

BLDC Motor Design with Enhanced Torque Density: A Systematic Review of Design Strategies, Optimization Methods, and Emerging Technologies

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Abstract

The demand for high-torque-density brushless DC (BLDC) motors has accelerated across robotics, electric vehicles, and electric aviation, driven by the need for compact, lightweight actuation without sacrificing performance. This review synthesizes recent advances in BLDC motor design strategies aimed at torque density enhancement. It identifies four principal design levers: (1) magnetic circuit topology innovations, including Halbach arrays, dual air-gap configurations, and multi-module spliced structures; (2) geometric parameter optimization through multi-objective algorithms such as quasi-Newton methods, Grey Wolf Optimization, and particle swarm optimization; (3) winding and material innovations, particularly flexible printed circuit board (FPCB) windings and segmented spiral topologies; and (4) loss minimization strategies that enable higher current density operation. The review further examines the persistent trade-off between torque density and manufacturability, and evaluates how emerging approaches balance these competing demands. Findings indicate that torque density improvements ranging from 8% to 28% are achievable through integrated structural-control optimization, with reported peak values of 56 N·m/kg for eVTOL applications and 4.08 N·m/kg for electric propulsion systems. Future research directions are identified, including thermal management under high current density, sensorless control integration, and sustainable material strategies that reduce rare-earth dependence.

Keywords: BLDC motor, torque density, Halbach array, multi-objective optimization, axial flux, outer rotor, finite element analysis

1. Introduction

The brushless DC (BLDC) motor has become the actuator of choice for applications demanding high efficiency, long lifespan, and precise torque control. Unlike brushed DC motors, which suffer from mechanical commutation wear, BLDC motors employ electronic commutation and permanent magnet excitation, yielding superior power-to-weight ratios and reliability. However, as application domains expand—from collaborative robots requiring compact joint actuators to electric vertical takeoff and landing (eVTOL) aircraft demanding extreme power density—the conventional BLDC design faces fundamental constraints. The torque output of a permanent magnet motor is limited by magnetic saturation, thermal dissipation, and the physical volume available for copper and iron.

This constraint has spawned a rich body of research on torque density enhancement. The design problem is inherently multi-objective: increasing current density improves torque but elevates copper loss and temperature; enlarging magnets increases air-gap flux but adds weight and cost; optimizing for cogging torque reduction may sacrifice average torque. As Guo et al. note, the persistent challenge is breaking “the inherent

contradiction between high torque density and manufacturing feasibility”.

This paper reviews the principal strategies for enhancing BLDC motor torque density, organized around four design levers: magnetic topology, geometric optimization, winding innovation, and loss reduction. It evaluates the effectiveness of each approach, examines the trade-offs involved, and identifies emerging directions for future research.

2. Magnetic Topology Innovations for Torque Density

2.1 Halbach Magnet Arrays

The Halbach array—a spatially rotating pattern of magnet magnetization—offers one of the most effective passive means of concentrating air-gap flux. By strengthening the magnetic field on the active side of the rotor while canceling it on the inactive side, Halbach arrangements increase the fundamental flux density without increasing magnet volume.

Recent research has quantified the benefits of Halbach segmentation for torque density. In an eVTOL motor optimization study, researchers analyzed the effect of different segment numbers on torque density, finding that the optimal segmentation depends on the trade-off between field concentration and manufacturing complexity. A separate project on low-rare-earth BLDC motors combined Halbach rotor molding with dual air-gap transverse flux stator technology, targeting a 400W motor with diameter-to-length ratio below 0.15 and rare-earth content under 10%. The approach demonstrated that Halbach arrays can simultaneously improve flux utilization and reduce dependence on scarce magnetic materials.

However, Halbach arrays introduce a design tension: the sinusoidal flux distribution they produce is ideal for reducing torque ripple, but the non-uniform field can complicate sensorless control. The project cited above addressed this by integrating sliding mode control with flux harmonic adjustment to compensate for non-sinusoidal flux effects.

2.2 Dual Air-Gap and Transverse Flux Configurations

A more radical departure from conventional radial-flux topology is the dual air-gap configuration. By employing a dual-rotor/single-stator or dual-stator/single-rotor architecture, the effective torque-generating area is doubled without increasing the motor’s radial envelope. The dual-winding arrangement also enables flux doubling through the magnetic circuit, providing what the project authors describe as “multiplied flux” and “increased air-gap action area”.

A patent describing a high-torque, low-current brushless motor exemplifies this principle: two Halbach arrays (inner and outer) cooperate to increase flux density in the volume where the coils reside, resulting in “higher output torque for a given current level relative to conventional designs employing only a single outer magnetic circuit”. This dual-cylinder architecture represents a distinct approach to torque density that does not rely solely on increased current or larger magnets.

2.3 Multi-Module Spliced Structures

For robotic actuation, where manufacturing cost and assembly complexity are critical constraints, the multi-module spliced outer rotor design offers a pragmatic path to torque density improvement. Guo et al. developed a novel multi-module spliced direct-drive outer rotor BLDC motor that simplifies manufacturing through split-slot

winding and modular stator tooth design . The structure enhances magnetic symmetry, reducing cogging torque by 38.89% while achieving a peak efficiency of 95.06%.

The key insight of this approach is that torque density gains need not come from exotic materials or complex topologies; careful structural modularization can simultaneously improve manufacturability and electromagnetic performance. The quasi-Newton optimization employed in this work refined pole-arc coefficient, air gap, and permanent magnet thickness, demonstrating that systematic parameter optimization can extract meaningful improvements even from conventional topologies .

2.4 Axial Flux Topologies

Axial flux permanent magnet (AFPM) motors occupy a distinct niche in high-torque-density applications. Their disk-like geometry provides a larger torque-generating surface for a given volume compared to radial flux machines, making them particularly suited to in-wheel traction and aerospace propulsion. The trade-off is manufacturing complexity and challenges in thermal management.

A multi-objective optimal design study for AFPM wheel motors in electric scooters reported commercial benchmarks illustrating the achievable range: Ashwoods' 27.6 kW motor achieves 6.95 N·m/kg, EVO Electric's 64 kW unit reaches 11.5 N·m/kg, and YASA Motors' 100 kW design achieves 30 N·m/kg . These figures, while impressive, come with higher driving voltages and peak currents exceeding 200A—a constraint that limits applicability in low-voltage systems.

More recent AFPM research has employed Grey Wolf Optimization (GWO) to refine stator teeth width, permanent magnet width, and inter-teeth

angles for EV applications, demonstrating significant torque improvement over baseline configurations .

3. Optimization Methodologies

3.1 Multi-Objective Algorithms

The BLDC design problem is inherently multi-objective: torque density, efficiency, cogging torque, torque ripple, and thermal performance must be balanced simultaneously. Single-parameter optimization, while simpler, often produces suboptimal configurations because these objectives are coupled.

Quasi-Newton methods have proven effective for robotic actuator design. Guo et al. employed a quasi-Newton multi-objective optimization algorithm that accelerated convergence toward globally optimal configurations, effectively balancing multiple design objectives . The method reduced cogging torque from 0.036 N·m to 0.022 N·m while maintaining torque ripple below the 30% threshold required for robot drive systems .

Grey Wolf Optimization (GWO) has been applied to AFPM BLDC motors for EV applications, targeting stator teeth width, PM width, and tooth angles to maximize torque while maintaining efficiency and compactness . The GWO approach is notable for its balance between exploration and exploitation, avoiding premature convergence to local optima.

Particle Swarm Optimization (PSO) has been used for AFPM motor design, where the algorithm determines optimal parameters by simulating social behavior of bird flocks . The method was applied to eliminate zero-flux regions in the rotor while preserving structural integrity, achieving a torque density of 1.56 N·m/kg in the optimized design.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) provides a systematic framework for evaluating trade-offs among competing optimization results. In eVTOL motor design, TOPSIS was used to weight torque density and efficiency equally, identifying the 23rd solution as optimal among multiple Pareto-optimal candidates.

3.2 Finite Element Analysis Integration

All modern BLDC optimization relies on finite element analysis (FEA) for validation and iterative refinement. ANSYS Maxwell is the dominant platform, enabling 2D and 3D electromagnetic simulation with coupled thermal analysis. The typical workflow involves analytical modeling for initial sizing, FEA for detailed parameter refinement, and prototype testing for final validation.

A critical insight from recent work is that structural-control co-optimization outperforms fragmented approaches. Guo et al. note that “most studies either optimize electromagnetic structures or improve control algorithms in isolation, while structural-control integration under space limitations is rarely addressed”. Their integrated framework dynamically couples FEA results with multi-objective optimization objectives, enabling iterative optimization under strict spatial constraints.

4. Winding and Material Innovations

4.1 FPCB and Spiral Winding Topologies

Flexible printed circuit board (FPCB) windings offer a manufacturing-friendly alternative to conventional enameled wire, with advantages in repeatability, assembly speed, and design flexibility. However, conventional FPCB winding topologies such as O-type and ∞ -type require

complex designs with up to 20 variables, limiting their practical application.

A recent innovation addresses this complexity through a **three-segment spiral winding** that reduces design variables to just two (vertical pitch ratio α and arc segment ratio β). The spiral topology achieves a 28.4% gain in motor constant, including a 26.3% increase in torque density and a 3.3% reduction in winding losses compared to traditional segmented designs. This represents a significant advance: torque density improvement without the loss penalty that typically accompanies increased current.

4.2 Magnet Segmentation and Composite Magnets

Permanent magnet segmentation—dividing magnets into electrically isolated segments—reduces eddy current losses in the magnets, enabling higher operating frequencies and current densities. For Halbach arrays, the number of segments per pole affects both field quality and manufacturing cost. The eVTOL study by systematically analyzed this trade-off, finding that optimal segmentation depends on the specific torque density target and loss constraints.

Composite magnet technology—combining different magnetic materials or layering magnets with soft magnetic composites—offers another route to torque density improvement with reduced rare-earth content. The low-rare-earth project described in employed laminated composite magnet technology with flux harmonic adjustment to achieve surface magnetic gradient control, reducing rare-earth usage while maintaining motor efficiency above 90%.

4.3 Back-EMF Waveform Engineering

Conventional BLDC motors are designed for trapezoidal back-EMF, which simplifies commutation but limits torque density. A modified BLDC motor with a **wide flat-topped back-EMF waveform** (approximately 169°) has been shown to provide 13.8% improvement in torque density while maintaining the same torque ripple as conventional BLDC drives. Critically, this improvement is achieved with only three Hall sensors and a simple two-phase conduction control scheme, preserving the cost advantage of conventional BLDC drives.

This approach highlights a broader principle: torque density enhancement need not require radical topology changes. By engineering the magnetic circuit to produce a more favorable back-EMF profile, meaningful gains can be extracted from conventional architectures.

5. Loss Minimization and Thermal Management

Torque density enhancement through increased current density is fundamentally limited by thermal dissipation. The copper loss (I^2R) scales quadratically with current, and winding temperatures must remain below insulation limits—typically $180\text{--}200^\circ\text{C}$ for Class H insulation.

5.1 Loss Reduction Strategies

The robotic actuator motor developed by Guo et al. achieved copper losses of only 12.8 W and iron losses of 22.5 W through careful electromagnetic design, representing a 16.36% reduction in iron loss compared to baseline. The optimization reduced air-gap flux density by 8.33% (from 0.72 T to 0.66 T), avoiding magnetic saturation while maintaining torque output.

For electric propulsion applications, a systematic efficiency-oriented design approach focusing on slot/tooth dimensioning and multistrand winding optimization achieved 90% efficiency at rated power, with steady-state winding temperatures of 140°C at 16.6 A/mm^2 and thermally sustainable operation up to 22.1 A/mm^2 under forced-air cooling. The reported torque density of $4.08\text{ N}\cdot\text{m/kg}$, while modest compared to eVTOL motors, reflects the thermal constraints of passively cooled aerospace propulsion systems.

5.2 Thermal-Electromagnetic Co-Design

The coupling between electromagnetic performance and thermal behavior necessitates co-design approaches. High current density operation increases torque but demands cooling solutions that add weight and complexity, partially offsetting torque density gains. The $4.08\text{ N}\cdot\text{m/kg}$ motor cited above maintained thermal margin of approximately 60°C below the insulation limit, suggesting headroom for further current density increases with enhanced cooling.

6. Comparative Analysis and Trade-Offs

6.1 Torque Density Benchmarks

The literature reveals a wide range of achievable torque densities depending on application context and cooling strategy.

Table 1 summarizes representative results:

Application	Topology	Torque Density	Key Strategy
eVTOL	Radial flux	56 N·m/kg	Multi-objective optimization, Halbach analysis
EV traction (AFPM)	Axial flux	30 N·m/kg	Commercial benchmark (YASA)
Electric propulsion	Outer rotor	4.08 N·m/kg	Efficiency-oriented design, forced-air cooling
Robotic actuation	Multi-module outer rotor	Not reported (95% efficiency)	Structural modularization, quasi-Newton optimization
AFPM wheel motor	Axial flux	11.5 N·m/kg	Commercial benchmark (EVO)
AFPM (optimized)	Axial flux	135 N·m/L (volumetric)	L/D ratio optimization

The variation reflects fundamental differences in cooling capability, duty cycle, and design constraints. Aerospace applications with liquid cooling achieve the highest gravimetric torque densities, while passively cooled systems sacrifice density for thermal robustness.

6.2 The Manufacturability Trade-Off

A recurring theme across the literature is the tension between torque density and manufacturing feasibility. Halbach arrays and dual air-gap configurations offer the highest theoretical torque densities but require precision assembly and complex magnetization patterns. The multi-module spliced structure represents a deliberate compromise: it sacrifices some theoretical torque

density for modularity, simplified winding, and reduced assembly cost.

This trade-off is particularly acute for robotic actuators, where unit volumes are lower than automotive applications and manufacturing cost per unit is correspondingly higher. The success of the modular approach suggests that for many applications, “good enough” torque density with excellent manufacturability outperforms “optimal” torque density with prohibitive production costs.

6.3 Torque Ripple Considerations

Torque density enhancement often exacerbates torque ripple—a critical concern for precision applications. The robotic actuator design maintained torque ripple at 24% (simulated) and 26% (measured), below the 30% threshold for robot drive systems. The modified BLDC motor with wide flat-topped back-EMF achieved torque density improvement “while ensuring that the torque ripple remains the same as that of a conventional BLdc motor drive”, demonstrating that torque density and smoothness are not inevitably in conflict.

Conclusion

Torque density enhancement in BLDC motors is achievable through multiple design levers: magnetic topology innovations (Halbach arrays, dual air-gap, multi-module structures), systematic geometric optimization (multi-objective algorithms with FEA validation), winding innovations (FPCB spiral topologies, back-EMF waveform engineering), and loss minimization strategies that enable higher current density operation. Reported improvements range from 8% to 28% relative to baseline designs, with absolute torque densities spanning 4 N·m/kg (passively cooled propulsion) to 56 N·m/kg (optimized eVTOL).

The persistent trade-off between torque density and manufacturability suggests that the “optimal” design is application-specific rather than universal. For robotic actuation, modular structures that sacrifice marginal torque density for simplified assembly and reduced cogging torque represent the pragmatic frontier. For aerospace and high-performance traction, aggressive topologies with advanced cooling justify their manufacturing complexity through superior gravimetric performance.

Future advances will likely come from integrated co-design approaches that treat electromagnetic, thermal, and control considerations as coupled rather than sequential design problems. The convergence of multi-objective optimization, high-fidelity FEA, and advanced manufacturing techniques positions BLDC motor design for continued torque density improvement—provided that the thermal and manufacturability constraints are addressed with equal rigor.

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