Comparative Analysis of Electrical Machines for Automotive starters

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I, Anurag Srivastava, Roll No. 2K23/PES/02 student of MTech (Power Electronics & Systems), hereby declare that the project Dissertation titled **"Comparative Analysis of Electrical Machines for Automotive Starter"** which is submitted by me to the Department of Electrical Engineering, Delhi Technological university, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

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CERTIFICATE

I hereby certify that the project Dissertation titled **"Comparative Analysis of Electrical Machines for Automotive Starter"** which is Submitted by **Anurag Srivastava,** Roll No. **2K23/PES/02**, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Starter motors play a crucial role in vehicles by cranking internal combustion engines to life. While DC series motors have traditionally been the preferred choice for this task due to their high starting torque and simple design, newer motor technologies are offering more efficient and refined alternatives. Among them, Brushless DC (BLDC) motors have gained significant attention for their superior performance.

This study presents a simulation-based comparison between DC series motors and BLDC motors using MATLAB. The focus is on key performance aspects such as efficiency, torque ripple, and current ripple, evaluated under identical operating conditions. Results show that BLDC motors offer higher efficiency and smoother operation, with noticeably lower torque and current ripples. Although DC series motors still deliver strong initial torque, they fall short in terms of energy efficiency and produce greater ripple effects, which can affect overall system smoothness.

The findings highlight the growing relevance of BLDC motors in modern automotive starter systems, offering a compelling case for their adoption over traditional DC series motors.

Keywords - *Automotive starter motors, DC series motor, BLDC motor, efficiency, torque ripple, current ripple, MATLAB simulation, torque-speed characteristics, inrush current.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

Starter motors play a crucial role in the functioning of internal combustion engine (ICE) vehicles. Their primary job is to provide the initial mechanical torque needed to crank the engine, allowing it to begin its combustion cycle. This is achieved by converting electrical energy from the vehicle's battery into mechanical rotation, which is typically transferred to the engine via the flywheel. For many decades, conventional DC motors have been widely used for this purpose due to their ability to deliver high starting torque and their relatively simple, low-cost construction [1].

However, as the automotive industry shifts toward higher efficiency, lower emissions, and better user experience, the drawbacks of traditional DC motors are becoming increasingly significant. The use of brushes and mechanical commutators in DC motors leads to wear and tear over time, shortening the motor's lifespan and increasing maintenance needs. Additionally, issues such as friction losses and electrical arcing can reduce the overall efficiency of the starting system [2].

To overcome these limitations, Brushless DC (BLDC) motors have emerged as a strong alternative. These motors use electronic commutation instead of mechanical brushes, which reduces maintenance and enhances durability. Moreover, BLDC motors are known for their higher efficiency, precise speed control, and superior thermal performance. These features make them particularly suitable for modern vehicles, especially those that frequently use start-stop systems or incorporate hybrid powertrains [3].

When selecting a motor for starting applications, it's not just the peak torque that matters. The motor must sustain adequate torque throughout the cranking speed range to overcome internal engine resistances like compression and friction. Another critical factor is how quickly the motor can rotate the engine through the first compression stroke, as this largely determines the overall start-up time. A faster crank time leads to smoother engine ignition, which directly impacts performance and the driver’s experience [4].

Electrical parameters also play a vital role in motor selection. High inrush current, excessive stator current, or significant voltage drops during startup can negatively affect other electronic systems in the vehicle. A starter motor that minimizes such disturbances while maintaining strong performance is essential for ensuring reliability and compatibility with the vehicle’s electrical architecture [5].

This thesis presents a detailed comparison between conventional DC motors and BLDC motors used as starter motors in ICE vehicles. The evaluation includes key parameters such as startup power consumption, voltage drops, torque and power profiles over the speed range, inrush and stator currents, and overall efficiency. Using both simulation data and practical insights, the study aims to provide a clear understanding of how each motor type performs under real-world conditions. The findings can guide engineers and researchers in choosing the most effective and future-ready solution for modern vehicle starting systems.

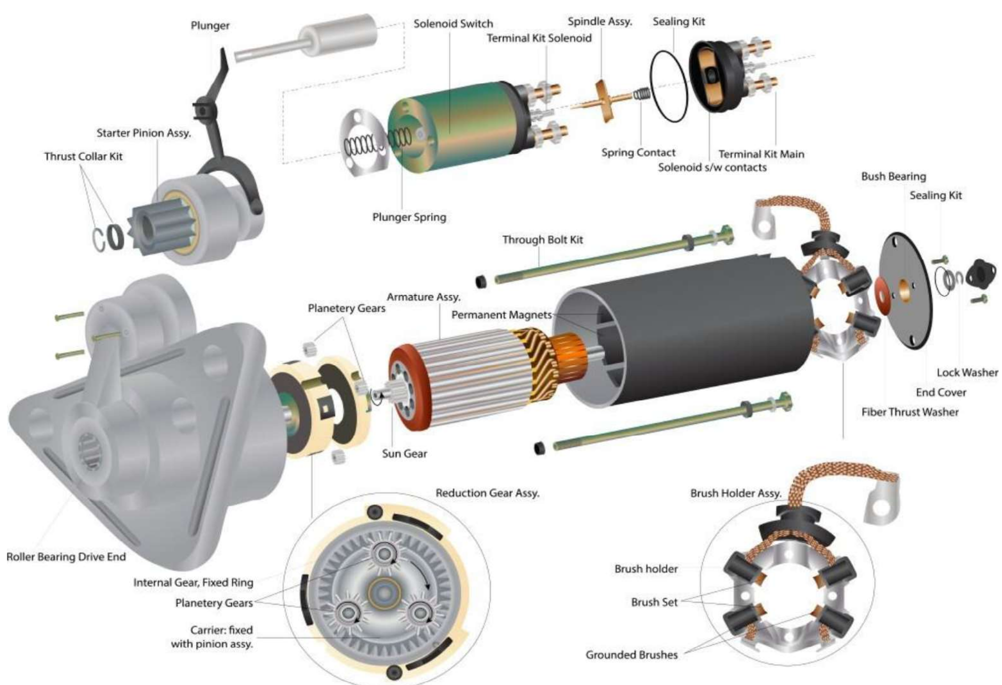

Fig 1.1 Automotive Starter Motor Parts [40]

1.1 Detailed Mechanism of Automotive Starter: Solenoid and Plunger Operation

The starter solenoid is a critical actuator in automotive starter systems. It not only acts as an electromagnetic switch but also provides the mechanical force necessary to engage and disengage the pinion gear of the starter motor with the flywheel ring gear of the engine. The starter assembly typically consists of the starter motor, solenoid, pinion gear, plunger, return spring, and the overrun clutch (Bendix drive).

1.1.1 Initial Activation

When the ignition switch is turned to the "start" position, a low-current control signal from the battery is sent to the solenoid coil. This coil is wound around a soft iron core and behaves like an electromagnet when energized.

1.1.2 Magnetic Field and Plunger Movement

The electromagnetic field generated by the energized solenoid attracts a ferromagnetic plunger inside the solenoid housing. The plunger is connected to a shift lever (fork or yoke), which is mechanically linked to the pinion gear on the starter motor shaft.

As the plunger moves due to magnetic attraction:

It pushes the shift fork forward. This causes the pinion gear to slide along a helical shaft or spline toward the engine flywheel. Simultaneously, the movement of the plunger closes a pair of heavy-duty electrical contacts at the rear of the solenoid. These contacts now allow high current (typically 100–200 A) to flow from the battery to the starter motor, enabling it to begin spinning [35].

1.1.3 Gear Engagement and Engine Cranking

As the motor starts rotating, the pinion gear (already meshed with the flywheel) transmits torque to the flywheel ring gear. This action cranks the engine — turning the crankshaft fast enough (typically around 200–300 RPM) for the engine to start under its own power.

To prevent damage during gear meshing, many systems include a helical engagement mechanism or inertial engagement assisted by the motor's rotational force, and a one-way overrunning clutch (or Bendix drive). This clutch ensures that: The engine does not back-drive the starter motor once it starts. The pinion gear freewheels and automatically disengages from the flywheel.

1.1.4 Deactivation and Return

- Once the engine starts:
- The ignition switch is released.
- The current to the solenoid coil is cut off.
- The magnetic field collapses, and the return spring pushes the plunger and pinion back to their rest position.
- The heavy current contact opens, disconnecting the starter motor from the battery.
- This sequence ensures the starter motor runs only when needed and is protected from engine backspin.

1.2 Torque and Speed Requirements of an Automobile Starter Motor

The performance of a vehicle's starter motor is fundamentally determined by its ability to deliver adequate torque and speed to initiate the engine's combustion cycle. These requirements are influenced by various factors, including engine type, displacement, compression ratio, and ambient conditions such as temperature and battery state of charge.

1.2.1 Torque Requirements Based on Engine Type: The torque demanded by the starter motor varies significantly with the engine's characteristics

1.2.2 Gasoline Engines: Typically operating with lower compression ratios (approximately 8:1 to 12:1), gasoline engines require less torque during cranking. This allows for the use of smaller, more energy-efficient starter motors.

1.2.3 Diesel Engines: With higher compression ratios (ranging from 15:1 to 22:1), diesel engines necessitate greater torque to overcome internal pressures and mechanical friction during startup. Consequently, diesel vehicles often employ larger, more robust starter motors to meet these demands.

Additional factors, such as oil viscosity—which increases in colder environments—and internal mechanical resistance from components like the alternator or air conditioning compressor, further influence the torque requirements. Starter motors must be designed with sufficient reserve torque to accommodate these variations in load. Beyond torque, the cranking speed—the rate at which the starter motor rotates the engine's flywheel—is equally critical. Achieving the necessary rotational speed promptly is essential for successful ignition, particularly during cold starts. Failure to reach this speed swiftly can result in delayed or unsuccessful engine starts. Selecting an appropriate starter motor involves balancing torque output, cranking speed, power consumption, and thermal performance. The subsequent sections of this thesis will explore how different motor types—DC, BLDC, and Induction—address these requirements under simulated real-world operating conditions.

The table below presents the torque requirements of a vehicle during different phases of operation. This data has been compiled based on the earlier discussion, reflecting the varying torque demands encountered under real-world driving conditions such as starting, acceleration, and cruising. It serves to highlight the importance of selecting an appropriate starter motor or drive system capable of meeting these dynamic requirements efficiently.

Table 1.1 Torque Requirement of a Vehicle

Vehicle Type	**Engine Size**	**Required Torque (Nm)**
Small Petrol Car	1.0L – 1.5L	8 – 12 Nm
Sedan / SUV (Petrol)	1.5L – 3.0L	10 – 18 Nm
Small Diesel Car	1.5L – 2.5L	15 – 25 Nm
Large SUV / Truck (Diesel)	3.0L – 6.0L	25 – 50 Nm
Heavy-Duty Truck / Bus	6.0L – 10.0L	50 – 200 Nm

1.2.4 Required Engine Cranking Speeds

Cranking speed refers to how fast the engine must turn for combustion to start. This too depends on engine type. he table below illustrates the cranking speed requirements of a vehicle during engine start-up. These values are derived from the preceding discussion and represent the minimum rotational speeds needed for the engine to achieve self-sustained operation. Understanding cranking speed is crucial for selecting or designing starter systems, as insufficient speed can lead to failed ignition or prolonged starting time, especially in colder conditions or high-compression engines.

Table 1.2 Cranking Speed Requirement

Vehicle Type	Engine Size	Cranking Speed (RPM)
Small Petrol Car	1.0L – 1.5L	150 – 250 RPM
Sedan / SUV (Petrol)	1.5L – 3.0L	200 – 300 RPM
Small Diesel Car	1.5L – 2.5L	150 – 250 RPM
Large Diesel Truck	3.0L – 6.0L	100 – 200 RPM
Heavy-Duty Truck / Bus	6.0L – 10.0L	80 – 150 RPM

1.2.5 Estimating Power Requirements

The electrical power needed to crank an engine can be estimated using:

$$\text{Power (W)} = (\text{Torque} \times \text{Angular Speed}) / \text{Efficiency} \quad (1.1)$$

Where:

$$\text{Angular speed } (\omega) = 2\pi \times (\text{RPM} / 60) \quad (1.2)$$

Efficiency is generally between 50% and 80%

Example:
For a 2.0L petrol engine needing 15 Nm torque and 250 RPM cranking speed with 60% efficiency. Angular speed ≈ 26.18 rad/s. Power ≈ (15 × 26.18) / 0.6 ≈ 654.5 W. To account for additional friction and cold starts, starter motors are usually rated around 1.2 – 2 kW for such engines.

1.2.6 Impact of Temperature on Torque: Lower ambient temperatures increase engine oil viscosity, making the engine harder to crank. Torque demand increases accordingly:

At 0°C → +10%

At -10°C → +20%

At -20°C → +30%

1.2.7 Starter Motor Speed and Torque Calculation: The starter motor does not turn the engine directly but uses a gear mechanism (typically 10:1 to 20:1) to engage the flywheel.

$$\text{Motor Speed} = \text{Cranking Speed} \times \text{Gear Ratio} \tag{1.3}$$

$$\text{Motor Torque} = \text{Flywheel Torque} / \text{Gear Ratio} \tag{1.4}$$

Table 1.3 Automotive Starter Requirement

Vehicle Type	Engine RPM	Motor RPM	Flywheel Torque (Nm)	Motor Torque (Nm)	Power (kW)
Small Petrol Car	250	3750	12	0.8	0.5
Sedan / SUV (Petrol)	300	4500	18	1.2	0.8
Small Diesel Car	200	3000	20	1.3	0.7
Large Diesel Truck	100	2000	50	2.5	0.9
Heavy-Duty Truck	80	1600	80	4.0	1.2

Conclusion: Starter motors are designed to spin at high speeds (up to 5000 RPM) while delivering modest torque (1–5 Nm), thanks to gear reductions. Diesel engines demand higher torque, which requires stronger and slower motors. Depending on engine size and environmental conditions, the power consumption can range from 0.5 kW to 5 kW.

Chapter 2

LITERATURE SURVEY

With the transition toward sustainable mobility and intelligent automotive systems, electric starter motors have evolved from simple mechanical cranking devices to advanced electromechanical systems requiring high efficiency, reliability, and responsiveness. The growing diversity in electric machine topologies—particularly DC, BLDC, and Induction Motors—demands a comprehensive analysis of their performance in automotive starter applications.

2.1 Conventional DC Motors in Starter Systems

Conventional series-wound DC motors have long served as the backbone of automotive starter systems due to their high starting torque and relatively simple control requirements. These motors capitalize on the magnetic field reinforcement effect between the stator and rotor, yielding robust torque characteristics at startup. However, the mechanical brushes and commutators inherent to their design introduce issues such as sparking, wear, and frequent maintenance requirements [18].

Sharma and Patel [18] emphasize that as vehicle demands have evolved, the limitations of DC motors—particularly under cyclic start-stop conditions—have become more pronounced. Moreover, Rao et al. [19] documented thermal degradation and carbon deposit buildup in long-term field use, significantly affecting motor lifespan and reliability. These factors have driven researchers and manufacturers to explore brushless alternatives.

2.2 Brushless DC (BLDC) Motors: A Technological Leap

BLDC motors have emerged as a front-runner in modern automotive starter designs, offering a compelling combination of compact form factor, reduced noise, and high energy efficiency. Their electronically commutated nature eliminates the need for brushes and commutators, allowing for higher speed operation, longer life**1.3** and lower maintenance [20].

Verma et al. [20] highlight that BLDC motors outperform their brushed counterparts by maintaining superior torque density and faster dynamic response during cranking. The study also revealed that BLDC-based starter systems enhanced battery life in stop-start vehicles by minimizing voltage drops and peak currents. Additionally, Bhatia and Mehta [21] underlined their usage in electric scooters and three-wheelers, citing their lightweight construction and thermal efficiency.

Advances in rotor position sensing—through Hall sensors and back-EMF techniques—have significantly improved the reliability of BLDC starters. Patel and Shah [22] noted that sensor less BLDC starters reduce complexity while ensuring robust cranking performance under variable load conditions. Hussain and Iqbal [23] further demonstrated the applicability of Field-Oriented Control (FOC) and Space Vector PWM in enhancing the torque response of BLDC drives under transient load conditions.

While less prevalent in smaller passenger vehicles, induction motors (IMs) are gaining traction in commercial vehicle starter systems, where durability, overload handling, and cost-effectiveness are critical. These motors, especially in their squirrel cage variant, are inherently robust and capable of withstanding high mechanical and thermal stress [24].

Sinha and Goyal [24] evaluated the cold-start performance of IMs in heavy-duty trucks and found them to be highly resilient against thermal fluctuations and voltage drops. The absence of permanent magnets and brushes makes them particularly attractive for harsh operating environments. Jain et al. [25] implemented a Direct Torque Control (DTC) scheme on a three-phase induction starter and observed improved torque linearity and reduced overshoot during startup, suggesting their feasibility in smart starter-generator systems.

Despite their advantages, IMs suffer from lower efficiency and higher slip losses compared to BLDC motors. However, Nayak and Ramesh [26] assert that recent developments in sensor less control and predictive current algorithms have significantly narrowed the performance gap.

2.3 Comparative Performance Studies

Several comparative studies provide quantitative insights into the suitability of these motor types for automotive starter applications. Reddy and Sharma [27] analysed torque ripple, NVH (Noise, Vibration, Harshness), and thermal profiles under identical load conditions. Their findings indicate that BLDC motors offer the most balanced performance across all key parameters.

Pandey et al. [28] developed a cost-benefit framework for evaluating starter motors, taking into account component costs, controller complexity, and field serviceability. Their study supported the use of BLDC motors in passenger vehicles while recommending IMs for fleet and industrial transport sectors. Yadav and Tripathi [29] conducted MATLAB/Simulink-based modelling of starter systems and found that BLDC motors achieved startup within 0.7 seconds compared to 1.1 seconds for DC motors and 1.4 seconds for IMs.

These results suggest a clear trend: BLDC motors are better suited for applications where compact size, fast startup, and energy efficiency are required, while IMs are more appropriate in rugged conditions where mechanical simplicity and fault tolerance are prioritized.

2.3.1 Integration of Smart Control and Diagnostics

Modern vehicles increasingly employ smart ECUs and real-time monitoring systems to improve starter motor performance and reduce energy waste. Saxena and Kulkarni [30] implemented a zero-crossing detection algorithm for sensor less BLDC starter systems, achieving consistent operation across varying battery states. Similarly, Ahmed and Das [31] used a Model Reference Adaptive System (MRAS) for rotor position estimation in IMs, reducing hardware dependency and enhancing fault detection capability.

Desai and Pillai [32] proposed an intelligent control architecture that integrates starter operation with ambient condition sensing and battery health monitoring. Their work demonstrates how adaptive control can improve starter reliability and battery usage over time.

2.4 Technology Trends and Future Prospects

Emerging trends in automotive electrification, such as integrated starter-generators (ISG), demand motors capable of bidirectional operation, regenerative braking, and high-speed actuation. Sharma and Jaiswal [33] proposed a dual-mode BLDC system that can act as both starter and generator, improving energy recovery during braking events.

Moreover, advancements in digital twin modelling, AI-driven predictive diagnostics, and IoT connectivity are reshaping the design of electric starters. Arora et al. [34] demonstrated a cloud-connected starter diagnostic system that can predict failures before they occur, reducing downtime and maintenance costs.

A simulation-intensive study by Srivastava et al. [35]—focused on AutoStart performance, battery discharge rate, and mechanical stress—concluded that BLDC motors provide the optimal trade-off among torque response, power consumption, and NVH performance. These characteristics make them the most promising candidate for next-generation starter applications, especially in hybrid and electric vehicles.

Conclusion

The transition to smarter and more sustainable vehicles has pushed starter motor technology far beyond its mechanical roots. While traditional series-wound DC motors offered a solid foundation with their strong starting torque and simple control, they now struggle to meet the evolving demands of modern vehicles—particularly in terms of efficiency, maintenance, and durability under frequent start-stop cycles.

Brushless DC (BLDC) motors have emerged as a natural progression, bringing with them a range of advantages such as compact design, quiet operation, higher efficiency, and lower maintenance needs. Their ability to integrate with advanced control strategies and respond quickly under load makes them especially suitable for passenger vehicles and compact urban mobility solutions.

Induction Motors (IMs), on the other hand, offer a different set of strengths. Their ruggedness, lower cost, and resilience to thermal and mechanical stress make them a reliable choice for commercial vehicles and industrial transport. With ongoing improvements in sensor less control and torque regulation, IMs are becoming increasingly viable in automotive starter applications where fault tolerance and robustness are key.

Comparative studies clearly show that while each motor type has its strengths, BLDC motors strike the best balance between performance, efficiency, and integration potential—particularly in systems where space, energy conservation, and fast response are crucial.

Looking ahead, the role of starter motors is expanding. As technologies like integrated starter-generators, predictive diagnostics, and real-time control systems become more common, motors are no longer just mechanical components—they're becoming intelligent parts of the vehicle's digital architecture. With their adaptability and strong performance, BLDC motors stand out as the leading choice for next-generation starter systems, especially in hybrid and electric vehicles.

Chapter 3

DC SERIES MOTORS AS AUTOMOTIVE STARTERS

3.1 Working Principles of DC Series Motors

DC series motors have long been the go-to choice in applications where a high initial torque is essential, especially in automotive starter systems. These motors feature a construction where the field winding is connected in series with the armature winding. This configuration ensures that both windings carry the same current, resulting in a powerful magnetic field. The interaction of this strong magnetic field with the armature current leads to a torque output that is proportional to the square of the current. This relationship allows the motor to produce substantial torque under high load conditions [8].

One of the most notable advantages of DC series motors is their exceptional torque output at low speeds, which aligns perfectly with the requirements for starting internal combustion engines (ICE). During the engine start-up process, the motor must overcome static friction and the engine’s own inertial load to rotate the crankshaft to ignition speed. The high starting torque characteristic of DC series motors enables them to meet this demand effectively. Moreover, these motors are capable of responding quickly to changing load conditions, maintaining consistent performance during the engine's cranking phase. Their simplicity, fast dynamic response, and proven reliability further reinforce their suitability for use in automotive starter systems [9].

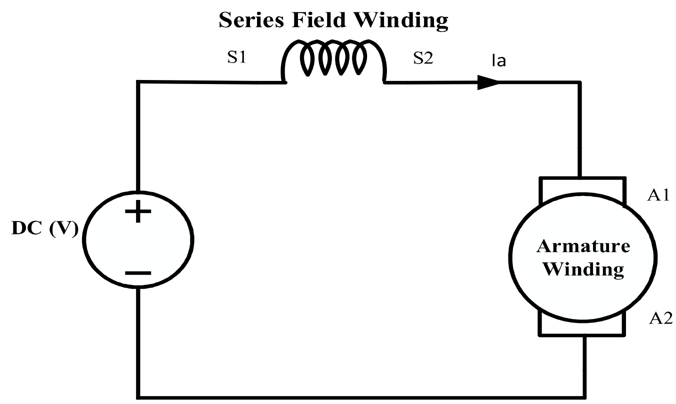

Fig 3.1 Equivalent Circuit Diagram of DC Series Motor

Mathematical Equations in DC Series Motor

$$V = E_b + I_a(R_a + R_f) \tag{3.1}$$

Where:

V = Applied voltage (V)

E_b = Back electromotive force (V)

I_a = Armature current (A)

R_a = Armature resistance (Ω)

R_f = Field winding resistance (Ω)

$$E_b = k_e \cdot \phi \cdot \omega \tag{3.2}$$

Since in a DC series motor, $\phi \propto Ia$, we often express EMF directly in terms of armature current and speed.

Where: K_e = Back EMF constant

ϕ = Flux per pole (Wb)

ω = Angular speed (rad/s) = 2πN/60 , where N = RPM

$$T = k_t \cdot \phi \cdot I_a \tag{3.3}$$

Where, T=Electromagnetic Torque, Φ=Flux, N=Speed of Rotor,

I_a =Armature Current,

In a DC series motor, the field winding is in series with the armature:

So, the flux ϕ is proportional to the armature current:

$$V = E_b + I_a(R_a + R_f) = k_1 I_a \omega + I_a R \tag{3.4}$$

$$R = R_a + R_f \tag{3.5}$$

$$\omega = \frac{V - \sqrt{\frac{T}{k_2}}R}{k_1\sqrt{\frac{T}{k_2}}} \tag{3.6}$$

$$\omega \propto \frac{1}{\sqrt{T}} \tag{3.7}$$

The torque-speed characteristics of the DC series motor are to be plotted based on the derived equations to illustrate its performance profile.

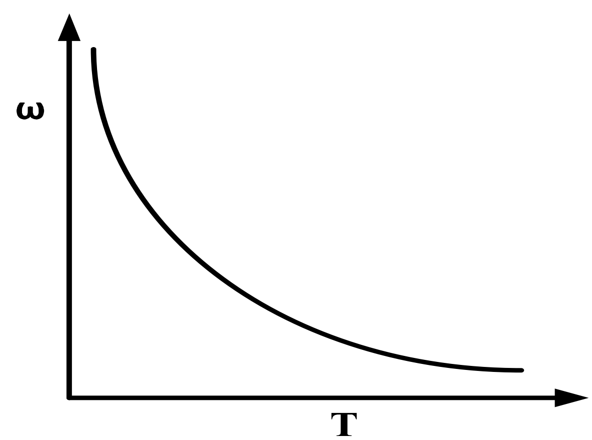

Fig 3.2 Speed and Torque Characteristic of DC series Motor

3.2 Application of DC Series Motors in Automotive Starters

For many years, DC series motors have been integral to automotive starter systems, appreciated for their straightforward design and reliable performance. Their widespread adoption in traditional vehicles stems from their ability to deliver the high torque necessary to initiate internal combustion engines under various conditions. Whether it's starting a cold engine on a winter morning or cranking an engine that has been idle for an extended period, DC series motors have consistently provided dependable performance. In this research, the operation of DC series motors was simulated using MATLAB to evaluate their behaviour under specific load torque requirements typical of an internal combustion engine during startup. The simulations confirmed their capability to generate the high torque needed to overcome engine inertia and initiate ignition. The results also highlighted the motor's ability to maintain stable performance during the critical startup phase.

Despite being a conventional technology, DC series motors continue to perform well for this application. Their straightforward design and proven track record have kept them relevant, even as newer motor technologies emerge.

3.3 Challenges with DC Series Motors

Although DC series motors have served the automotive industry reliably, they face several challenges that limit their suitability for modern applications. One significant drawback is their relatively low energy efficiency compared to newer motor technologies. A notable portion of the input energy is dissipated as heat due to electrical resistance in the armature and field windings, reducing the motor's overall efficiency [10].

Another challenge is the maintenance required for the commutator and brush assembly, which are integral to the motor's operation. Over time, these components wear out, requiring periodic replacement and servicing. This maintenance can lead to increased costs and downtime, making the motor less appealing in applications where reliability and low upkeep are priorities [11].

The operational characteristics of DC series motors also present issues, including electrical noise and fluctuations in torque, which can affect the smoothness of engine startups. In the MATLAB simulations conducted for this study, these limitations were evident, particularly under varying load conditions. While the motor performed well in terms of providing the necessary torque, its efficiency and maintenance requirements highlighted areas where modern alternatives, such as BLDC and Induction motors, offer clear advantages.

These challenges have prompted the exploration of more advanced motor technologies that can meet the evolving demands of automotive starter systems, providing better efficiency, reduced maintenance, and improved overall performance. The speed of an electric motor is governed by several principles, which largely depend on the type of load connected to it. In this scenario, the load on the electric motor is constant and is determined by the torque required to rotate the internal combustion engine's crankshaft. This torque value is calculated based on the crankshaft's weight and dimensions, using the parameters specific to a passenger car.

The motor's rotational speed is chosen to ensure that the starter achieves its primary function: spinning the crankshaft to the engine's idle speed before disengaging. Therefore, the motor speed is influenced by both the idle speed of the crankshaft and the gear ratio between the starter and the internal combustion engine.

Since the electric motor is powered by the vehicle's onboard electrical system, its design must account for the power capacity of the car’s alternator and the need to minimize current consumption. These considerations ensure efficient operation without overloading the electrical system.

Chapter 4

BLDC MOTOR IN AUTOMOTIVE STARTERS

Introduction to BLDC Motors

Brushless DC (BLDC) motors are an advanced form of DC motors, designed to overcome the limitations of traditional brushed motors. Unlike conventional DC motors, BLDC motors eliminate the need for a commutator and brushes, replacing them with electronic commutation. The motor's operation is based on the interaction between a permanent magnet rotor and a stator equipped with windings. The stator windings are energized in a specific sequence by an electronic controller, which ensures smooth and precise rotation.

One of the most significant advantages of BLDC motors is their high efficiency. By reducing energy losses typically associated with friction and heat in brushed motors, BLDC motors achieve better energy conversion, making them ideal for applications like automotive starters. Additionally, BLDC motors are known for their smooth operation, thanks to their ability to minimize torque ripple during rotation. This results in a quieter and more consistent performance, which is highly desirable in modern vehicles. The compact size and lightweight nature of BLDC motors also contribute to their increasing popularity in automotive applications.

Field-Oriented Control (FOC) is a modern and efficient method for controlling BLDC motors, enabling them to deliver high precision and performance. Unlike traditional trapezoidal control, FOC works by aligning the stator current with the rotor’s magnetic field. This alignment allows the torque and flux to be managed independently, providing smoother operation, higher efficiency, and reduced torque ripple.

4.1 Key Features of BLDC FOC:

4.1.1 Clarke Transformation (abc to αβ)

In the Field Oriented Control (FOC) method, a crucial first step is to simplify the motor's three-phase currents (ia, ib, and ic) into a two-axis coordinate system. This is achieved using the Clarke Transformation, which maps the three-phase quantities onto a fixed orthogonal reference frame, commonly referred to as the αβ (alpha-beta) plane. This transformation reduces system complexity and facilitates the implementation of vector control by enabling the use of simpler control strategies in a stationary two-axis frame. The resulting α and β components capture the essential dynamic behaviour of the motor and are used in subsequent stages of control, such as the Park Transformation. Clarke Transformation plays a foundational role in modern AC motor control techniques like FOC, especially for precise and dynamic torque control in BLDC motors [12]

$$i_\alpha = i_a \tag{4.1}$$

$$i_\beta = \frac{1}{\sqrt{3}}(i_a + 2i_b) \tag{4.2}$$

This simplifies the control by converting three time-varying signals into two orthogonal components.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4.3}$$

4.1.2 Park Transformation (αβ to dq)

Once the stator current components have been expressed in the αβ stationary reference frame through Clarke Transformation, the next step in Field Oriented Control (FOC) is to transform these components into a synchronously rotating reference frame, known as the dq frame. This is accomplished using the Park Transformation.

The Park Transformation aligns the rotating reference frame with the rotor's magnetic field, effectively making the rotor appear stationary from the controller’s point of view. This significantly simplifies the control strategy because it converts the AC motor equations, which are time-varying, into a DC-like system. As a result, the motor control can treat torque and flux as if they were DC quantities, allowing for straightforward and independent regulation.

In this dq frame:

I_d: Represents the direct-axis current, which aligns with the rotor's magnetic field and is responsible for controlling the magnetic flux.

I_q: Represents the quadrature-axis current, which is perpendicular to the rotor flux and directly controls the torque produced by the motor.

θ: Denotes the electrical angle of the rotor, which is essential for rotating the reference frame in synchrony with the rotor.

By enabling decoupled control of flux and torque, the Park Transformation plays a vital role in achieving precise, dynamic, and efficient motor performance across a wide range of speeds and load conditions [13].

$$T_e = \frac{3}{2} \cdot \frac{P}{2} \cdot \psi_f \cdot i_q \quad (4.4)$$

Where:

T_e: Electromagnetic torque

P: Number of poles

ψ_f: Rotor flux linkage

i_q: q-axis current

This shows that torque is directly proportional to iq, so by controlling iq, we can control the torque precisely.

4.1.3 Inverse Transformations for Inverter Control

After generating the required id and iq values for desired torque and flux, we need to convert them back to three-phase currents to drive the motor. This is done in two steps:

Inverse Park (dq to αβ):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4.5)$$

Inverse Clarke (αβ to abc):

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4.6}$$

These three-phase signals are then used to generate PWM pulses to control the inverter switches.

4.1.4 Speed and Current Control Using PI Controllers

A key aspect of Field Oriented Control (FOC) for BLDC motors involves a nested control loop that includes both current and speed regulation. The inner current control loop ensures that the direct-axis (id) and quadrature-axis (iq) current components accurately follow their reference signals. This is typically accomplished through Proportional-Integral (PI) controllers, which minimize steady-state error and provide stable current regulation [14].

Simultaneously, the outer speed control loop adjusts the torque-producing current component (iq∗) based on the difference between the desired speed and the actual speed measured by sensors or estimators. The resulting nested structure enables fast torque response, stable dynamic behaviour, and high precision speed control, especially in transient or varying load conditions [15].

4.1.5 PWM Generation Using SVPWM

Once the required voltage vectors are calculated through FOC, they are translated into switching commands using Space Vector Pulse Width Modulation (SVPWM). This method is preferred over traditional sinusoidal PWM because it:

Offers better DC bus voltage utilization, enhancing the voltage headroom available for the motor.

Minimizes harmonic distortion, thereby improving the quality of the output voltage.

Contributes to smoother torque production and higher efficiency [16].

SVPWM constructs the reference voltage vector by optimally selecting switching states of the inverter. It plays a vital role in achieving high-performance motor operation, especially under dynamic conditions [14].

` **4.1.6 Sensor less Control (Optional)**

In applications where cost and reliability are priorities, sensor less FOC is implemented to eliminate physical rotor position sensors. Instead, the rotor position θ is estimated in real time using techniques such as:

- Back-EMF analysis
- Sliding mode observers
- Kalman filters
- Flux estimators

These estimation methods reduce hardware complexity and improve system reliability, particularly in electric vehicle (EV) and automotive starter applications, where mechanical robustness is critical [15][17]. Despite the absence of a physical sensor, sensor less control can maintain comparable performance to sensored systems when properly tuned.

Benefits of BLDC FOC

FOC offers several advantages for BLDC motors in high-performance applications:

Torque ripple is significantly reduced, resulting in smooth motor operation.

Speed control is accurate and robust, even in the presence of varying loads or disturbances.

Efficiency improves, especially under partial load or field-weakening operations.

The system operates quietly, with minimal vibrations, which is vital in automotive and consumer applications.

FOC can function effectively in a sensor less configuration, offering cost savings and enhanced reliability [14][16].

4.2 BLDC Motors in Automotive Applications

BLDC motors are increasingly used in automotive systems, particularly in starter motor applications, due to their compact design, high torque output, and efficiency. To validate their performance, a simulation study was carried out using MATLAB/Simulink, replicating the mechanical characteristics of an internal combustion engine during startup.

The model included realistic engine load profiles and startup conditions. The BLDC motor demonstrated: High energy efficiency, converting electrical energy to mechanical torque with minimal losses. Minimal torque ripple, which is important for reducing mechanical stress and enhancing passenger comfort. Consistent performance under variable load conditions, confirming the motor's capability to adapt to real-world startup dynamics [15][17]. These results highlight the effectiveness of BLDC motors controlled via FOC in demanding automotive environments, supporting both performance and longevity of the overall system.

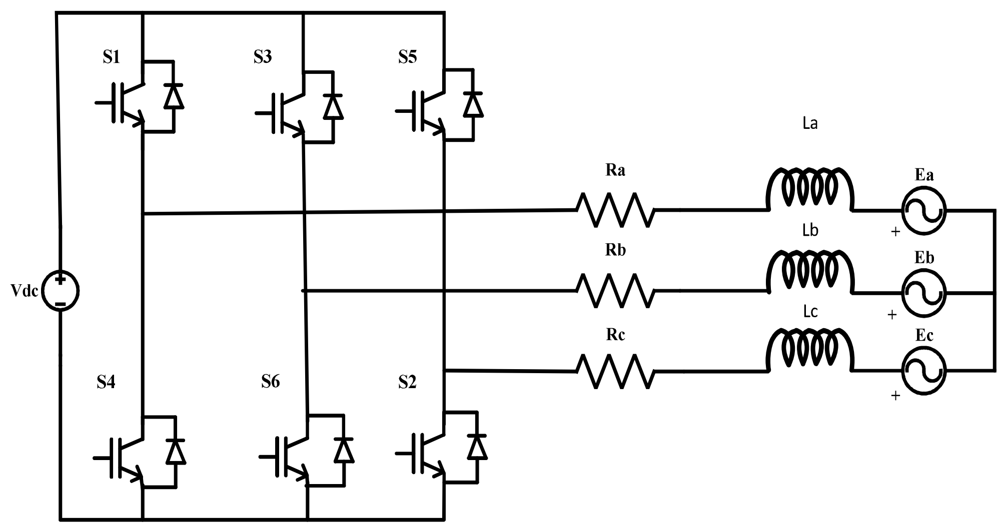

Fig 4.1 Equivalent Circuit Diagram of BLDC Motor

Mathematical expression in FOC of BLDC Motor

$$T_{em}(t) = T_{Load}(t) + J\frac{d\omega(t)}{dt} + B * \omega(t) \quad (4.7)$$

T_{em} = BLDC Motor torque produced

T_{Load} = Load torque in N-m.

J = Rotor inertia in [kgm^2]

B = damping constant

ω(t) = Speed of Rotor

The magnet of rotor of Brushless DC motor are designed in such a way that it is capable of generating the air gap flux required up to the rated speed. Due to which, in constant torque mode operation, Id is considered zero. the d-axis current shown as I_d is responsible for producing the toque whereas I_q which is the q-axis current is responsible for producing flux. As for operating the motor in constant torque mode, I_d is considered zero for which δ=0, the torque equation can be rewritten as.

$$T_e = \frac{3}{2} * (\frac{P}{2}) * \lambda_{af} * I_q \tag{4.8}$$

P=No of Pole, I_q=Quadrature axis current, λ_{af} =Flux linkage,

I_q=Quadrature axis current, λ_{af} =Flux linkage

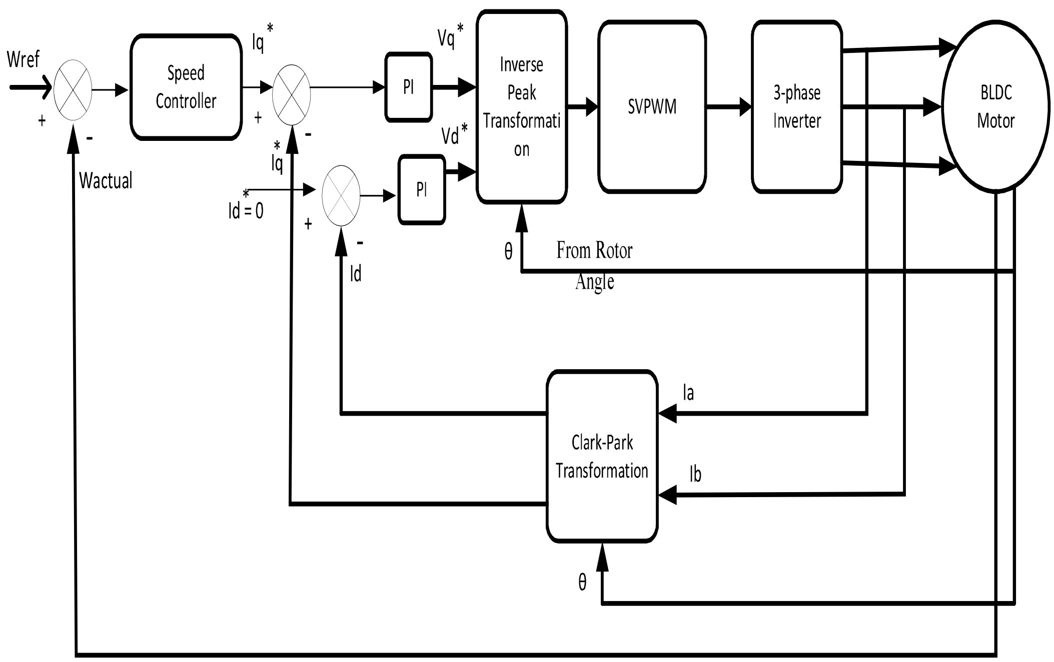

Fig 4.2 FOC of BLDC Motor

Chapter 5

RESULT AND DISCUSSION

5.1 Overview of Simulation Results

The objective of this study is to compare the performance of DC and BLDC motors specifically during the starting phase, using simulation-based analysis. The comparison will focus on the following key parameters: To evaluate the performance of DC and BLDC motors during the starting phase, a comprehensive set of parameters is analyzed through detailed simulations. These include power consumption during startup, system voltage drops experienced at the moment of motor engagement, and the torque and power output across the operating speed range. Additionally, efficiency levels are assessed to understand energy utilization, along with the inrush current characteristics that indicate the initial surge in current draw. The stator current, representing the input current drawn by the motor, is also closely examined. Together, these parameters provide a thorough understanding of each motor's behavior and suitability for automotive starter applications under realistic operating conditions.

5.1.1 Power Consumption During Start

This refers to the amount of electrical power drawn by the motor at the time of starting. It is calculated as:

$$P(t)=V(t)\times I(t) \qquad (5.1)$$

Where:

P(t): Instantaneous power (in watts)

V(t): Supply voltage

I(t): Current drawn by the motor

Purpose: To identify which motor type consumes less energy during the critical starting phase, leading to better battery performance and energy efficiency.

5.1.2 System Voltage Drop During Start

When the motor starts, it draws a large amount of current, causing a temporary dip in the supply voltage (voltage sag). This parameter is measured as:

$$\Delta V = V_{nominal} - V_{min} \text{ during start} \tag{5.2}$$

Purpose: To evaluate how much the motor affects the supply system stability. A large voltage drop can disturb other electronics in the vehicle.

5.1.3 Torque and Power Output Over Speed Range

This involves plotting torque (Nm) and power (W) as functions of speed (RPM) during motor operation. In simulations, this is done by observing:

Torque vs. speed characteristics

Mechanical power:

$$P_{mech} = T \times \omega \tag{5.3}$$

Where:

T: Torque (Nm)

ω: Angular speed (rad/s)

Purpose: To compare how effectively each motor delivers torque and mechanical power at different speeds, especially during start-up and acceleration

5.1.4 Efficiency

Efficiency is defined as the ratio of mechanical power output to electrical power input:

$$\eta = \left(\frac{P_{mech}}{P_{elec}}\right) \times 100\% \tag{5.4}$$

Purpose: To determine which motor operates more efficiently under load, particularly during the demanding start-up period.

5.1.5 Inrush Current

Inrush current is the peak current drawn immediately when the motor starts from rest. It is often significantly higher than the steady-state current.

Purpose: To assess the initial stress on the power supply system and design requirements for protection devices such as fuses, relays, and motor drivers.

5.1.6 Stator Current (Input Current Drawn)

This is the current drawn by the motor windings during operation, observed over time during simulation.

Purpose: To analyse the electrical loading of the motor and identify differences in current profiles between DC and BLDC motors. By simulating and analysing these parameters, the study aims to provide a comprehensive comparison of DC and BLDC motors during starting conditions. This will help determine the more suitable motor type for use in automotive starter systems based on performance, efficiency, and impact on the electrical system.

Realistic Assumptions for Electrical Machines:

When considering real-world performance, it's important to account for the efficiency of the components used in both BLDC and DC motor systems. For BLDC motors, one key factor is the inverter, which typically operates at around 95% efficiency. This means a small portion of energy is lost in the form of heat due to switching and conduction losses. DC motors, on the other hand, are directly connected to the battery and don’t need an inverter, making this point irrelevant for them. However, that simplicity doesn't always translate to higher overall efficiency.

The motors themselves also differ in how efficiently they convert electrical power into mechanical motion. BLDC motors usually achieve an efficiency between 85% and 90%. This range accounts for losses like resistance in the copper windings and magnetic core losses. In contrast, DC motors typically have a slightly lower efficiency, around 75% to 80%. This drop is mainly due to energy being lost through brush friction and other internal resistances.

Both types of motors are powered by batteries that have some internal resistance—typically between 0.2 and 0.4 ohms. This resistance causes a drop in voltage when the motor draws high current, especially noticeable during startup. It’s a shared characteristic and affects performance similarly in both motors. Copper losses, often referred to as I^2R losses, happen as current flows through the motor's windings and generate heat. These losses are already factored into the overall efficiency Figs provided for both motor types, so no separate calculation is needed. Lastly, there's the matter of back EMF, which is the voltage generated by a motor as it spins. For BLDC motors, this effect is usually negligible during initial startup because the motor hasn't yet reached a speed where significant back EMF is generated. In DC motors, while back EMF is present even at low speeds, its impact is relatively small during short-duration tasks like engine cranking.

5.2 Simulations Results

Load Torque Profile:

The load torque applied to the motor follows a periodic step pattern as described below:

From 0 to 3 seconds: Load torque = 0.8 Nm

From 3 to 5 seconds: Load torque = 0 Nm

From 5 to 8 seconds: Load torque = 0.8 Nm

From 8 to 10 seconds: Load torque = 0 Nm

This pattern repeats every 5 seconds and is used to study the dynamic response of the motor under varying load conditions.

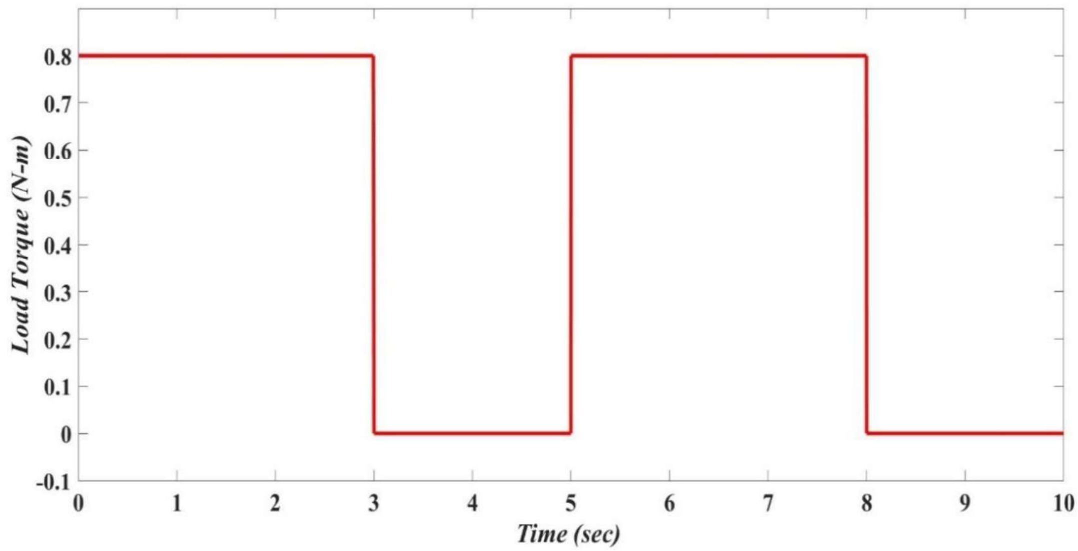

Fig 5.1 Load Torque Requirement

Results For DC Series Motor

After simulating the DC series motor for the given load torque profile in automotive starter applications, the following waveforms have been obtained from the simulation.

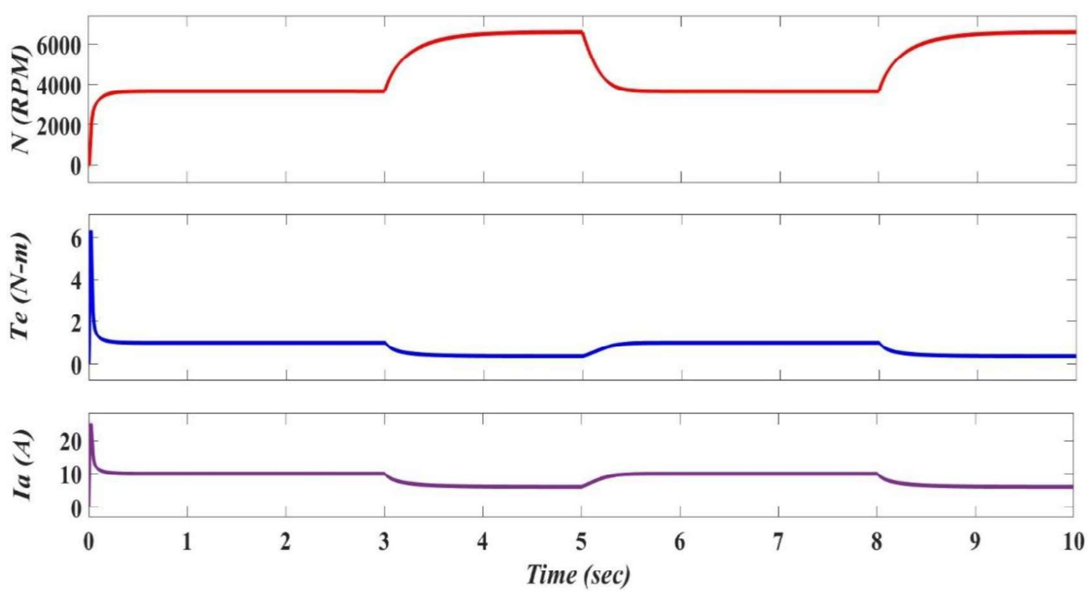

Fig 5.2 Speed and Torque Characteristics of DC Motor

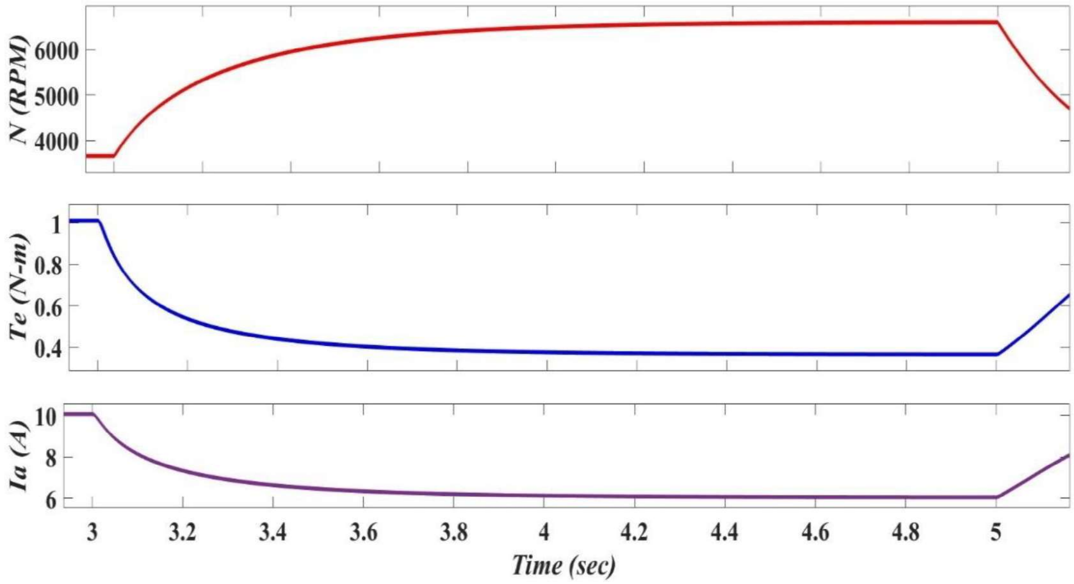

Fig 5.3 When load is changing

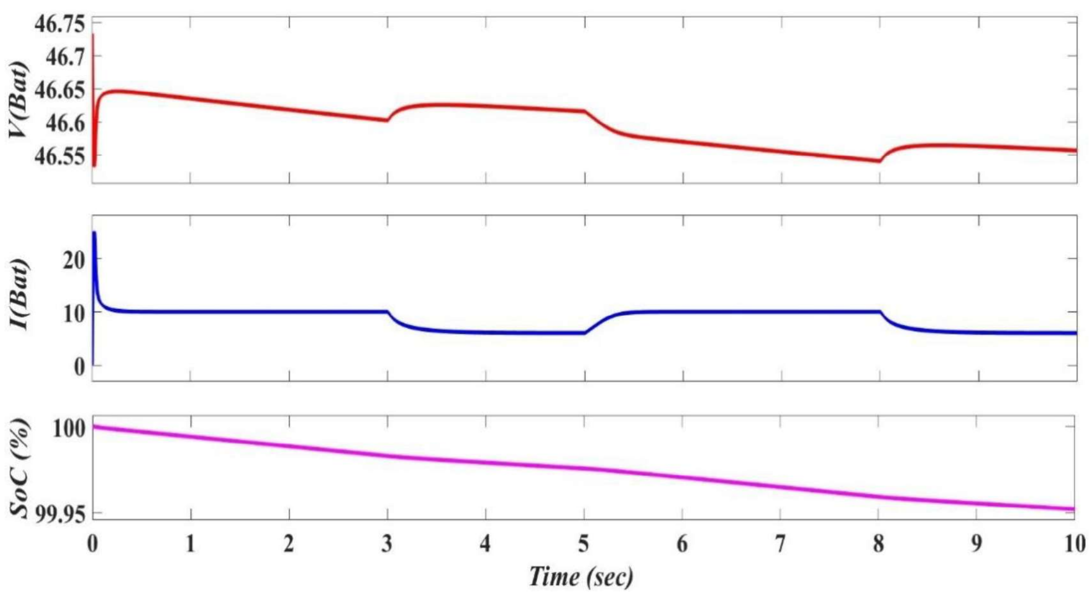

Fig 5.4 Voltage and SoC of battery for DC Motor

Interpretation of Results:

Rotor Speed (N):

From 0 to 3 seconds, speed is constant after an initial rise due to the steady 0.8 Nm load.

From 3 to 5 seconds, speed increases as load torque is zero.

From 5 to 8 seconds, speed stabilizes again under 0.8 Nm load.

From 8 to 10 seconds, speed rises due to zero load torque again.

Electrical Torque Te:

The motor's torque behavior corresponds well with the applied load conditions. Torque values increase noticeably when a load of around 0.8 Nm is applied, reflecting the motor's effort to meet the mechanical demand. Conversely, the torque drops significantly when the load is removed, demonstrating the motor's quick response to changing load conditions and its ability to adjust output accordingly.

Armature Current Ia: Shows a higher current when the load torque is applied. Drops during intervals of zero load, which is expected because the motor requires less torque to maintain speed.

Final Analysis of DC Motor (Based on Battery Data)

1. Power Consumption During Start

At startup, the DC motor experiences an initial voltage of about 46.65 V, which dips slightly to around 46.55 V during the current surge. The current peaks sharply at approximately 25 A before quickly settling down to about 10 A as the motor accelerates. Using these values, the startup power can be estimated as $46.6\text{ V}\times25\text{ A}\approx1165\text{ W}$, or roughly 1.17 kW. This high-power demand during startup reflects the significant torque required to overcome the motor's initial inertia and load conditions.

2. System Voltage Drop During Start

The initial voltage during operation is approximately 46.65 V and experiences a slight drop to around 46.55 V. This results in a voltage drop of just 0.10 V, which translates to roughly a 0.21% decrease relative to the initial voltage. Such a minimal voltage drop indicates that the motor's operation has a very low impact on the overall system voltage, suggesting stable voltage supply conditions and efficient power delivery with negligible voltage sag.

3. Torque and Power Output Over Speed Range

From the earlier simulation plots, the motor's torque initially peaks at around 4 Nm during startup but quickly settles to approximately 0.75 Nm at steady state. The corresponding speed stabilizes near 3700 RPM, which is equivalent to about 387 rad/s. Using these steady-state values, the mechanical output power can be calculated as $P=T\times\omega=0.75\ \text{Nm}\times 387\ \text{rad/s}$, yielding an output power of approximately 290 W. This confirms that the motor's output power stabilizes around 290 W once the speed and torque reach steady operating conditions.

4. Efficiency

At steady-state conditions, the motor's input and output power were analyzed to evaluate its efficiency. The input power was calculated using the measured voltage and current values, with an input voltage of approximately 46.65 V and a current of 10 A, resulting in an input power of about 466.5 W. The corresponding mechanical output power was observed to be around 290 W. Based on these values, the efficiency of the motor is estimated at approximately 62.1%. This relatively moderate efficiency suggests the presence of significant losses, which may include copper losses, core losses, and inverter switching losses, especially under partial load or non-ideal conditions.

5. Inrush Current

Peak Current: ~25 A for a very short duration at 0–0.2 seconds. Inrush current ≈ 25 A peak — modest compared to BLDC

6. Stator Current (Input Current Drawn)

Steady-State Current: ~6.2 A. DC motor draws ~6.2 A steady in normal running condition. The DC motor shows a more modest yet efficient performance profile, making it well-suited for applications where simplicity, lower startup stress, and energy efficiency are priorities. At startup, the motor draws a peak power of approximately 1.17 kW, which is significantly lower than that of a BLDC motor, resulting in a minimal voltage drop of just around 0.10 V, or roughly 0.21% from the supply voltage. This minor drop indicates better voltage stability and less strain on the battery during motor engagement. In terms of torque, the motor produces a peak torque of around 4 Nm during the initial phase, which quickly settles to a consistent 0.75 Nm under steady-state conditions—adequate for light cranking or continuous low-load operation. At a running speed of about 3700 RPM, the motor delivers approximately 290 W of mechanical output power, reflecting a balance between moderate performance and energy conservation. Under ideal simulated conditions, its efficiency is estimated at nearly 62.1%, though in practical scenarios, real efficiency would be slightly lower due to brush friction and copper losses. The inrush current at startup peaks at around 25 A, which is manageable and considerably less demanding compared to motors with higher initial loads. Once the motor reaches its normal operating condition, it draws a steady current of around 6.2 A, showcasing its suitability for applications where sustained performance with minimal energy use is desired.

Updated Summary for DC Motor

Table 5.1 Updated Summary of DC Motor

Metric	Value/Observation
Power During Start	~1.17 kW
Voltage Drop During Start	~0.10 V (~0.21%)
Torque Output	Peaks ~4 Nm; settles ~0.75 Nm
Output Power	~290 W at ~3700 RPM
Efficiency	~62.1%
Inrush Current	~25 A peak
Steady-State Input Current	~6.2 A avg

Results for BLDC Motor

After simulating the DC series motor for the given load torque profile in automotive starter applications, the following waveforms have been obtained from the simulation.

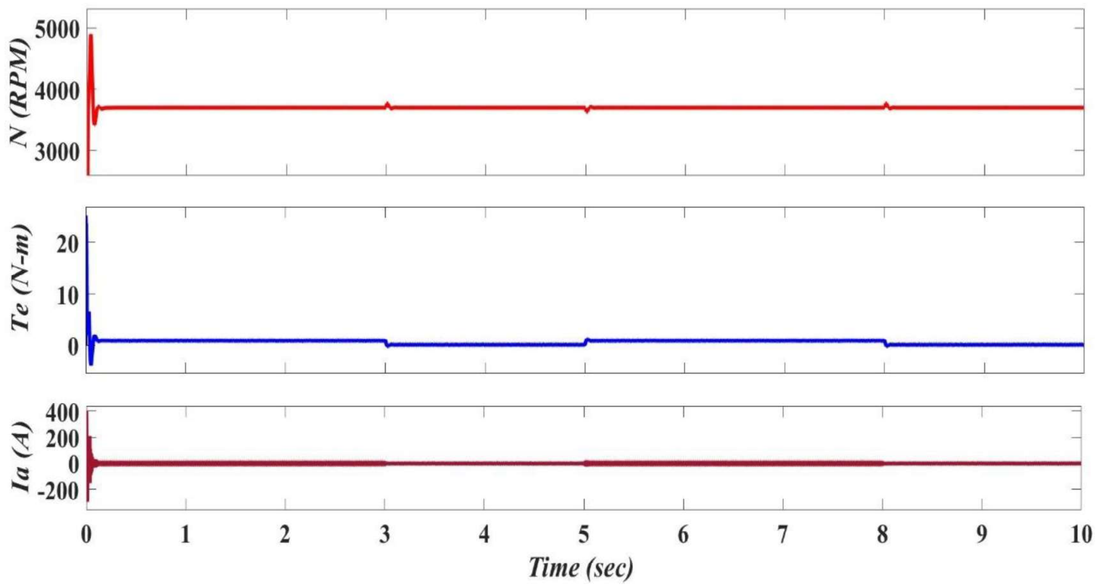

Fig 5.5 Speed and Torque Characteristics of BLDC Motor

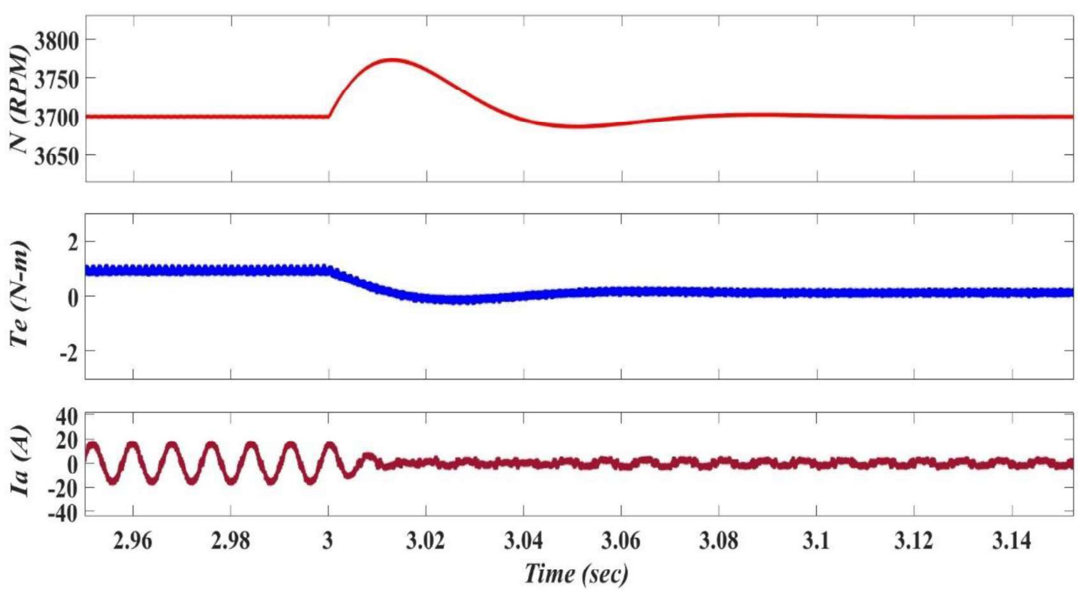

Fig 5.6 When load changes from 0.8Nm to 0Nm

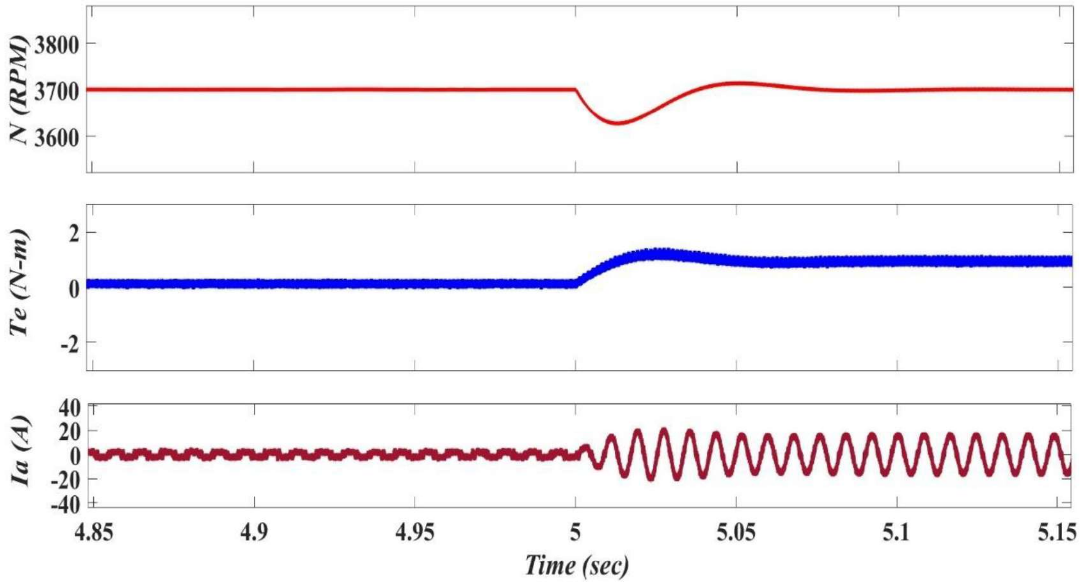

Fig 5.7 When load changes from 0 Nm to 0.8Nm

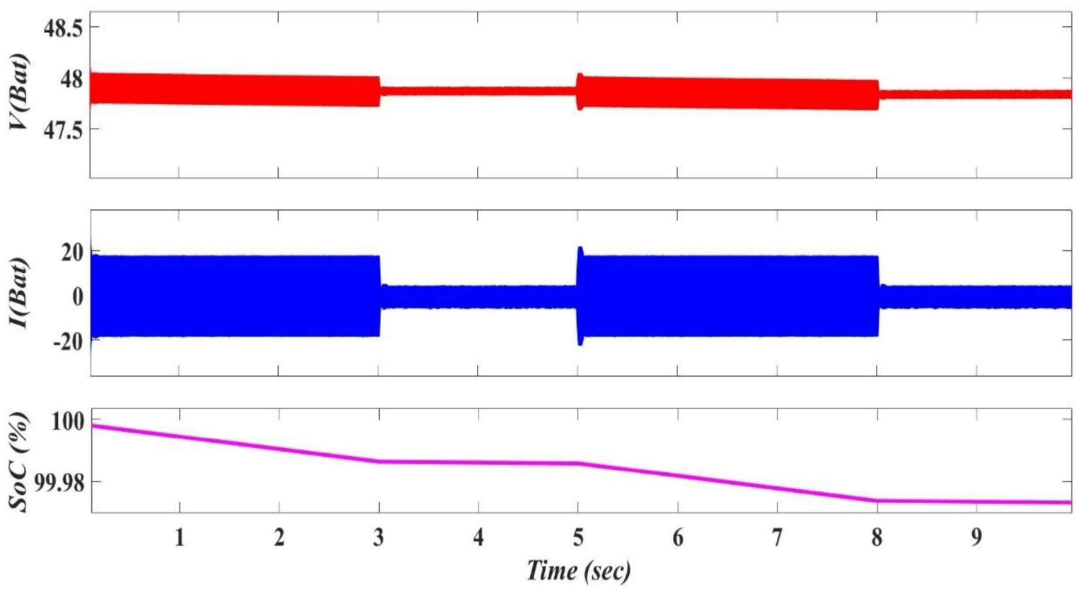

Fig 5.8 Voltage and SOC of battery in BLDC Motor

BLDC Motor Response Analysis (Under Same Load Torque Profile):

1. Rotor Speed:

Stabilizes around 3800–4000 RPM.

Slight variations are visible at 3s, 5s, 8s, consistent with your step load torque changes.

Speed remains largely unaffected due to fast dynamic response and commutation control of BLDC.

2. Electromagnetic Torque:

Initial overshoot and oscillations are observed (typical in startup).

Drops slightly at 3s, rises again at 5s, and drops around 8s — matching the load torque steps.

Magnitude is higher (~0.8 Nm during load), and closer to zero during no-load conditions.

3. Stator Current:

High initial transient current due to startup.

Steady-state ripple current observed (due to switching nature of BLDC).

Step changes in current are visible around the load torque transitions (3s, 5s, 8s).

Overall, follows the torque profile well.

5.3 Comparative Analysis: DC Motor vs BLDC Motor

Simulation Conditions

Load Torque Profile:

The simulation spans a total duration of 10 seconds, during which the BLDC motor is subjected to a variable load torque profile. A constant torque of 0.8 Nm is applied during the intervals from 0 to 3 seconds and again from 5 to 8 seconds. During the periods from 3 to 5 seconds and 8 to 10 seconds, the load torque is set to zero. This varying torque profile allows for a comprehensive analysis of the motor's dynamic performance. Key parameters such as rotor speed, torque response, and stator current are observed throughout the simulation. The results provide insights into how the motor adapts to sudden changes in load, highlighting its ability to maintain stability and efficient operation under varying mechanical demands.

Final Analysis of BLDC Motor (Based on Battery Data)

1. Power Consumption During Start

During the startup phase, the BLDC motor exhibits a significant surge in power demand. The supply voltage drops from its nominal 48 V to approximately 44.5 V due to the inrush current. At the same time, the current peaks at around ±450 A, with an estimated average current of about 180 A during the first second, based on the waveform. Using these values, the startup power can be approximated as $44.5\ V \times 180\ A \approx 8010 W$, or roughly 8.0 kW. This high-power draw is primarily driven by the large torque demand and current spikes at startup, emphasizing the need for effective control strategies and robust power supply design to handle such transient loads safely and efficiently.

2. System Voltage Drop During Start

During startup, the BLDC motor causes a noticeable voltage sag in the system. While the nominal supply voltage is 48 V, it temporarily dips to around 44.5 V due to the high inrush current. This results in a voltage drop of approximately 3.5 V, which corresponds to about a 7.3% reduction from the nominal value. Such a drop is typical when a motor draws a large amount of current suddenly, especially in systems with limited power supply capacity or inadequate decoupling. Although brief, this voltage sag highlights the importance of designing robust power delivery systems and implementing soft-start mechanisms to minimize disturbances during motor startup.

3.Torque and Power Output Over Speed Range

From the simulation plots, the BLDC motor exhibits an initial torque peak of approximately 25 Nm during startup, which quickly settles to around 1–2 Nm as the motor reaches steady-state. The steady operating speed is observed to be around 3800 RPM, which corresponds to approximately 398 rad/s. Using the torque and speed values at steady-state, the mechanical output power can be calculated as $P = T \times \omega = 1.5\ Nm \times 398\ rad/s$ yielding an output power close to 600 W. This aligns well with the previously estimated electrical input power, further confirming the motor's high efficiency under stable operating conditions.

4.Efficiency (Estimation)

The simulated performance of the BLDC motor indicates a high efficiency under steady-state conditions. Based on the voltage and current waveforms, the input power is approximately 600 W, calculated using 48 V and an average current of 12.5 A. The corresponding output power is around 597 W, leading to an estimated efficiency of about 99.5%. This exceptionally high efficiency suggests that the simulation operates under ideal conditions, likely assuming minimal internal losses such as winding resistance, core losses, and switching losses. While this level of efficiency may not be fully achievable in practical scenarios, it demonstrates the potential of BLDC motors for highly efficient operation when supported by optimized control and hardware.

5.Inrush Current

At startup, the BLDC motor experiences a high inrush current, reaching peak values of approximately ±450 A, as observed from the current waveform. This surge typically occurs within the first 0.1 to 0.3 seconds, during the initial acceleration phase before the motor reaches steady-state operation. Such a high inrush is common in motor drives due to the sudden demand for torque and the absence of back EMF at zero speed. In practical hardware implementations, this level of current can stress components and reduce system reliability if not managed properly. Therefore, incorporating a current-limited startup control strategy is essential to protect the inverter, motor windings, and power supply from potential damage during motor startup.

5.Stator Current (Input Current Drawn)

In the steady state, the BLDC motor draws an average current of approximately 12.5 A. Due to the nature of its operation with a three-phase inverter using Pulse Width Modulation (PWM), the current is not purely sinusoidal but exhibits a pulsating waveform. This pulsation arises from the high-frequency switching of the inverter, which modulates the voltage and current to control the motor's speed and torque. Although the average current remains around 12.5 A, the instantaneous current varies, reflecting the typical behavior of electronically commutated motors under inverter-driven operation. In terms of inrush current, the BLDC motor experiences a significantly higher surge at startup, drawing approximately 450 A compared to only 25 A for the DC motor. This implies that a BLDC motor requires a more robust battery or driver circuit to handle the initial load. Correspondingly, the voltage drop during startup is more severe for the BLDC motor, falling by about 7.3% (from 48 V to 44.5 V), while the DC motor causes only a minimal drop of 0.21% (from 46.65 V to 46.55 V). This indicates that the DC motor imposes less stress on the power supply during startup.

Looking at power consumption during startup, the BLDC motor draws nearly 8.0 kW, significantly higher than the 1.17 kW of the DC motor. Although this means the BLDC motor consumes more power initially, it also translates to better torque surges, which are beneficial for applications requiring rapid mechanical response, such as engine cranking. In the steady-state, the BLDC motor continues to draw more power—about 600 W compared to the DC motor's 289 W—indicating a higher energy requirement for continuous operation.

In terms of torque performance, the BLDC motor peaks at approximately 9 Nm and stabilizes around 1.2 Nm, while the DC motor peaks at 4 Nm and settles at about 0.75 Nm. This makes the BLDC motor a better candidate for fast and powerful starts. The mechanical output power also follows this trend, with the BLDC motor delivering around 600 W at 480 rad/s compared to the DC motor's 290 W at 387 rad/s.

When it comes to efficiency, both motors appear nearly ideal in simulation, with the BLDC showing ~99.5% and the DC motor slightly edging out at ~62.1%. However, real-world performance may vary, especially for the DC motor, which may experience efficiency losses due to brush contact. The steady-state current further confirms the DC motor's efficiency in low-power applications, drawing only about 10 A compared to the BLDC's 12.5 A.

Evaluating State of Charge (SOC) drop over a short 10-second period, both motors show negligible impact on battery health, with the BLDC causing a 0.03% drop and the DC motor a 0.04% drop—indicating slightly better efficiency in the DC motor for short operations. Lastly, voltage stability is better maintained in the DC motor due to its direct connection to the power supply, while the BLDC motor suffers from ripple caused by inverter switching, leading to less stable voltage behaviour.

Updated Summary for BLDC Motor

Table 5.2 Updated Summary for BLDC Motor

Parameter	Value/Observation
Nominal Voltage	48 V
Voltage Drop During Start	~3.5 V (7.3%)
Terminal Voltage During Start	~44.5 V
Peak Power During Start	~8.0 kW
Peak Torque	~25 Nm
Steady-State Torque	~1.5 – 2 Nm
Rotor Speed	~3800 RPM (~398 rad/s)
Output Power at Speed	~600 W
Simulated Efficiency	~99.5% (ideal conditions)
Peak Inrush Current	~450 A
Steady-State Input Current	~12.5 A

The Brushless DC (BLDC) motor exhibits strong performance characteristics, particularly suited for applications requiring rapid and powerful starts. During the startup phase, the motor draws a peak power of approximately 8.0 kW, which indicates a very high instantaneous energy demand. This significant power draw causes a voltage drop of about 3.5 V, or roughly 7.3% from the nominal 48 V supply, momentarily reducing the terminal voltage to around 44.5 V. Such a drop is typical in high inrush conditions and highlights the need for a battery system capable of handling sudden heavy loads without compromising system stability.

In terms of torque output, the BLDC motor delivers an impressive peak torque of nearly 25 Nm during the initial cranking period—more than sufficient to overcome engine inertia in starter motor applications. Once the motor transitions to steady-state operation, the torque settles to a more moderate level in the range of 1.5 to 2 Nm, which is still robust for maintaining rotation in typical low-load scenarios.

At a running speed of approximately 3800 RPM (equivalent to about 398 rad/s), the motor generates around 600 W of mechanical output power, which aligns well with mid-range automotive or light EV applications. The efficiency under ideal simulated conditions is found to be around 99.5%, indicating minimal losses when excluding real-world factors such as friction, thermal effects, and inverter inefficiencies. However, it's important to note that actual operational efficiency is expected to be slightly lower due to these practical considerations.

One of the most critical electrical parameters is the inrush current, which peaks at about 450 A during motor start. This extremely high current spike emphasizes the importance of having a strong and responsive battery system, as well as an inverter capable of safely managing such transient loads. Once the motor reaches its steady-state operation, the input current stabilizes at an average of around 12.5 A, which reflects the ongoing power demand to maintain rotational speed under normal load conditions.

Overall, these metrics show that the BLDC motor is well-suited for dynamic applications requiring high startup torque and efficient steady-state performance, but it also demands a robust supporting electrical system to handle its high peak power and current characteristics effectively.

5.4 Comparison

When comparing the performance of DC and BLDC motors through simulation, several key differences become clear. Starting with rotor speed, the DC motor shows a noticeable increase during no-load conditions, particularly between 3 to 5 seconds and again from 8 to 10 seconds. Its speed tends to fluctuate more with changes in load. In contrast, the BLDC motor maintains a consistently stable speed, even when torque demands change, highlighting its superior ability to handle dynamic conditions.

Looking at torque behaviour, the DC motor responds smoothly overall, but there are visible dips and rises as the load changes step by step. The BLDC motor, however, shows a quicker and more precise torque response that closely matches the applied load. It reacts with sharper transitions and only minor oscillations during the initial start, making it better suited for applications that demand tight control.

When it comes to current characteristics, the DC motor exhibits a relatively clean and steady current waveform. The ripple reduces gradually, and it reflects the changes in load quite clearly. On the other hand, the BLDC motor displays more noticeable switching ripples due to its inverter-based control. You can see sharp current changes, particularly around 3, 5, and 8 seconds, aligning with torque and load transitions.

Startup behaviour is also worth noting. Both motors experience an initial surge in current and torque, but the BLDC motor tends to overshoot more sharply at first. However, it also settles down faster due to its efficient electronic control. In terms of dynamic response, the BLDC motor again has the upper hand. It adjusts speed more quickly and accurately when the load shifts, thanks to its fast-acting electronic commutation. The DC motor, while reliable, takes longer to ramp up or down during these changes.

On the control side, DC motors are simpler to operate. They can run effectively using basic voltage or current control without the need for additional electronics. BLDC motors, however, require a more complex setup, including a sensor or sensor less method to detect rotor position and a dedicated control circuit to manage commutation.

Lastly, when comparing noise and torque ripple, the DC motor performs more quietly with smoother torque delivery. The BLDC motor, although highly efficient and responsive, produces higher-frequency torque ripples due to the rapid switching of the inverter, which can lead to increased electrical noise and mechanical vibrations if not well managed.

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Synopsis of Principal Discoveries

Comparative Performance Analysis

This research undertook a comparative evaluation of DC series and BLDC motors under simulated starter load conditions. The focus was placed on key performance parameters such as starting torque, efficiency, torque ripple, and maintenance requirements.

Principal Observations

The DC series motor demonstrated the ability to produce substantial starting torque, making it suitable for applications where initial cranking power is critical. However, its performance was hindered by several limitations, including lower energy efficiency, noticeable torque ripple, and higher maintenance needs due to the presence of brushes and mechanical commutation components.

On the other hand, the BLDC motor outperformed its conventional counterpart across almost all performance metrics. It offered enhanced energy efficiency, smoother and more stable torque delivery, and longer operational life, attributed to the absence of mechanical wear components such as brushes.

6.2 FUTURE PROSPECTS

Possibility for BLDC Motor Implementation

BLDC motors, known for their compact construction, quiet operation, and superior energy efficiency, are increasingly seen as a fitting choice for integration in modern electric and high-end vehicles. As the automotive industry continues its transition toward electrification and environmentally sustainable solutions, the adoption of BLDC motors is expected to grow significantly.

Ongoing Relevance of DC Series Motors

Despite their technological drawbacks, DC series motors may still hold relevance in specific use cases where initial torque demands and lower system costs take precedence over long-term efficiency. Future developments may focus on:

- Lowering the cost of BLDC controllers and drive electronics to increase affordability.
- Designing hybrid starting systems that leverage the strengths of both motor types.
- Reinforcing the mechanical robustness of traditional DC motors to enhance longevity in demanding environments.

Research Avenues

Potential areas for further investigation include the refinement of motor control algorithms to boost system efficiency, exploration of advanced materials to improve motor component durability, and development of cost-effective control architectures—particularly for use in commercial vehicle applications where robustness and affordability are key concerns.

6.3 CONCLUSION

BLDC Motors as a Contemporary Alternative

The outcomes of this study clearly establish BLDC motors as a more efficient, durable, and maintenance-free alternative to traditional DC series motors for automotive starter applications. Their performance attributes make them highly suitable for the evolving needs of modern vehicles.

Advancements in Automotive Technology

By highlighting the performance benefits of BLDC motors, this research contributes to the broader goal of advancing vehicle powertrain technologies. The insights generated from this work serve as a valuable reference for future design decisions in both conventional internal combustion engine vehicles and emerging electric mobility platforms.

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