidate designs and multiple competing objectives [27], [28]. In the present study, these settings provided stable convergence behavior throughout the optimization process.

The optimization was terminated after a maximum of 1500 function evaluations, corresponding to 1500 candidate machine designs analyzed by the coupled optimization and electromagnetic evaluation framework. This value was selected to provide sufficient exploration of the design space while maintaining a practical computational cost [25].

The optimization results for the machine with surface-mount PM rotor configuration are depicted in Fig. 9. All designs deliver the rated torque, and each scatter's color and size correspond to the total active mass and current density, respectively. Squares represent designs on the Pareto front, and the star marker indicates the recommended optimal design. Table 2 presents the electromagnetic performance of the selected optimal design, evaluated with the analytical approach and 3D FEA. The optimal design was selected from the Pareto front among relatively high-cost, high-efficiency design candidates.

The optimization results for the coreless AFPM machine with Halbach array rotor are depicted in Fig. 10 on a largely different Y-axis scale compared to Fig. 9. Each scatter plot's color and size represent the total active mass and current

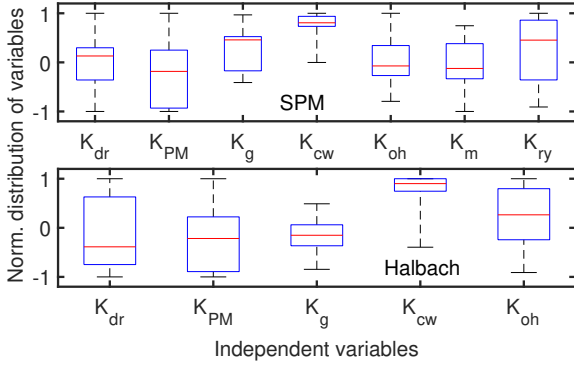


FIGURE 11. Distribution of variables for the Pareto front designs of the coreless AFPM machines with surface PM and Halbach array rotors.

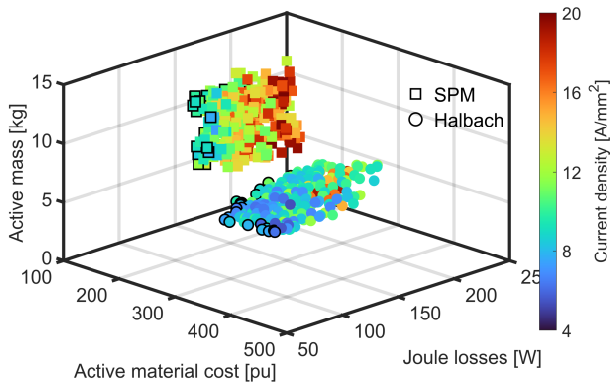


FIGURE 12. Evaluated designs with current densities lower than 20 A/mm² for both surface PM and Halbach array rotor variants in terms of active mass, material cost, and Joule loss.

density, respectively. Squares denote the designs on the Pareto front, and the diamond marker signifies the recommended optimal design. A sectional view of the recommended optimal coreless AFPM machine with a Halbach array rotor is shown in the right corner of Fig. 10, with its performance characteristics calculated using analytical methods and 3D FEA listed in Table 3.

The normalized distributions of the independent design variables for the Pareto-optimal solutions are illustrated using box plots in Fig. 11. It can be observed that most variables are distributed within their predefined ranges, indicating that the selected bounds are appropriate and do not impose overly restrictive constraints on the optimization process. Shifts in the median values reflect preferred regions of the design space for optimal solutions. A comparison between the SPM and Halbach configurations further highlights differences in the distributions of key variables, revealing distinct optimal design tendencies for each rotor topology.

The optimization results of both motor topologies are shown in Fig. 12, comparing the per-unit active material cost, Joule loss, active mass, and current density. It should be noted that all design candidates meet the required rated torque, albeit at different current densities. The Halbach-array

TABLE 4. Geometric Dimensions and Electromagnetic Characteristics of Representative Optimum Designs for Coreless AFPM Machines with Surface PM and Halbach Array Rotor Variants.

Parameter	Surface PM	Halbach	Unit
Pole pitch, τ_p	22.3	23.5	mm
PM axial length, L_{PM}	5.0	11.3	mm
Magnet-to-magnet gap, g_{M2M}	7.8	9.4	mm
Mechanical air-gap, l_g	1.0	1.0	mm
Rotor back iron length, L_{ry}	6.7	N/A	mm
Rotor radial length, $\frac{D_{ro}-D_{ri}}{2}$	48	35	mm
PM mass, m_{PM}	2.5	5.0	kg
Total active mass, m_T	6.5	5.1	kg
Per-unit active material cost	198.2	310.1	pu
Current density, J	9.6	7.0	A/mm ²
Joule loss, P_l	125.4	107.3	W

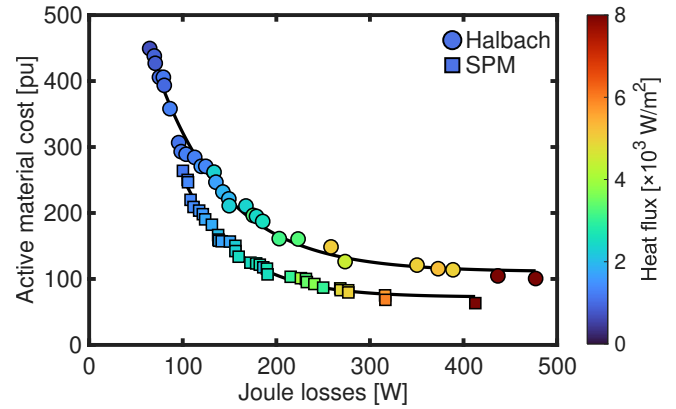


FIGURE 13. Pareto-optimal designs from the multi-objective optimization of coreless AFPM machines with surface-mounted and Halbach array PM rotors. The marker color represents the corresponding heat flux of each design candidate.

PM rotor variants are lighter but at substantially higher costs due to increased PM material usage compared to the surface-mount variant.

To evaluate the thermal performance of both motor topologies and provide insight into the required cooling capability, the Pareto-optimal designs are presented in Fig. 13, where the scatter color indicates the corresponding heat flux of each design. A commonly cited design guideline from [29] suggests that, for a temperature rise of approximately 40°C, forced-air convection cooling can typically accommodate heat fluxes up to about 3,000 W/m². It should be noted that designs with lower heat flux can also be achieved by increasing magnet volume and reducing current density, although this generally results in higher material costs.

The coreless AFPM machine with the Halbach array rotor can produce a higher flux density and greater magnetic loading within the same motor volume than its surface PM counterpart. This results in a reduced electric loading requirement to generate the same power output for the Halbach array rotor variant. The colors of the scatters in Fig. 12 indicate current density, with lower values for the Halbach array variant.

Coreless AFPM machines with surface PM rotors are heavier than those with Halbach arrays. Given that the PCB mass is negligible relative to the rotor mass, the rotor mass is the primary factor affecting the total active mass. Since the surface PM rotor is less expensive but heavier than the Halbach variant, it probably contains less PM mass, but is heavier because of the rotor back iron.

A comparison of designs on the Pareto front for each rotor type shows that, for similar Joule losses, the surface-PM rotor variants exhibit significantly higher active mass than the Halbach-array rotor designs. This indicates that the coreless AFPM machine with a Halbach-array rotor achieves a higher specific power density (kW/kg) compared to the surface-PM variant. This criterion is of substantial importance in applications such as electric aircraft propulsion; however, in HVAC fans, cost and efficiency are the primary drivers.

The geometric dimensions and electromagnetic characteristics of the recommended optimal designs are listed in Table 4. Geometrically, the optimal Halbach-array rotor design features thicker magnets, a larger magnet-to-magnet gap, and a shorter rotor radial length compared to the surface-PM rotor variant. This optimal design is consistent with the previously established geometric relationships.

The optimal Halbach-array rotor variant has approximately half the mass of the optimal surface-PM rotor design and achieves slightly higher efficiency; however, it is approximately 30% more expensive. It should be noted that the recommended surface-mounted PM design was selected from among relatively high-cost candidates to achieve higher efficiency, although it still remains less expensive than the Halbach-array variant.

V. DISCUSSION

A. MINIMAL EDDY AND CIRCULATING CURRENT LOSSES

The eddy current losses in conductors of a coreless stator AFPM machine depend on the frequency, conductor cross-sectional geometry, and the amplitude of the flux density experienced by the conductors. Since the conductors are directly exposed to the time-varying magnetic flux from the rotors, eddy currents are induced in the conductors. The normal and tangential flux density harmonic spectra of the optimal coreless AFPM machine designs with surface-mounted and Halbach-array PM rotors are shown in Fig. 14. The normal component induces eddy currents across the conductor width, while the tangential component induces eddy currents across the conductor depth [21].

Thin conductors with multiple parallel paths are therefore required to mitigate these losses. The systematic PCB design for the prototyped machine has been detailed in prior work by the same research group [23]. In this approach, multiple parallel conductors with smaller cross-sections are implemented in a multilayer PCB to reduce eddy current losses.

Since the parallel conductors are positioned at different distances from the rotor surface, each layer experiences a different flux density, leading to higher induced EMF in conductors closer to the magnets than in those farther away.

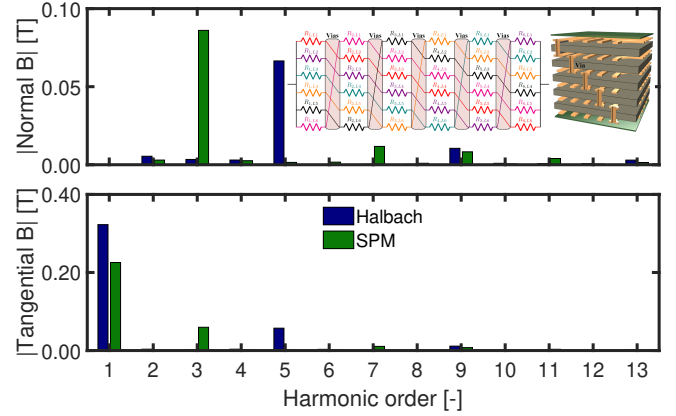


FIGURE 14. Normal and tangential flux density harmonic spectrum of the at the center of the top stator surface for surface PM and Halbach array rotor optimum designs. The normal flux density fundamentals are omitted from the plot and are 0.82 T and 1.18 T for the surface PM and Halbach array, respectively. An example parallel and transposition scheme is also depicted to mitigate eddy and circulating currents.

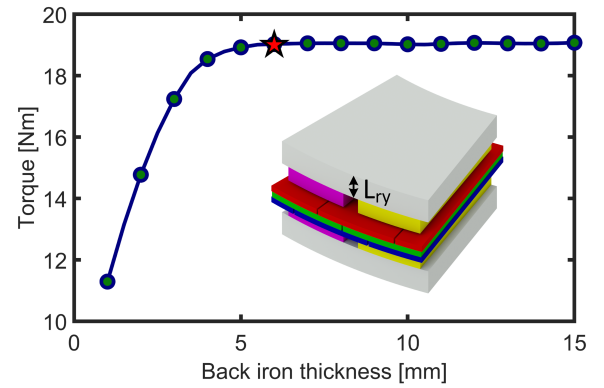


FIGURE 15. Results of the parametric study to see the effect of rotor back iron thickness on saturation and torque capability. The thickness of the rotor back iron for the machine under study is denoted by the star symbol, *.

These potential differences between conductors give rise to circulating currents within the parallel layers, resulting in additional losses. To mitigate this effect, the induced EMF in all parallel conductor layers were equalized using a transposition technique. An example illustrating the implementation of multiple parallel paths and transposition is shown in Fig. 14.

B. ROTOR BACK IRON IN SURFACE-MOUNT AND NON-MAGNETIC DISK IN HALBACH ARRAY PM ROTORS

A parametric study was carried out to determine the axial length of the rotor back iron to observe the effect of saturation on the torque production capability of the surface-mount PM rotor variant, as shown in Fig. 15. The results indicate that increasing the back iron thickness beyond 5 mm does not increase torque production, although it increases the machine's active mass.

It must be noted that while the back iron in a surface PM rotor increases the design's active mass compared to a Hal-

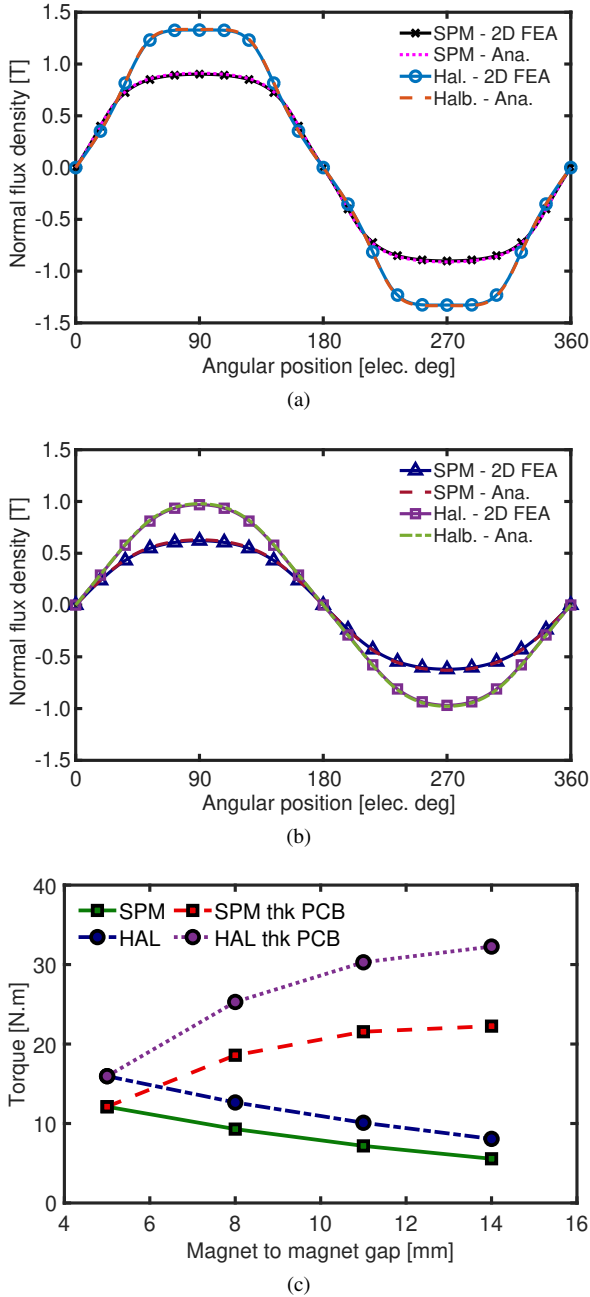


FIGURE 16. Magnet-to-magnet gap parametric study for coreless AFPM machines with surface PM and Halbach array rotor variants showing air-gap flux density at the middle of the air-gap calculated using 2D analytical and FEA tools for M2M gap of (a) 5 mm, (b) 10 mm, and (c) output torque with constant and modified ampere-turn. Two curves denoted by “- thk PCB” represent the output torque values when the ampere-turn of thicker PCBs was modified accordingly.

bach array rotor, it also serves a dual purpose. Besides acting as a flux return path, it functions as a mechanical component for the rotor, eliminating the need for additional mechanical elements. In contrast, the Halbach array rotor design requires a robust, non-ferromagnetic backplate to secure the PMs. Since the PMs in the Halbach array rotor do not naturally attract to the back plate, the mechanical components of this rotor can be more expensive. The mechanical structure must

TABLE 5. Active material costs used in the cost analysis. The listed values represent typical market prices obtained from widely available and credible sources and are applicable to materials purchased in the USA.

Material	Min	Max	Avg	Unit	References
PM (NdFeB)	80	120	100	\$/kg	[31]–[33]
PCB (Multilayer)	100	500	300	\$/m ²	[34], [35]
Electrical steel	1.4	2.8	2.1	\$/kg	[36]

withstand the significant normal force between the opposing rotors and keep the magnets in place.

C. SPECIFICS OF SMALL AND LARGE AIR-GAP DESIGNS

The higher air-gap flux density in the motor with a Halbach-array PM configuration enables a larger magnet-to-magnet gap. This increased gap is beneficial in two ways: it provides additional space to accommodate more conductors (ampere-turns), thereby increasing torque, and it allows for direct forced cooling, as demonstrated in [30]. For example, doubling the PCB thickness per phase to accommodate twice the ampere-turns reduces the air-gap flux density amplitude by approximately 20%, as shown in Fig. 16(a) and (b). However, the increased ampere-turns can effectively compensate for the reduced flux density caused by the wider gap.

The computational results presented in Fig. 16(c) indicate that, at higher electric loading achieved through a larger magnet-to-magnet air-gap filled with thicker PCBs, the Halbach design can deliver approximately 50% more torque. The implementation of such designs, however, requires specialized cooling solutions to manage the increased losses in the stators located between the rotors. This capability of the Halbach-array configuration is particularly beneficial for applications requiring very high power density, where cost is not the primary consideration.

D. PRODUCTION AND OPERATING COST ANALYSIS

A cost analysis was conducted in this subsection to compare the production costs of coreless AFPM machines equipped with surface-mounted and Halbach-array PM rotors. As shown, a machine with a Halbach-array PM rotor can achieve higher efficiency, albeit at increased cost. Whether the additional cost of the Halbach array rotor variant is economically justified was assessed with payback period analysis.

To estimate the final product cost of the electric machines, a general and well-established preliminary approach was adopted. First, the active material cost was calculated based on average prices obtained from credible references, as summarized in Table 5. Subsequently, the total product cost, including housing, bearings, cooling, labor, and manufacturing energy, was estimated by multiplying the active material cost by a factor.

A factor of two was applied to machines with SPM rotors, consistent with typical cost-estimation approaches, as can be seen in [37]. For machines employing Halbach array PM rotors, this factor is increased to 2.5. This adjustment reflects the

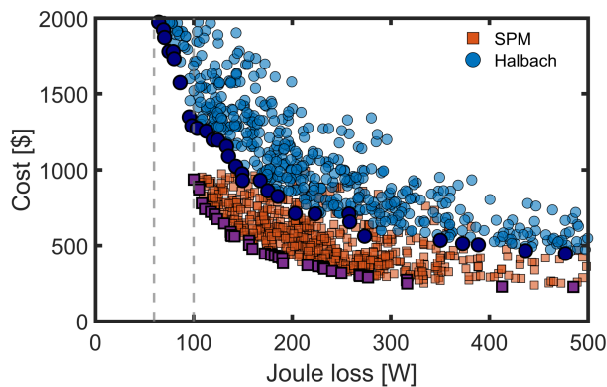


FIGURE 17. Optimization results of coreless AFPM machines with surface-mount and Halbach array PM rotors in terms of cost (USD) and Joule losses. Darker markers indicate designs located on the Pareto front. The dashed lines indicate the minimum achievable Joule losses within the considered design space.

additional cost associated with the use of a non-ferromagnetic back plate required to support and secure the magnets, as well as the more labor-intensive manufacturing process compared to surface-mount PM rotor configurations.

The optimization results for cost (USD) and Joule losses are presented in Fig. 17. It can be observed that coreless AFPM machines with surface-mount PM rotors, operating with Joule losses of 100–150 W at a 4.2 kW rated power, can be manufactured at a cost of \$500–700. Hence, this type of motor represents a strong alternative, in terms of both efficiency and cost, to conventional 5 HP electric machines available in the market, such as products from very large and well-established manufacturers [38]–[41].

Several other manufacturers in the United States, such as [42]–[44], have recently commercialized AFPM motors employing PCB stators and integrated drive electronics. These products are offered across a range of power ratings as complete motor-drive packages and are reported to achieve IE5-level efficiencies for the combined motor-inverter system. Furthermore, manufacturers report that the price of these integrated AFPM motor-drive products is comparable to that of conventional radial-flux motors from established suppliers, even though the latter are typically supplied without a drive inverter.

It should be noted that production costs can be further reduced if manufacturing processes are optimized by well-established electric machine manufacturer companies. For example, fully automated PCB stator production and the solid rotor back iron (i.e., no lamination requirement) can significantly reduce labor costs and increase manufacturing speed. Moreover, these motors are substantially lighter than conventional machines such as induction motors, which can lead to additional cost reductions in housing and bearings, further lowering overall production costs.

Regarding coreless AFPM machines with a Halbach-array PM rotor variant, a design with a Joule loss comparable to

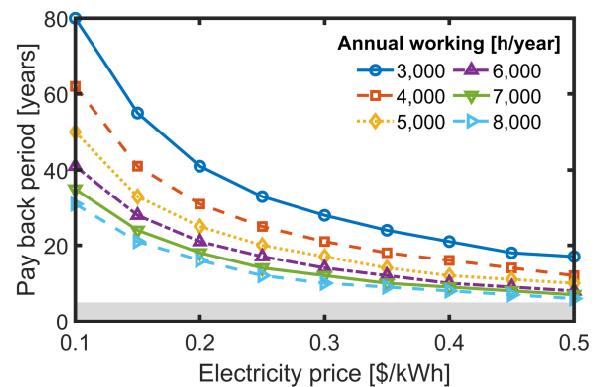


FIGURE 18. Payback period parametric study for employing the recommended coreless AFPM machine with a Halbach array rotor in place of the surface-mount PM design as a function of electricity cost and annual operating hours.

TABLE 6. Representative residential electricity price benchmarks for selected regions, compiled from credible sources and provided for contextual reference in interpreting the payback period results.

Location	Price [\$/kWh]	References
United States of America	0.18	[45]
United Kingdom & European Union	0.32	[46], [47]
People's Republic of China	0.08	[48]

that of the surface-mounted PM variant costs substantially more. Although the Halbach configuration benefits from a lower active material mass, since cost and efficiency are the primary objectives for the applications considered in this study, the coreless AFPM machine with a Halbach array PM rotor cannot be a competitive alternative for HVAC and fan applications. Compared with currently available electric motors in the market, including the references cited above, this type of motor remains more expensive. In addition to the higher material costs, manufacturing Halbach-array PM rotors is significantly more labor-intensive, which may further increase overall production costs.

The machine variant equipped with a Halbach-array PM rotor achieves higher efficiency, albeit at increased cost, as shown in Fig. 17. To further evaluate whether this efficiency improvement is economically beneficial, a payback analysis was conducted, considering electricity costs and relative motor costs to those of the surface-mount PM variant for the recommended optimal designs.

The payback period as a function of electricity price for multiple motor operating-hour cases is calculated and presented in Fig. 18. Based on residential electricity prices across three regions, as listed in Table 6, the results indicate that the compensation period required to offset the higher initial cost of the Halbach array variant significantly exceeds the typically acceptable payback period of 4 to 5 years. This suggests that the additional cost associated with the Halbach array rotor configuration is not economically justified for the

applications considered in this study.

It should be emphasized that the cost analysis presented in this section is intended for comparative evaluation rather than as a definitive economic assessment or investment recommendation. The estimated manufacturing costs, operating costs, and payback periods are based on material prices, electricity costs, and other economic assumptions applicable to a specific time and location. Advancements in manufacturing technology, such as those developed by well-established and reputable manufacturers [49], variations in market conditions, regional manufacturing costs, or future fluctuations in material and energy prices will inevitably affect predictions of absolute cost and payback period.

Nevertheless, the primary conclusion of this study remains robust. The predicted differences in manufacturing cost and payback period between the surface-mounted PM and Halbach-array PM coreless AFPM machines are sufficiently large that variations in the underlying economic assumptions are unlikely to alter the overall conclusion. This outcome is fundamentally driven by the electromagnetic characteristics demonstrated throughout this paper, which shows that although the Halbach-array design achieves a lower machine mass, it requires a greater PM volume to attain efficiency levels comparable to those of the surface-mounted PM design. Since PMs are the most expensive components of these machines, the increased magnet requirement dominates the overall manufacturing cost, resulting in a significantly longer payback period that outweighs the benefits of reduced weight for the application considered.

VI. PROTOTYPE AND EXPERIMENTAL RESULTS

Given the results of the cost analysis and the desired objectives for HVAC and fan applications, the Halbach-array PM rotor variant is considered not financially viable in the example case study. The surface-mount PM rotor variant, however, demonstrates strong potential for these applications with the integration of PCB stators that reduce volume and weight. As a result of these conclusions, the more viable and suitable machine, the surface-mount PM rotor variant, was prototyped and tested to validate the analytical and FEA results used for optimization and comparison."

One side of the prototyped surface-mount PM rotor and a PCB corresponding to one phase of the three-phase stator are shown in Fig. 19(a). To fabricate the stator, three identical PCBs are stacked with a 120° electrical phase shift to form the three-phase winding. The assembled prototype is shown in Fig. 19(b).

Back-EMF measurements were performed by coupling the prototype machine to a servomotor operating as the prime mover, as shown in Fig. 20. The servo motor was controlled by a drive system, both of which were manufactured by Kollmorgen. The prototype was driven to its rated speed of 2,100 rpm, and the voltage waveforms were recorded using a YOKOGAWA oscilloscope. The measured single-phase back-EMF at rated speed are compared with analytical and FEA results in Fig. 21.

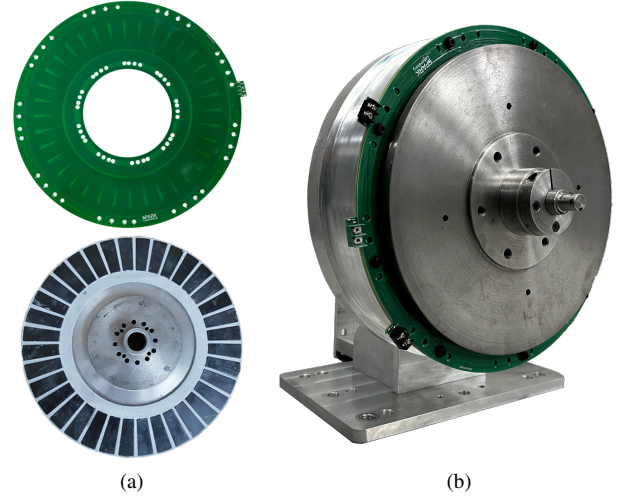


FIGURE 19. Coreless PCB stator AFPM machine with surface PM rotor, rated for 19 N.m at 2,100 rpm, selected for prototyping based on the comprehensive optimization study, showing (a) surface PM rotor and PCB stator prototypes and (b) the assembled coreless AFPM prototype.

TABLE 7. Specifications and main dimensions of the prototyped coreless-stator AFPM machines.

Parameter	Value	Unit
Outer diameter, D_o	310	mm
Pole number, P	36	–
PM axial length, L_{pm}	5	mm
PM arc-to-pole pitch ratio, $k_{w_{pm}}$	0.8	–
PCB axial length per phase, L_{pcb}	2	mm
Mechanical airgap, g	1.0	mm

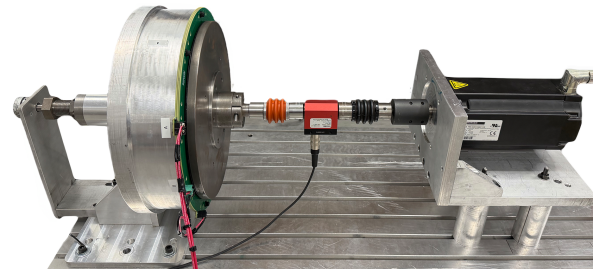


FIGURE 20. Experimental setup for b-EMF measurement, in which the prototype machine is mechanically coupled to a servo motor operating as a prime mover, with rotational speed controlled via a drive system.

Static torque was evaluated by mechanically locking the rotor at multiple angular positions and applying DC voltages corresponding to various excitation currents. Torque measurements were obtained using a non-contact FUTEK torque sensor installed between the prototype motor shaft and a mechanical lock. The operating current at the rated torque was then used to compute the Joule losses based on the measured phase resistance. The resulting measured and calculated performance parameters are summarized in Table 8.

The performance of the prototype machine was additionally validated using a second test configuration illustrated

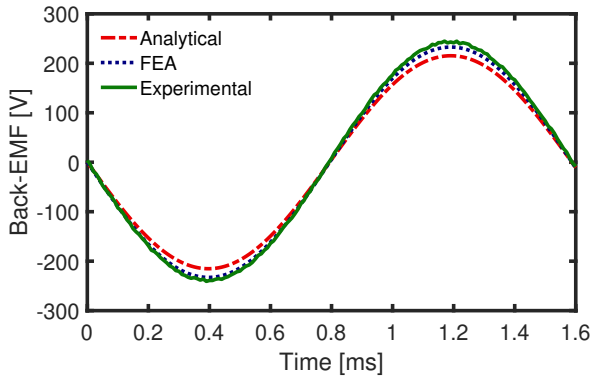


FIGURE 21. Analytically calculated, FEA simulated, and experimentally measured Back-EMF waveforms for the prototyped coreless PCB stator AFPM machine with dual surface PM rotors.

TABLE 8. Experimentally Measured and Calculated Parameters and Losses of the Prototyped Surface PM Rotor Coreless AFPM Machine at the Rated Condition.

Parameter	Analy.	3D FEA	Exp.	Unit
Torque	18.6	19.0	19.1	N.m
Torque constant	2.1	2.1	2.1	Nm/A
Phase resistance	0.56	0.55	0.57	Ω
Phase inductance	-	28.2	32.3	μH
Joule losses	121.3	125.4	129.5	W

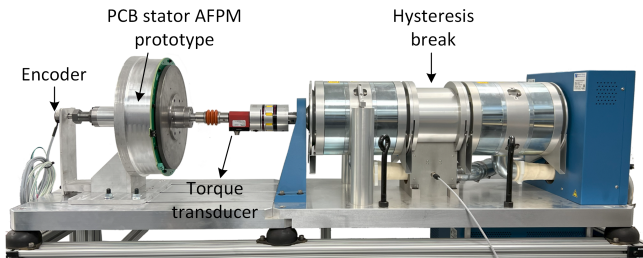


FIGURE 22. Experimental setup for the dynamic performance evaluation of the coreless AFPM prototype, with the machine mechanically coupled to a controllable hysteresis brake that serves as an adjustable load.

in Fig. 22. The machine was mechanically coupled to an electronically controlled hysteresis brake manufactured by Magtrol, which served as a programmable load. A non-contact torque transducer was installed between the prototype motor and the brake to measure the output torque. The machine was supplied by a two-level inverter with silicon carbide (SiC) switches, enabling high switching frequency.

A hardware-in-the-loop (HiL) platform was utilized to facilitate real-time control and data acquisition. Specifically, the models were developed in MATLAB/Simulink and were interfaced with a dSPACE MicroLabBox to generate gate signals, execute control algorithms, process encoder feedback, and measure phase currents and output torque in real time.

Field-oriented control (FOC) was implemented to control the machine, and its dynamic performance was experimentally assessed. The speed control loop was carefully designed

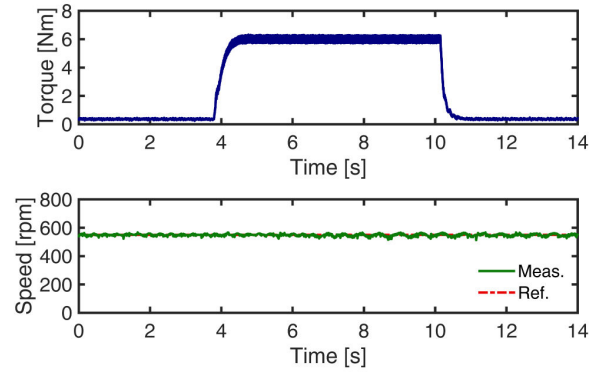


FIGURE 23. Measured output torque and speed of the machine under FOC during a sudden step change in load applied by the hysteresis brake, demonstrating accurate speed regulation at the commanded value.

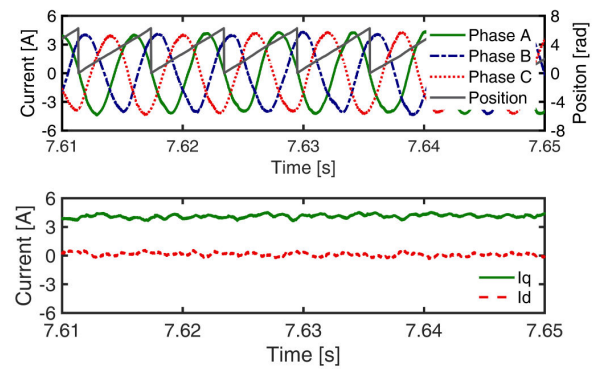


FIGURE 24. Zoomed-in view of the measured three-phase and dq-axis current waveforms corresponding to the torque profile shown in the previous figure.

based on the mechanical time constant of the system to ensure stable transient behavior. The drive response under a step change in load torque is presented in Fig. 23. The measured phase currents, near-sinusoidal waveforms, and the corresponding dq-axis currents are shown in Fig. 24. This low-ripple current waveform is primarily attributed to the 65 kHz switching frequency, which reduces current distortion and enhances control precision.

VII. CONCLUSION

This paper provided a systematic comparison of the cost and performance of coreless AFPM machines with surface mount and Halbach-array PM rotors. The Halbach array rotor enables the removal of rotor back iron and increases the air-gap flux density within the same rotor volumetric envelope. Coreless AFPM machines employing PCB stators were optimized with both rotor configurations, considering cost and loss objectives. The optimization results indicated that, for an identical efficiency target, the machine employing a Halbach array PM rotor is approximately 30% more expensive when only active electromagnetic components are considered. A more comprehensive cost evaluation, including manufacturing aspects such as the non-ferromagnetic back plate and increased manufacturing complexity, showed that

the Halbach rotor variant machine can be about 50% more expensive. The Halbach array rotor requires a greater volume of PM material to achieve comparable efficiency, but it offers the potential for reduced mass due to the elimination of rotor back iron, particularly when lightweight composite materials are utilized for structural support.

The optimal Halbach array designs tend towards a larger magnet-to-magnet gap than the surface PM rotor, enabling more PCB layers in the stator and reducing current density for the same rated power. Reducing the current density improves the cooling capability of the Halbach array rotor variant by lowering Joule losses and also enabling additional air-gap space for forced cooling in applications with high electrical loading, such as aerospace. Consequently, the comparison study indicated that Halbach array rotor designs may achieve higher efficiency and lighter mass, but cost significantly more than their surface PM counterparts. Depending on whether the application is cost-restricted, such as in HVAC fans, or volume and mass-restricted, as in electric propulsion, the surface PM or Halbach array variants may be better fits, respectively.

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REFERENCES

- [1] J. Gieras, R.-J. Wang, and M. Kamper, "Axial Flux Permanent Magnet Brushless Machines". 2nd Edition, Springer, Berlin, 2008.
- [2] M. Rosu, P. Zhou, D. Lin, D. Ionel, M. Popescu, F. Blaabjerg, V. Rallabandi, and D. Staton, "Multiphysics Simulation by Design for Electrical Machines, Power Electronics and Drives". J. Wiley - IEEE Press, 2017.
- [3] 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.
- [4] M. Vatani, D. D. Lewis, J. Frederic Eastham, and D. M. Ionel, "Review of coreless axial flux permanent magnet machines with applications including electric aircraft propulsion," *IEEE Transactions on Transportation Electrification*, vol. 11, no. 5, pp. 11 358–11 384, 2025.
- [5] J. Cotrell, "Boulder wind power advanced gearless drivetrain: Cooperative research and development final report, crada number crd-12-00463," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2013.
- [6] B. Anvari, P. Guedes-Pinto, and R. Lee, "Dual rotor axial flux permanent magnet motor using PCB stator," in *2021 IEEE International Electric Machines & Drives Conference (IEMDC)*, 2021, pp. 1–7.
- [7] B. Anvari, P. Guedes-Pinto, and R. A. Lee, "Printed circuit board stator axial field rotary energy device with ferromagnetic yoke," Patent US 12,224,635 B2, Feb. 11, 2025, u.S. Patent.
- [8] Y. Chulaee, A. Mohammadi, M. Vatani, A. M. Cramer, and D. M. Ionel, "Fault-tolerant high-power two-phase coreless AFPM motor-drive system concept," *IEEE Transactions on Industry Applications*, vol. 61, no. 6, pp. 9372–9383, 2025.
- [9] N. S., S. P. Nikam, S. Singh, S. Pal, A. K. Wankhede, and B. G. Fernandes, "High-speed coreless axial-flux permanent-magnet motor with printed circuit board winding," *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1954–1962, 2019.
- [10] F. Marignetti, G. Volpe, S. M. Mirimani, and C. Cecati, "Electromagnetic design and modeling of a two-phase axial-flux printed circuit board motor," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 67–76, 2017.
- [11] M. Vatani, A. Mohammadi, D. D. Lewis, J. F. Eastham, and D. M. Ionel, "Axial flux permanent magnet generators for direct-drive wind turbines - review and optimal design studies," *IEEE Transactions on Industry Applications*, vol. 61, no. 6, pp. 9615–9627, 2025.
- [12] M. Vatani, J. F. Eastham, and D. M. Ionel, "Multi-disk coreless axial flux permanent magnet synchronous motors with surface PM and Halbach array rotors for electric aircraft propulsion," in *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2024, pp. 4986–4992.
- [13] D. Talebi, M. C. Gardner, S. V. Sankarraman, A. Daniar, and H. A. Toliyat, "Electromagnetic design characterization of a dual rotor axial flux motor for electric aircraft," *IEEE Transactions on Industry Applications*, vol. 58, no. 6, pp. 7088–7098, 2022.
- [14] Z. S. Du and J. Tangudu, "Novel compact 3-D PM machines for ultra high power density applications," in *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*. IEEE, 2023, pp. 1–7.
- [15] M. Vatani, Y. Chulaee, A. Mohammadi, D. R. Stewart, J. F. Eastham, and D. M. Ionel, "On the optimal design of coreless AFPM machines with Halbach array rotors for electric aircraft propulsion," in *2024 IEEE Transportation Electrification Conference & Expo (ITEC)*. IEEE, 2024.
- [16] M. R. Ricci, J. G. Sugar, B. E. Paden, and D. B. Paden, "Axial flux brushless permanent magnet electrical machine rotor," Nov. 27 2018, uS Patent 10,141,822.
- [17] Y. Chulaee, D. Lewis, M. Vatani, J. F. Eastham, and D. M. Ionel, "Torque and power capabilities of coreless axial flux machines with surface PMs and Halbach array rotors," in *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, 2023, pp. 1–6.
- [18] S. Gair, A. Canova, J. Eastham, and T. Betzer, "A new 2D FEM analysis of a disc machine with offset rotor," in *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*, vol. 1. IEEE, 1996, pp. 617–621.
- [19] Ansys, Inc., "Ansys Electronics Desktop," Release 2025 R2, Canonsburg, PA, USA, 2025.
- [20] 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 *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2024, pp. 5205–5211.
- [21] R.-J. Wang and M. J. Kamper, "Calculation of eddy current loss in axial field permanent-magnet machine with coreless stator," *IEEE Transactions on Energy Conversion*, vol. 19, no. 3, pp. 532–538, 2004.
- [22] W. H. Hayt and J. A. Buck, *Engineering Electromagnetics*, New York, NY, USA, 2006.
- [23] Y. Chulaee, G. Heins, B. Robinson, A. Mohammadi, M. Thiele, D. Patterson, and D. M. Ionel, "Design and optimization of high-efficiency coreless PCB stator axial flux PM machines with minimal eddy and circulating current losses," *IEEE Transactions on Industry Applications*, vol. 60, no. 6, pp. 8722–8735, 2024.
- [24] Y. Chulaee and D. M. Ionel, "Ultra-fast finite element analysis of coreless axial flux permanent magnet synchronous machines," *IET Electric Power Applications*, vol. 18, no. 8, pp. 883–896, 2024. [Online]. Available: <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/elp2.12439>
- [25] G. Y. Sizov, P. Zhang, D. M. Ionel, N. A. O. Demerdash, and M. Rosu, "Automated multi-objective design optimization of PM AC machines using computationally efficient FEA and differential evolution," *IEEE Transactions on Industry Applications*, vol. 49, no. 5, pp. 2086–2096, 2013.
- [26] R. Storn and K. Price, "Differential evolution: A simple and efficient heuristic for global optimization over continuous spaces," *Journal of Global Optimization*, vol. 11, no. 4, pp. 341–359, 1997.
- [27] P. Zhang, G. Y. Sizov, M. Li, D. M. Ionel, N. A. O. Demerdash, S. J. Stretz, and A. W. Yeaton, "Multi-objective tradeoffs in the design optimization of a brushless permanent-magnet machine with fractional-slot concentrated windings," *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3285–3294, 2014.
- [28] Y. Wang, "Coupled electromagnetic and thermal analysis and design optimization of synchronous electric machines," Master's thesis, Department of Electrical and Computer Engineering, University of Wisconsin–Madison, Madison, WI, USA, 2014.

- [29] J. R. Hendershot and T. J. E. Miller, *Design of brushless permanent-magnet motors*. Oxford university press, 1995.
- [30] M. Vatani, C. Sailabada, P. Masson, J. C. Ordonez, and D. M. Ionel, "Cryogenic thermal system for coreless axial flux PM machine with Litz wire winding for electric aircraft propulsion," in *2025 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)*, 2025, pp. 1–6.
- [31] Discovery Alert, "NdFeB magnets north america market 2025: Demand outlook," 2025, accessed: Apr. 5, 2026. [Online]. Available: <https://discoveryalert.com.au/ndfeb-magnets-north-america-market-2025-demand/>
- [32] CoTec Holdings Corp., "HyProMag USA feasibility study demonstrates robust economics and the opportunity to develop a major new domestic source of recycled rare earth magnets for the united states," Nov. 2024, accessed: Apr. 5, 2026. [Online]. Available: <https://www.cotec.ca/news/hy-promag-usa-feasibility-study-demonstrates-robust-economics-and-the-opportunity-to-develop-a-major-new-domestic-source-of-recycled-rare-earth-magnets-for-the-united-states>
- [33] Trading Economics, "Neodymium," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://tradingeconomics.com/commodity/neodymium>
- [34] PCBCart, "PCB instant quote," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.pcbcart.com/quote>
- [35] ALLPCB, "Decoding PCB manufacturing costs: A comprehensive guide for 2025," 2025, accessed: Apr. 5, 2026. [Online]. Available: <https://www.allpcb.com/allectrohub/decoding-pcb-manufacturing-costs-a-comprehensive-guide-for-2025>
- [36] Ryerson, "Are steel prices coming down?" 2025, accessed: Apr. 5, 2026. [Online]. Available: <https://www.ryerson.com/metal-resources/metal-market-intelligence/are-steel-prices-coming-down/>
- [37] V. Madonna, C. M. Meano, R. Cossu, M. Pensato, and K. F. Hansen, "Investigating the impact of material cost fluctuations on the total manufacturing cost of ev traction machines," in *2023 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, 2023, pp. 1–6.
- [38] Baldor, "Em3615t," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.baldor.com/catalog/EM3615T>
- [39] Galco Industrial Electronics, "Em3615t-8-bldr," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.galco.com/em3615t-8-bldr.html>
- [40] WEG, "W22 NEMA premium efficiency 5 hp 4p 182/4t 3ph 230/460/380 v 60/50 hz ic411 - tefc - foot-mounted," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.weg.net/catalog/weg/US/en/Electric-Motors/AC-Motors---NEMA/General-Purpose-/TEFC-Cast-Iron/W22/W22-/W22-NEMA-Premium-Efficiency-5-HP-4P-182-4T-3Ph-230-460-380-V-60-50-Hz-IC411---TEFC---Foot-mounted/p/11416668>
- [41] MROSupply, "WEG 00518et3e184t-w22 5hp 1800 3 60 208-230/460v tefc-NEMA premium," 2026, accessed: Apr. 5, 2026. [Online]. Available: https://www.mrosupply.com/electric-motors/1312205_00518et3e184t-w22_weg/
- [42] Infinitum, "Infinitum: Sustainable air-core motor systems," <https://goinfinitum.com/>, 2026, accessed: 2026-06-22.
- [43] DE Staff, "Rockwell, Infinitum to develop VFD drive and PCB stator motor combo," *Design Engineering*, Sep. 2023. [Online]. Available: <https://www.design-engineering.com/rockwell-infinitum-to-develop-vfd-drive-and-pcb-stator-motor-combo-1004041027/>
- [44] ECM PCB Stator Technology, "PCB stator technology," <https://pcbstator.com/>, 2026, accessed: 2026-06-22.
- [45] U.S. Energy Information Administration (EIA), "Electricity monthly update," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.eia.gov/electricity/monthly/update/print-version.php>
- [46] Ofgem, "Energy price cap explained," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.ofgem.gov.uk/information-consumers/energy-advice-households/energy-price-cap-explained>
- [47] Eurostat, "Household electricity prices in the first half of 2025," Oct. 2025, accessed: Apr. 5, 2026. [Online]. Available: <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20251029-2>
- [48] CEIC Data, "China: Service price: 36 city avg: Electricity for resident (220v)," 2026, accessed: Apr. 5, 2026. [Online]. Available: <https://www.ceicdata.com/en/china/electricity-price-36-city/cn-service-price-36-city-avg-electricity-for-resident-220v>
- [49] Arnold Magnetic Technologies, "L-Type Laminated Magnets," <https://www.arnoldmagnetics.com/products/l-type-laminated-magnets/>, 2026, accessed: 2026-06-27.



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