

Halbach–Mallinson Array Rotor with Variable Length PMs for Axial-Flux Machines

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Abstract—This paper proposes new topologies for axial-flux Halbach–Mallinson permanent magnet (PM) array rotors, which employ the optimal material usage, improve the specific power, and enhance the rotor manufacturability. The air-gap flux density variation along the radial direction of conventional Halbach–Mallinson PM rotors is analyzed to establish the PM impact of axial length impact on the electromagnetic performance, showing that the optimal magnet cross section occurs when the PM width equals the PM length in the axial direction of magnetization. New proposed topologies are particularly advantageous by appropriating a square cross section at multiple radii. Parametric studies using 2D and 3D finite element analysis (FEA) simulations were conducted to quantify the performance improvements. The results indicate that for the machine design studied, employing the proposed rotor would increase the electromagnetic torque by nearly 10% and the specific torque by approximately 5%, as compared to the machine equipped with the conventional Halbach–Mallinson rotor.

Index Terms—Halbach array, Mallinson array, axial flux PM machines, coreless stator, permanent magnet loss.

I. INTRODUCTION

Permanent magnet synchronous machines (PMSMs) play a central role in modern electromechanical systems due to their high efficiency, robust performance, and compact form factor [1], [2]. The adoption of high-energy magnets has allowed these machines to increase their power density [3], positioning them as a preferred choice for traction and propulsion applications over the past two decades [4]. Of particular timely interest, are machines that employ a special permanent magnet (PM) array that yields high air-gap flux density. The concept was first proposed by Mallinson [5] and later implemented by Halbach [6], who derived the analytical field equations governing this class of PM arrangements [7].

Among the various PMSM configurations, axial-flux permanent magnet (AFPM) machines, in which the air-gap flux travels parallel to the axis of rotation rather than radially, present a compelling alternative [8], [9]. Such machines have been reported to have very high volumetric power density and specific power, making them particularly well suited for electric aircraft propulsion [4], [10], [11].

Coreless stator designs of AFPM type have attracted growing interest due to their advantages [12]. Without ferromag-

netic saliency, cogging, or reluctance torque, these machines exhibit lower torque ripple, vibration, and acoustic noise [13], while the absence of a ferromagnetic core also eliminates associated losses, enabling coreless AFPM machines to potentially reach higher efficiencies and power densities than their iron-cored counterparts [14], [15]. Combined with the increasing design maturity and manufacturing processes, these advantages make coreless AFPM machines attractive across a broad range of applications, from low-power HVAC systems to high-power-density electric aircraft propulsion and large direct-drive wind turbine generators [16].

By rotating the magnetization direction from one PM to the next [17], the Halbach–Mallinson array concentrates flux on one side of the rotor while canceling it on the other, increasing the air-gap flux density by approximately 30% relative to conventional surface-mounted PM topologies, for an equivalent rotor volume [18]. Because the flux path closes through the tangentially magnetized PMs, the rotor back iron can be omitted entirely, reducing rotor mass and further improving specific power density [14]. Halbach–Mallinson arrays have been adopted across industrial, automotive, aerospace, household-appliance, and wind-turbine generator applications [19], [20].

Improvements to the motor configuration offer an additional path to higher output power. Although AFPM torque capability scales with the cube of the rotor diameter, simply enlarging the diameter is constrained by the design envelope and the additional axial forces imposed on bearings and mechanical joints [21]. Alternatively, stacking multiple AFPM units on a common shaft increases power while holding diameter constant, extending only the total axial length of the machine [22], [23]. This multi-unit approach also improves system fault-tolerance, since even if one unit fails, the remaining ones can continue delivering power [24]. Recent studies have identified mechanically coupled multi-stator multi-rotor configurations as an attractive design solution due to their combined efficiency, flexibility, and redundancy [25], [26].

Due the annular geometry of AFPM machines, the circumferential dimensions of the PMs increase with diameter, which is a source of variation in the air-gap flux density along the radial direction. Commonly known as the curvature effect [27], this paper addresses it by introducing a novel Halbach–Mallinson PM rotor topology in which the PM length in the axial direction of magnetization varies along the radial direction. This variation yields optimal PM dimensions across all radii, improving electromagnetic performance relative to

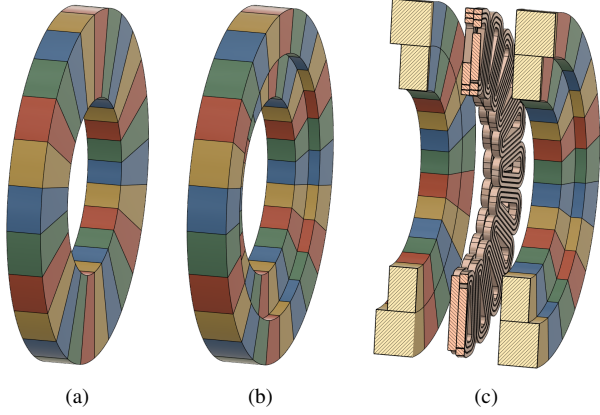


Fig. 1. (a) Conventional Halbach-Mallinson array rotor with uniform PM axial length, (b) stepped rotor with trapezoidal PMs providing diameter-dependent axial length, and (c) exploded cross-sectional view of an example coreless AFPM machine with double sided stepped Halbach-Mallinson rotor.

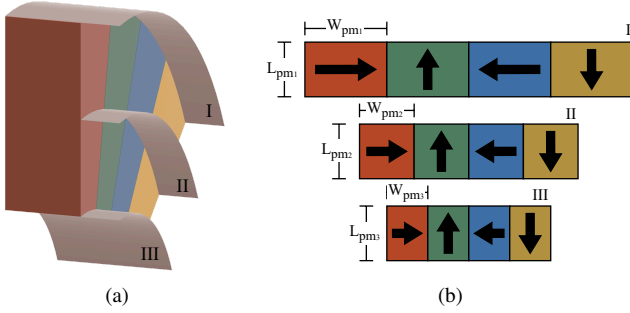


Fig. 2. Conventional Halbach-Mallinson array rotor: (a) two pole-pitch section with planar cuts along the outer, average, and inner diameters, and (b) respective unrolled 2D models.

the conventional topology while preserving approximately the same PM volume.

To assess whether the proposed rotor topology provides a meaningful performance benefit, the electromagnetic performance and PM volume are compared against a conventional Halbach-Mallinson rotor. Multiple topology variants are proposed, further improving manufacturability and mitigating eddy-current losses.

II. PROPOSED ROTOR TOPOLOGIES

In axial-flux machines with a conventional Halbach-Mallinson PM rotor, such as the one shown in Fig. 1(a), the pole pitch at the inner diameter is smaller than that at the outer diameter due to the curvature effect. Illustrated in Fig. 2(a) and 2(b), the PM width W_{pm} increases with the diameter while the PM axial length remains constant, which causes a variation of the flux density distribution in the air gap along the radii.

Considering that a square PM cross section yields optimal utilization of PM material in Halbach-Mallinson rotors [18], this work proposes rotor topologies in which the PM length in the axial direction of magnetization is defined as a function of diameter rather than held constant, as seen in Fig. 3. Since the pole pitch increases linearly with diameter, the proposed

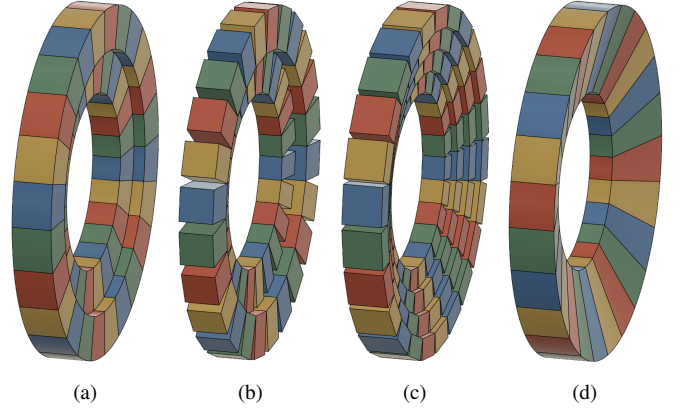


Fig. 3. Examples proposed variable length Halbach-Mallinson PM rotors: (a) stepped with two trapezoidal-shaped radial PM segments (b) stepped with two squared-prism radial PM segments, (c) stepped with four squared-prism radial PM segments, and (d) continuously taper.

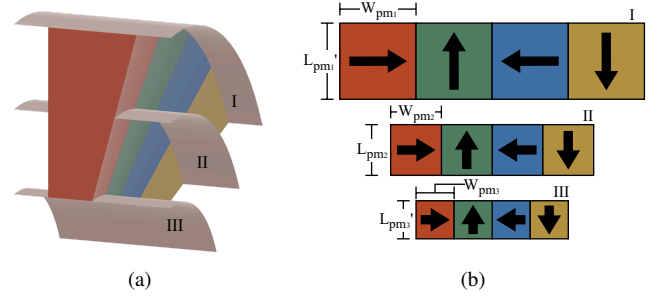


Fig. 4. Proposed continuous-taper rotor: (a) two pole-pitch section with planar cuts along the outer, average, and inner diameters, and (b) respective unrolled 2D models.

rotor yields a PM axial length that varies linearly from the inner to the outer diameter, preserving an optimal cross section throughout the entire PM, as shown in Fig. 4(a) and 4(b).

The proposed rotor topology is well suited for radial PM segmentation, which is an effective method to mitigate eddy-current losses [28]. The PM eddy current losses can be expressed as [29]–[31]:

$$P_{edd_{pm}} = \frac{V\pi^2 f^2 B_m^2}{6\rho} \left(\frac{W}{N} \right)^2, \quad (1)$$

where V is the PM volume, B_m is the flux density from the stator armature winding, W is the PM width, ρ is the PM electrical resistivity, and N is the number of segments.

This creates the opportunity to employ PMs in which each segment has a different axial length, allowing the optimal cross-sectional geometry to be approximated in discrete steps, as shown in Fig. 3(a). In this topology, each segment has a square cross section at its corresponding average diameter, and the combination of all segments results in a total volume nearly identical to that of the continuously tapered geometry shown in Fig. 3(d).

This approach can also be implemented with rectangular PMs, which improves manufacturability due to the simplified shape. In this case, the same block can be employed either as

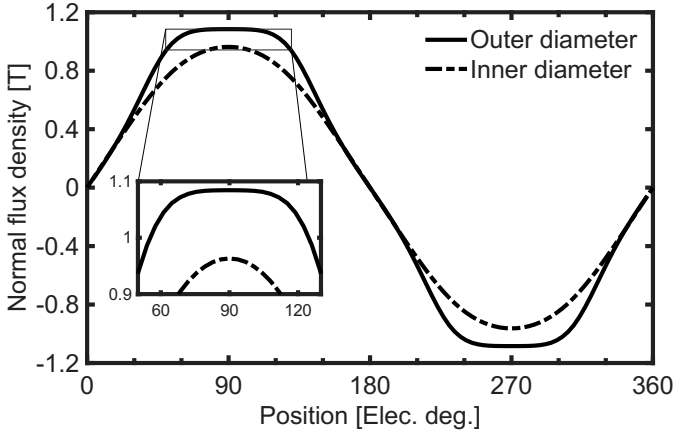


Fig. 5. Normal air-gap flux density at the mid-air-gap plane, evaluated at the outer and inner diameters, for an example coreless AFPM machine with a conventional Halbach-Mallinson rotor.

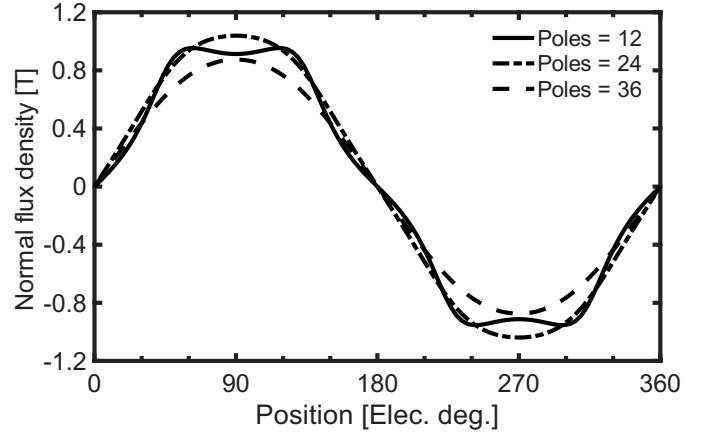


Fig. 6. Normal component of the air-gap flux density at the mid-air-gap plane, evaluated at the average diameter, for varying pole numbers in an example coreless AFPM machine with a conventional Halbach-Mallinson rotor.

an axially or tangentially magnetized PM within the Halbach-Mallinson array by simply rotating it, which further improves the manufacturability of the rotor by reducing the number of PM variations needed. Example implementations with two and four PM blocks are shown in Fig. 3(b) and 3(c). The proposed rotors may be implemented in coreless machines, as seen in 1(c), as well as in machines with cored stators.

The normal flux density component for a conventional Halbach-Mallinson array PM rotor can be expressed as in [16], and extended to a stepped rotor with N radial segments, each having its own PM axial length $L_{pm,j}$ and pole pitch $\tau_{p,j}$:

$$B_{y_{HM},j}(x, y) = \sum_{i=0}^{\infty} 2B_r \frac{\sin(\alpha k \pi / 4)}{k \pi / 4} \left[1 - \exp\left(\frac{-k \pi L_{pm,j}}{\tau_{p,j}}\right) \right] \exp\left(\frac{-k \pi g_{m2m}}{2 \tau_{p,j}}\right) \cosh\left(\frac{k \pi y}{\tau_{p,j}}\right) \sin\left(\frac{k \pi x}{\tau_{p,j}}\right), \quad (2)$$

where B_r is the PM remanence, α a constant typically equal to unity, L_{pm} the PM axial length, τ_p the pole pitch width, g_{m2m} the magnet-to-magnet gap. Lastly, the term $k = 1 + 4\nu$, where ν denotes the harmonic order and 4 is the number of PM per wavelength.

This formulation assumes that each set of segments behaves as a local Halbach-Mallinson array, radially separated from its neighbors, with magnetic decoupling between segments of the same PM. Therefore, 3D finite element analysis (FEA) should be employed to capture the magnetic coupling between segments as well as other aspects neglected by the equivalent 2D modeling of the analytical model.

An essential term in (2) is the PM axial length to pole pitch ratio, L_{pm}/τ_p , referred to in this paper also as k_{pm} , which captures the dependency of the L_{pm} on pole pitch. Since the pole pitch varies along the radius in axial-flux machines, the selection of L_{pm} becomes critical.

III. ELECTROMAGNETIC FIELD STUDIES

The 3D FEA electromagnetic model used for these studies was based on, and verified by, a 36-pole, 300 mm outer-diameter, coreless-stator AFPM motor prototype [16]. A parametric study conducted to compare the air gap flux density distributions at the inner and outer diameters of a conventional Halbach-Mallinson rotor. Results, illustrated in Fig. 5, show an approximately 15% difference in amplitude, indicating a non-uniform flux density distribution along the radial direction of the air gap.

The curvature effect has a greater impact as the pole number decreases in a conventional Halbach-Mallinson rotor, considering that the PM width $W_{pm} = \frac{\pi}{p} R$, where p is the pole number and R the radius. This was examined and shown in Fig. 6, where the flux density distribution at average diameter is presented across varying pole numbers.

The fundamental normal flux density component at the mid-air-gap plane varies with k_{pm} and is illustrated for a conventional Halbach-Mallinson rotor in Fig. 7, where the flux density varies almost linearly up to a knee point at $k_{pm} = 0.5$. Beyond this point, the flux density saturates and further increases in the PM axial length yield negligible improvement. This knee point corresponds to a square PM cross section, which also represents the optimal trade-off between flux density production and PM material utilization.

The parametric studies in this section demonstrated how significant the impact of the curvature effect can be on the rotor's magnetic field. The flux density distributions were obtained using 2D FEA models representing cross-sections at different diameters of the rotor. To further investigate the proposed rotor, 3D FEA parametric models have been developed for the continuous-taper topology, as illustrated in Fig. 8, and implemented in Ansys Electronics Desktop software [32].

IV. PERFORMANCE COMPARISON AND DISCUSSION

Parametric studies were conducted to quantify the performance improvement of the proposed Halbach-Mallinson PM

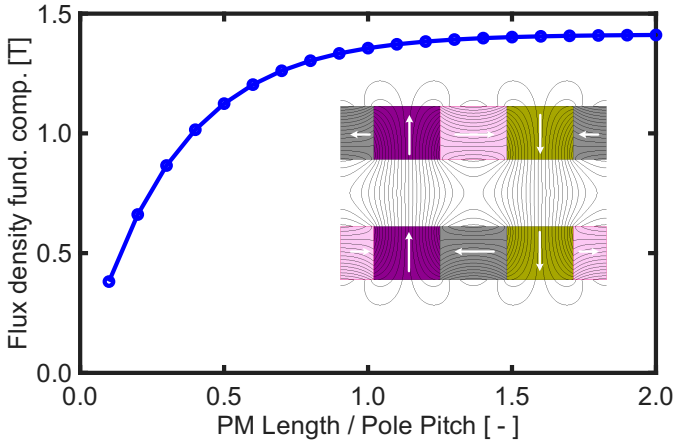


Fig. 7. Fundamental normal component of the air-gap flux density at the mid-air-gap plane, evaluated at the average diameter and calculated using 2D FEA, for varying PM axial lengths in an example coreless AFPM machine with a conventional Halbach-Mallinson rotor.

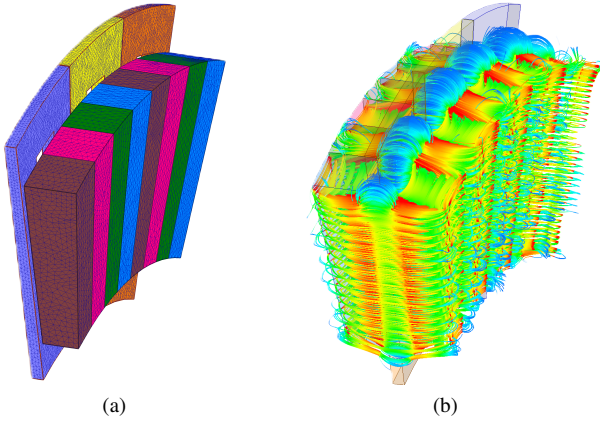


Fig. 8. Three-dimensional electromagnetic FEA model of an example coreless AFPM machine employing a continuous-taper Halbach-Mallinson rotor: (a) finite-element mesh and (b) magnetic flux density distribution.

rotor in a coreless-stator AFPM machine. Results from 3D FEA, illustrated in Fig. 9, indicate almost 10% higher electromagnetic torque production by the proposed rotor topology, when compared to the conventional rotor for inner-to-outer diameter ratio $\lambda = 0.5$.

At lower λ values, i.e., PMs with larger radial lengths, the torque of the conventional topology decreases due to a change winding geometry and winding factor reduction [16], while the proposed rotor compensates for this with increased air-gap flux density from the modified PM geometry, improving the electromagnetic torque production. In contrast, at higher λ values, both rotors perform similarly, since at smaller PM radial lengths, the difference in τ_p between the inner and outer diameter decreases, narrowing the gap in PM axial length L_{pm} between the conventional and the proposed rotors.

This is advantageous since the AFPM machines typically tend to have large outer diameters and small radial length, ring-shaped design, to allow optimal material utilization [33]–[36]. The proposed topology enables longer radial lengths, which is

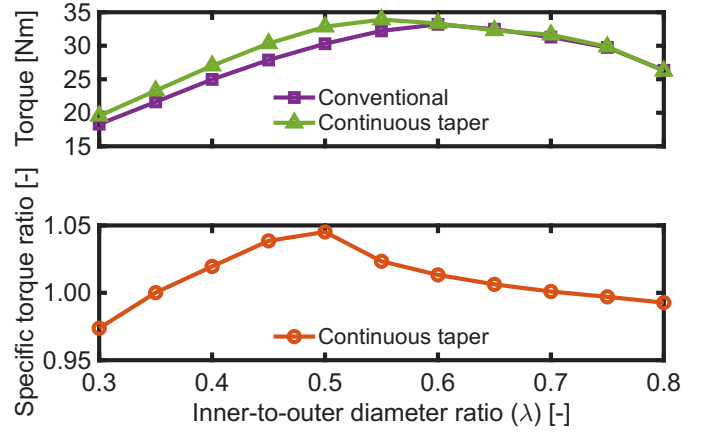


Fig. 9. Torque comparison between coreless AFPM machines employing either a conventional or a continuous-taper Halbach-Mallinson rotor for varying motor radial lengths.

particularly important for the cases with size constraints.

To compare the PM material utilization between the two rotors, the volume equations are derived in terms of the ratio $k_{pm} = L_{pm}/\tau_p$, inner-to-outer diameter ratio λ , outer diameter OD , and number of poles p :

$$V_{conv} = \frac{\pi^2 k_{pm} OD^3}{8p} (1 - \lambda)(1 + \lambda)^2 \quad (3)$$

$$V_{tap} = \frac{\pi^2 k_{pm} OD^3}{6p} (1 - \lambda^3) \quad (4)$$

$$\frac{V_{tap}}{V_{conv}} = \frac{4}{3} \frac{1 + \lambda + \lambda^2}{(1 + \lambda)^2}. \quad (5)$$

Due to the distribution of PM material in each topology, the continuous-taper rotor produces nearly 10% more torque and yields approximately 5% more specific torque (Nm/kg of PM), for $\lambda = 0.5$. The conventional rotor has excess material near the inner diameter, where the local k_{pm} exceeds its optimal value, while having deficiency of material near the outer diameter, where k_{pm} falls below optimal. As opposed to the continuous-taper rotor, which corrects this by shifting material away from the inner diameter to the outer diameter, where the same material is used more effectively.

V. CONCLUSION

This paper presented new axial-flux Halbach-Mallinson PM array rotor topologies designed to make more efficient use of PM material while improving specific power and manufacturability. Parametric 2D and 3D FEA studies were carried out to quantify the resulting performance gains.

The results show that, for the machine design considered, employing the proposed Halbach-Mallinson rotor increases the electromagnetic torque by nearly 10% and the specific torque by approximately 5% relative to the machine using the conventional rotor.

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