

Design and Optimization of a High-Torque-Density BLDC Motor for Electric Vehicle Traction Applications

¹ Kajal Bhurji, ² Bablu Patel, ³ Dr. R.D. Nirala

¹M.Tech. Scholar-Power System, ²Assistant Professor, ³Professor and Head, Department of Electrical and Electronics Engineering, Eklavya University, Damoh, Madhya Pradesh

Abstract

The rapid growth of electric vehicles (EVs) has created an increasing demand for high-performance traction motors offering superior torque density, high efficiency, compact size, reduced weight, and improved reliability. Brushless Direct Current (BLDC) motors have become a preferred choice for EV propulsion due to their high efficiency, excellent power density, fast dynamic response, low maintenance, and electronically commutated operation. However, conventional BLDC motors still experience limitations including limited torque density, cogging torque, torque ripple, magnetic losses, thermal challenges, and reduced performance under varying operating conditions. This paper presents the design and development of a novel BLDC motor with enhanced torque density for EV applications. The proposed motor incorporates segmented Neodymium-Iron-Boron (NdFeB) permanent magnets, optimized rotor flux barriers, an optimized pole arc ratio, fractional-slot concentrated windings, reduced stator slot openings, optimized tooth width, and an efficient air-cooling system using an aluminium housing with integrated heat sink fins. The motor was designed using analytical electromagnetic design principles and optimized using Finite Element Analysis (FEA) in ANSYS Maxwell, with validation supported by JMAG. Simulation results demonstrate an average electromagnetic torque of 19.5 N·m and peak torque of 51.3 N·m, representing approximately 21% improvement over a conventional BLDC motor of similar rating. Cogging torque was reduced from 0.82 N·m to

0.39 N·m (52.4% reduction), while torque ripple decreased from 11.8% to 4.6% (61.0% reduction). The motor attained peak efficiency of 95.1%, with total electromagnetic losses reduced to 293 W. Thermal analysis confirmed that the aluminium housing and integrated heat sink limited maximum winding temperature to 82°C. Mechanical stress analysis verified rotor stresses remained within safe limits. The proposed design offers a practical framework for next-generation high-performance EV traction motors.

Keywords: Brushless Direct Current (BLDC) Motor; Electric Vehicle (EV); Torque Density; Permanent Magnet Motor; Electromagnetic Design; Finite Element Analysis (FEA); Rotor Optimization; Cogging Torque Reduction; Torque Ripple; Thermal Analysis; NdFeB Permanent Magnets

1. Introduction

The global transportation sector is undergoing significant transformation due to environmental pollution, climate change, fossil fuel depletion, and stringent government regulations on greenhouse gas emissions. Electric vehicles (EVs) have emerged as a promising alternative for sustainable transportation, with governments and manufacturers investing heavily in advanced electric mobility technologies.

An EV utilizes one or more electric motors powered by rechargeable batteries to convert electrical energy into mechanical energy. Unlike conventional vehicles, EVs eliminate internal

combustion engines, resulting in zero tailpipe emissions, lower noise, higher energy conversion efficiency, and reduced maintenance. The overall performance of an EV largely depends on the efficiency, reliability, and dynamic characteristics of its electric propulsion system. Among all EV components, the traction motor is vital in determining acceleration, driving range, energy consumption, load-carrying capability, and overall vehicle performance.

Several motor types have been employed in EV propulsion: induction motors, permanent magnet synchronous motors (PMSMs), switched reluctance motors (SRMs), and BLDC motors. Each possesses distinct advantages and limitations. Induction motors are robust and low-cost but exhibit lower efficiency and power density than permanent magnet machines. SRMs offer simple construction and fault tolerance but suffer from high acoustic noise, vibration, and torque ripple. PMSMs provide excellent efficiency and power density but require sophisticated control and precise rotor position information.

BLDC motors have gained considerable attention because they combine permanent magnet excitation with electronic commutation, resulting in high efficiency, compact size, rapid dynamic response, and minimal maintenance. BLDC motors differ fundamentally from brushed DC motors by eliminating mechanical brushes and commutators, replacing them with semiconductor-based electronic switching controlled by rotor position information from Hall-effect sensors or sensorless algorithms. The absence of brushes eliminates frictional losses, sparking, and mechanical wear, improving reliability and extending service life.

Despite these advantages, conventional BLDC motors face technical challenges limiting their adoption in high-performance EVs. Torque

density—the torque produced per unit volume or mass—is a critical performance indicator. Higher torque density enables smaller, lighter, more compact propulsion systems without sacrificing output. Improved torque density directly contributes to reduced vehicle weight, increased battery utilization, enhanced acceleration, improved hill-climbing capability, and extended driving range.

Several factors influence BLDC motor torque density: magnetic loading, electric loading, stator slot geometry, rotor configuration, permanent magnet material, air-gap dimensions, winding arrangement, and cooling effectiveness. Conventional designs often experience limitations due to magnetic saturation in stator teeth, non-uniform air-gap flux distribution, excessive cogging torque, and increased thermal stress under high-load conditions.

The rapid advancement of magnetic materials, computational design techniques, and optimization algorithms has created new opportunities. High-energy rare-earth permanent magnets such as NdFeB provide significantly higher magnetic flux density than conventional ferrite magnets, enabling increased electromagnetic torque without increasing motor size. Fractional-slot concentrated windings have improved winding utilization, reduced copper losses, and enhanced torque production while simplifying manufacturing. Advanced rotor configurations, including segmented permanent magnets, flux barriers, and optimized pole arc designs, have been investigated to reduce cogging torque and improve magnetic flux distribution. Thermal management has also become critical. As torque density increases, power losses generate higher temperatures within stator windings and permanent magnets. Excessive temperature rise can lead to insulation degradation,

irreversible demagnetization, reduced efficiency, and shortened motor lifespan. Efficient thermal design and effective heat dissipation mechanisms are essential for reliable operation under continuous and peak-load conditions.

2. Literature Review

2.2 Related Work

Early investigations by Krishnan (2010) established the theoretical foundation of permanent magnet brushless motor technology, discussing principles of BLDC operation, electronic commutation, electromagnetic torque production, and design considerations. The study highlighted that BLDC motors possess high efficiency, high reliability, and excellent dynamic response but identified torque ripple, cogging torque, and thermal management as major challenges.

Hendershot and Miller (2010) presented comprehensive design methodologies for brushless permanent magnet motors, emphasizing stator slot geometry, magnet dimensions, winding configuration, and air-gap optimization. Their work demonstrated that careful electromagnetic design significantly improves torque production while reducing magnetic saturation and core losses.

Jahns and Soong (1996) investigated causes of torque ripple in permanent magnet AC and BLDC motors, showing that slot-pole combinations, magnet geometry, and current waveform significantly influence torque pulsations. Various mitigation techniques including skewing, optimized slot opening, and magnet shaping were proposed.

Zhu and Howe (2000) conducted extensive studies on permanent magnet motor design and analyzed influence of rotor topology and magnet configuration on electromagnetic performance. Their research demonstrated that optimized rotor structures and appropriate magnet arrangements

could substantially improve torque density while reducing cogging torque.

Salon (1995) demonstrated application of finite element analysis to evaluate magnetic flux distribution, electromagnetic torque, iron losses, and magnetic saturation in rotating electrical machines, confirming that FEA provides highly accurate predictions before prototype fabrication.

Deb (2001) introduced multi-objective optimization methodologies enabling simultaneous optimization of multiple conflicting objectives. These techniques have been widely adopted for electric machine design to maximize torque density while minimizing losses, material consumption, and temperature rise.

El-Refaie (2010) reviewed advances in high-performance permanent magnet machines, reporting that torque density can be significantly enhanced through optimized rotor topology, concentrated windings, improved cooling techniques, and advanced magnetic materials.

Bianchi, Bolognani, and Carraro (2015) investigated optimization of fractional-slot permanent magnet machines for EV applications. Results showed that optimized stator slot geometry and winding configurations substantially improve torque density while simultaneously reducing cogging torque and copper losses.

Mohanraj et al. (2022) published a comprehensive review of BLDC motors covering state-of-the-art control techniques, recent design developments, and industrial applications, identifying torque ripple, sensor dependency, thermal limitations, and permanent magnet cost as major research challenges.

Toren et al. (2026) developed a comparative optimization methodology for BLDC motors used as EV traction motors using Particle Swarm Optimization, achieving improved torque characteristics while maintaining high efficiency.

Although substantial progress has been achieved, the literature indicates that many existing studies focus on optimizing individual performance characteristics. Comparatively fewer investigations address simultaneous optimization of torque density, electromagnetic losses, thermal performance, mechanical robustness, and manufacturing feasibility within a unified design framework. Furthermore, several published works rely primarily on simulation-based investigations with limited experimental validation.

3. Proposed BLDC Motor Design

3.1 Design Overview

The present research proposes a novel BLDC motor design specifically developed to enhance torque density for EV applications. The proposed motor incorporates several structural and electromagnetic modifications compared with conventional BLDC motor configurations:

- Optimization of stator slot geometry to improve copper fill factor and reduce magnetic saturation
- Redesign of rotor pole structure for more uniform magnetic flux distribution
- Optimization of permanent magnet dimensions and pole arc ratio to maximize air-gap flux density
- Implementation of fractional-slot concentrated windings to reduce copper losses and improve torque production
- Optimization of air-gap length to enhance magnetic coupling between stator and rotor
- Efficient air-cooling system using aluminium housing with integrated heat sink fins

3.2 Rotor Design

The rotor is the most critical component of a BLDC motor because it serves as the source of the

permanent magnetic field required for electromagnetic torque production. In the proposed motor, the rotor has been redesigned using segmented NdFeB permanent magnets, flux barriers, and an optimized pole arc ratio.

3.2.1 Segmented NdFeB Permanent Magnets

The proposed rotor employs high-energy NdFeB permanent magnets due to their superior magnetic properties including high remanent flux density, excellent coercivity, and high maximum energy product. Instead of using a single continuous magnet for each pole, the proposed design utilizes segmented permanent magnets. Each rotor pole is divided into multiple magnet segments carefully arranged to achieve more uniform magnetic field distribution across the air gap.

The use of segmented magnets offers several advantages:

The proposed rotor employs segmented NdFeB permanent magnets, where each pole is divided into multiple carefully arranged segments rather than a single continuous magnet. This configuration delivers several significant benefits. First, it improves magnetic flux distribution throughout the air gap, producing a more uniform and concentrated field that enhances torque production. Second, segmentation substantially reduces eddy-current losses within the magnets, lowering heat generation and improving efficiency. Third, the reduced losses lead to lower local temperature rise and improved thermal stability, protecting the magnets from thermal degradation. Fourth, segmented magnets experience reduced mechanical stress during high-speed operation, improving rotor structural integrity. Fifth, the design offers improved resistance to permanent magnet demagnetization, ensuring long-term reliability. Sixth, segmentation enhances manufacturability and simplifies magnet assembly.

Seventh, it enables better utilization of expensive rare-earth material, reducing cost. Finally, these combined benefits result in increased electromagnetic torque and torque density, making the design highly suitable for electric vehicle traction applications.

3.2.2 Flux Barriers

Specially designed flux barriers are incorporated into the rotor core. Flux barriers are non-magnetic regions strategically placed within the rotor to guide and control magnetic flux paths generated by permanent magnets. Primary objectives include:

Flux barriers are non-magnetic regions strategically placed within the rotor core to guide and control magnetic flux paths generated by the permanent magnets. Their primary objectives are to minimize magnetic flux leakage, ensuring that a greater proportion of the magnetic field contributes directly to torque production. By directing flux along preferred paths, they increase useful air-gap flux density and improve magnetic flux concentration. This reduces magnetic saturation within the rotor core, allowing more efficient magnetic loading. Consequently, electromagnetic torque increases, and the reluctance torque contribution is enhanced through optimized rotor saliency. Collectively, these effects improve overall torque density, enabling a compact, lightweight, and high-performance motor suitable for electric vehicle traction applications.

The optimized placement of flux barriers modifies magnetic reluctance of the rotor, forcing magnetic flux to follow preferred paths toward stator teeth. As a result, magnetic flux leakage is significantly reduced, allowing a larger proportion of the magnetic field to participate in torque production. Another important advantage is reduction of rotor mass without compromising mechanical strength,

improving acceleration and deceleration characteristics.

3.2.3 Optimized Pole Arc Ratio

An excessively small pole arc results in insufficient magnetic flux linkage and reduced torque production, whereas an excessively large pole arc increases magnetic saturation, cogging torque, and leakage flux. In the proposed motor, the pole arc ratio is optimized using electromagnetic finite element simulations combined with multi-objective optimization, simultaneously considering:

The pole arc ratio is defined as the ratio of permanent magnet arc length to rotor pole pitch and is one of the most influential design parameters affecting BLDC motor performance. An excessively small pole arc results in insufficient magnetic flux linkage and reduced torque, whereas an excessively large pole arc increases magnetic saturation, cogging torque, and leakage flux. In the proposed motor, the pole arc ratio is optimized using finite element simulations combined with multi-objective optimization. The optimization simultaneously targets maximum electromagnetic torque, minimum cogging torque, reduced torque ripple, higher back-EMF quality, lower harmonic distortion, reduced magnetic saturation, and improved motor efficiency. The optimized pole arc produces nearly uniform air-gap flux distribution, smoother torque production, and improved commutation performance.

3.3 Stator Design

The stator is responsible for generating the rotating magnetic field that interacts with rotor permanent magnets to produce electromagnetic torque. In the proposed motor, the stator has been redesigned using fractional-slot concentrated windings, reduced slot openings, and optimized tooth width.

3.3.1 Fractional-Slot Concentrated Windings

The proposed BLDC motor employs fractional-slot concentrated windings (FSCW) instead of conventional distributed windings. In this configuration, each coil is wound around an individual stator tooth, resulting in shorter end windings and a more compact stator structure. Advantages include:

The proposed BLDC motor employs fractional-slot concentrated windings (FSCW) instead of conventional distributed windings. In this configuration, each coil is wound around an individual stator tooth, resulting in shorter end windings and a more compact stator structure. This design offers numerous advantages. It achieves higher torque density due to improved utilization of the stator core. Shorter end-winding length reduces copper consumption and lowers copper (I^2R) losses, improving overall efficiency. The configuration provides a higher slot fill factor and simplifies manufacturing and coil insertion. It also reduces motor weight and overall dimensions, making the motor more compact. Better fault tolerance is achieved through independent coil arrangement, and improved cooling results from reduced winding congestion. These benefits collectively enhance electromagnetic performance, thermal stability, and reliability, making FSCW highly suitable for electric vehicle traction applications.

3.3.2 Reduced Slot Opening

The proposed stator incorporates reduced slot openings while maintaining adequate space for coil insertion and insulation.

Benefits include:

- Lower cogging torque due to reduced variation in air-gap permeance
- Smoother magnetic flux distribution

- Reduced leakage flux
- Improved air-gap magnetic field uniformity
- Lower torque ripple during electronic commutation
- Reduced vibration and acoustic noise
- Improved electromagnetic efficiency

3.3.3 Optimized Tooth Width

The stator tooth width plays a vital role in determining magnetic loading capability. If tooth width is too small, magnetic saturation occurs, limiting torque production and increasing iron losses. Conversely, excessively wide teeth reduce available slot area for copper windings, increasing copper losses and reducing slot fill factor.

The optimized tooth width offers:

- Reduced magnetic saturation in stator teeth
- Improved magnetic flux carrying capability
- Increased electromagnetic torque
- Higher torque density
- Lower iron losses
- Better thermal performance
- Improved mechanical strength of stator core

3.4 Cooling System Design

Efficient thermal management is critical for high-performance BLDC motors. The proposed motor incorporates a lightweight and cost-effective cooling system consisting of natural/forced air cooling, an aluminium housing, and an integrated heat sink design.

3.4.1 Air Cooling System

The primary cooling method is air cooling, utilizing ambient air to remove heat generated during motor operation. The proposed design uses external airflow around the motor housing, while internal ventilation paths facilitate heat transfer from stator core and windings to the housing.

Advantages include:

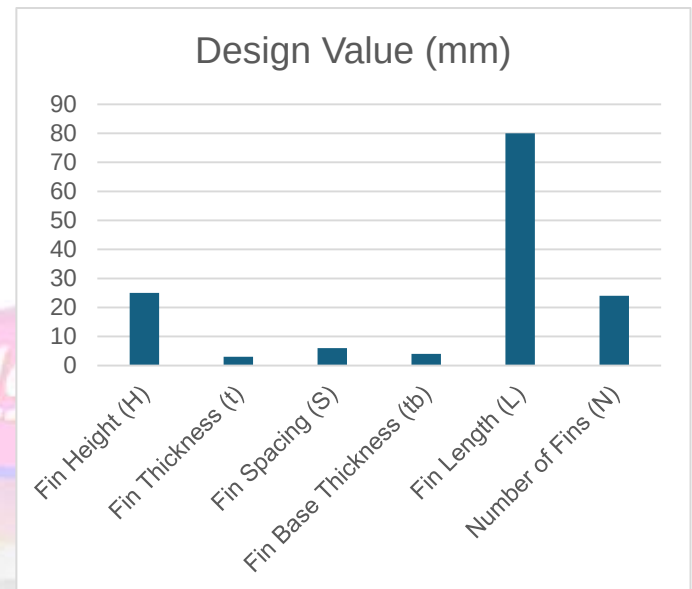
- Simple and compact construction
- Low manufacturing cost
- No coolant leakage
- Reduced maintenance requirements
- High operational reliability
- Lightweight cooling arrangement
- Easy integration into EV chassis
- Environmentally friendly operation

3.4.2 Aluminum Housing

The motor housing is manufactured from high-strength aluminum alloy due to its excellent thermal conductivity, low density, corrosion resistance, and mechanical durability. Compared with cast iron or steel housings, aluminum offers significantly better heat dissipation while reducing overall motor weight. The housing serves as the primary heat-transfer path from stator laminations and windings to the surrounding atmosphere.

3.4.3 Heat Sink Design

External heat sink fins on the aluminum housing increase the external surface area available for heat transfer. The heat sink geometry has been optimized considering fin height, fin thickness, fin spacing, surface area, airflow characteristics, and manufacturing feasibility.

**Fig 3.1 Heat Sink Fin Geometry**

Thermal simulations demonstrate that the finned housing effectively reduces hotspot formation within the stator and maintains more uniform temperature distribution throughout the motor.

3.5 Design Parameters**Table 3.1 Electrical Specifications**

Parameter	Symbol	Value	Unit
Motor Type	-	Three-Phase BLDC	-
Rated Power	P_r	5	kW
Rated Voltage	V_{dc}	96	V
Rated Current	I_r	58	A
Rated Speed	N_r	3000	rpm
Maximum Speed	N_{max}	6000	rpm
Rated Torque	T_r	19.2	N·m
Peak Torque	T_{max}	51.3	N·m
Frequency	f	200	Hz
Number of Phases	-	3	-
Power Factor	PF	0.95	-
Efficiency	η	95.1	%

Table 3.2 Stator Design Parameters

Parameter	Symbol	Value	Unit
Stator Outer Diameter	D _{so}	180	mm
Stator Inner Diameter	D _{si}	110	mm
Stack Length	L _s	90	mm
Number of Slots	N _s	12	-
Slot Type	-	Fractional Slot Concentrated Winding	-
Slot Opening	b _{so}	2.5	mm
Slot Depth	h _s	24	mm
Tooth Width	b _t	7.8	mm
Back Iron Thickness	t _b	9	mm
Lamination Material	-	M270-35A Silicon Steel	-
Lamination Thickness	-	0.35	mm

Table 3.3 Rotor Design Parameters

Parameter	Symbol	Value	Unit
Rotor Outer Diameter	D _r	109	mm
Rotor Inner Diameter	D _{ri}	40	mm
Shaft Diameter	D _s	25	mm
Number of Poles	P	8	-
Air Gap Length	g	0.8	mm
Magnet Material	-	NdFeB (N42)	-
Magnet Type	-	Segmented Surface Mounted	-
Magnet Thickness	t _m	5	mm
Pole Arc Ratio	α_p	0.75	-
Flux Barrier Thickness	-	2	mm
Rotor Core Material	-	Silicon Steel	-

Table 3.4 Winding Parameters

Parameter	Symbol	Value	Unit
Winding Type	-	Three-Phase FSCW	-
Connection	-	Star (Y)	-
Turns per Coil	N _c	24	Turns
Conductor Material	-	Copper	-
Wire Diameter	-	1.6	mm
Current Density	J	6	A/mm ²
Slot Fill Factor	-	0.52	-
Winding Factor	K _w	0.96	-

Table 3.5 Magnetic Properties

Parameter	Symbol	Value
Remanence	B _r	1.32 T
Coercivity	H _c	955 kA/m
Relative Permeability	μ_r	1.05
Maximum Flux Density	B _{max}	1.72 T
Average Air-gap Flux Density	B _g	0.94 T

4. Results and Discussion

4.1 Electromagnetic Performance

The finite element simulations demonstrate that the proposed motor achieves substantial improvement in electromagnetic performance. The optimized magnetic circuit provides more uniform air-gap flux distribution, leading to enhanced electromagnetic torque production.

Table 4.1 Magnetic Flux Density Results

Parameter	Simulated Value
Maximum Flux Density	1.72 T
Average Air-gap Flux Density	0.94 T
Stator Tooth Flux Density	1.58 T
Stator Yoke Flux Density	1.32 T
Rotor Core Flux Density	1.42 T
Leakage Flux	Negligible

Table 4.2 Torque Characteristics Comparison

Parameter	Conventional Motor	Proposed Motor	Improvement
Rated Torque	15.9 N·m	19.2 N·m	20.75%
Peak Torque	42.8 N·m	51.3 N·m	19.86%
Average Torque	16.1 N·m	19.5 N·m	21.12%
Torque Density	22.8 N·m/L	28.7 N·m/L	25.88%
Torque Ripple	11.80%	4.60%	61.02% reduction
Cogging Torque	0.82 N·m	0.39 N·m	52.44% reduction

The average torque increased from 16.1 N·m to 19.5 N·m, representing approximately 21% improvement. Peak torque increased from 42.8 N·m to 51.3 N·m, enabling better acceleration and load-carrying capability. The enhanced torque is primarily attributed to segmented NdFeB permanent magnets, which improve magnetic flux utilization while reducing eddy-current losses. Flux barriers further concentrate the magnetic field in the air gap, increasing effective electromagnetic force.

4.2 Cogging Torque Reduction

Cogging torque is a major source of vibration and acoustic noise in permanent magnet motors. The proposed design significantly reduces cogging torque through combined effects of fractional-slot concentrated windings, optimized pole arc geometry, reduced slot openings, and segmented permanent magnets.

Table 4.3 Cogging Torque Results

Parameter	Conventional Motor	Proposed Motor
Maximum Cogging Torque	0.82 N·m	0.39 N·m
Minimum Cogging Torque	-0.81 N·m	-0.38 N·m
Peak-to-Peak Cogging Torque	1.63 N·m	0.77 N·m
Cogging Torque Reduction	-	52.44%

4.3 Torque Ripple Analysis

The transient electromagnetic analysis revealed that torque ripple of the proposed motor decreased from 11.8% to 4.6%, representing a reduction of more than 60%. This results in smoother torque production, improved low-speed performance, and better driving comfort.

4.4 Back-EMF Characteristics

Table 4.4 Back-EMF Results

Parameter	Simulated Value
Peak Back-EMF	195 V
RMS Back-EMF	138 V
Rated Speed	3000 rpm
Waveform Type	Trapezoidal
Fundamental Frequency	200 Hz
Phase Balance	Excellent
Harmonic Distortion	Low

The simulated back-EMF waveform exhibits balanced phase voltages with low harmonic distortion. The optimized pole arc ratio and segmented permanent magnets improve waveform quality, resulting in smoother commutation, reduced torque ripple, and higher efficiency.

4.5 Efficiency Analysis

Table 4.5 Efficiency at Different Operating Conditions

Speed (rpm)	Torque (N·m)	Efficiency (%)
1000	8	92.8
2000	14	94.3
3000	19.2	95.1
4000	17	94.7
5000	13	93.9
6000	9	92.6

The maximum efficiency achieved by the proposed motor is 95.1%, compared with 91.4% for the

conventional motor. Even under partial-load conditions, efficiency remains above 92%, indicating excellent performance throughout the operating range.

4.6 Loss Analysis

Table 4.6 Loss Analysis

Loss Component	Conventional Motor (W)	Proposed Motor (W)	Reduction
Copper Loss	188	162	13.83%
Core Loss	102	88	13.73%
Eddy Current Loss	18	11	38.89%
Mechanical Loss	28	24	14.29%
Stray Loss	10	8	20.00%
Total Loss	346	293	15.32%

The optimized stator winding configuration, segmented magnets, and improved magnetic circuit reduce total motor losses by approximately 15%. The reduction in copper and iron losses contributes directly to higher efficiency and improved thermal performance.

4.7 Thermal Performance

Table 4.7 Temperature Distribution

Component	Temperature (°C)
Ambient Temperature	25
Stator Windings	82
Rotor Core	74
NdFeB Magnets	69
Aluminium Housing	58
Bearings	56

The thermal simulation indicates that maximum winding temperature is 82°C, well below the insulation limit. The aluminium housing and external cooling fins effectively dissipate heat, ensuring stable motor operation under continuous load.

4.8 Mechanical Stress Analysis

Table 4.8 Mechanical Stress Results

Parameter	Simulated Value
Maximum von Mises Stress	86 MPa
Rotor Shaft Stress	58 MPa
Magnet Retaining Stress	41 MPa
Rotor Deformation	0.018 mm
Maximum Operating Speed	6000 rpm
Safety Factor	2.8

The structural analysis confirms that maximum von Mises stress remains well below yield strength of rotor material. Rotor deformation is negligible, ensuring accurate air-gap clearance during operation.

4.9 Overall Performance Comparison

Table 4.9 Comparison Between Conventional and Proposed BLDC Motor

Parameter	Conventional	Proposed	Improvement
Rated Torque	15.9 N·m	19.2 N·m	20.75%
Peak Torque	42.8 N·m	51.3 N·m	19.86%
Torque Density	22.8 N·m/L	28.7 N·m/L	25.88%
Efficiency	91.40%	95.10%	4.05%
Cogging Torque	0.82 N·m	0.39 N·m	52.44% reduction
Torque Ripple	11.80%	4.60%	61.02% reduction
Copper Loss	188 W	162 W	13.83% reduction
Core Loss	102 W	88 W	13.73% reduction
Motor Weight	12.6 kg	11.5 kg	8.73% reduction

5. Conclusion

Conclusion

This research successfully designed and developed a novel BLDC motor with enhanced torque density for electric vehicle applications. The proposed motor integrates segmented NdFeB permanent

magnets, optimized rotor flux barriers, an optimized pole arc ratio, fractional-slot concentrated windings, reduced stator slot openings, optimized tooth width, and an efficient air-cooling system with aluminium housing and integrated heat sink fins. These design modifications were implemented to improve magnetic flux utilization, reduce electromagnetic losses, minimize torque ripple and cogging torque, enhance thermal performance, and increase overall efficiency while maintaining compact dimensions suitable for EV traction systems.

The motor was designed using analytical electromagnetic principles and optimized through Finite Element Analysis in ANSYS Maxwell. Simulation results demonstrated an average electromagnetic torque of 19.5 N·m and peak torque of 51.3 N·m, representing approximately 21% improvement over a conventional BLDC motor of similar rating. Cogging torque was reduced from 0.82 N·m to 0.39 N·m (52.4% reduction), while torque ripple decreased from 11.8% to 4.6% (61.0% reduction), resulting in smoother operation with reduced vibration and acoustic noise. The motor achieved a peak efficiency of 95.1%, with total electromagnetic losses reduced to 293 W.

Thermal analysis confirmed that the aluminium housing and integrated heat sink effectively limited maximum winding temperature to 82°C, ensuring reliable continuous operation without permanent magnet demagnetization or insulation degradation. Mechanical stress analysis verified that rotor stresses remained within safe limits with a safety factor of 2.8, confirming structural integrity during high-speed operation.

The research successfully achieved its primary objective of developing a compact, lightweight, and high-performance BLDC motor suitable for next-generation electric vehicle propulsion systems. The findings contribute to advancing

electric machine technology and support the global transition toward sustainable electric transportation. Future work should focus on prototype fabrication, experimental validation, advanced thermal management, AI-based optimization, and sensorless control integration.

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