

DESIGN OF INTELLIGENT BLDC MOTOR ARCHITECTURES FOR THE NEXTGEN ELECTRIC VEHICLES

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Abstract

One of the cornerstones of developing energy-efficient policies in the field of electric mobility is the arrival of brushless direct current (BLDC) motors. In this paper, a detailed discussion of the BLDC motor systems is presented, including the design, modelling, and control strategies to ensure more efficient use of the motor system to achieve greater energy efficiency in car motors. The paper talks about the principles of the work of the BLDC motors as well as the use of position sensors, electronic commutation, and the dynamics of the inverter. The mathematical model of BLDC motors is described in detail, with the focus being placed on the reduction of the highly complicated 3-phase systems to simpler d-q reference frames to simplify the analysis. A range of control methods, including proportional-integral-derivative (PID) controllers, is also examined in the research, and the importance of their role in obtaining accurate control of speed and torque is mentioned. Introduction of power electronics, such as inverters and pulse-width modulation (PWM) methods, is also dealt with to enhance the efficient functioning of a motor. Moreover, the paper discusses closed-loop control systems that stabilise and operate under a diverse environment, and this is fundamental to the application of electric vehicles. Transient analysis and dynamic response of the BLDC motors are given special attention so as to optimise the use of energy. The work will be used as a reference guiding researchers and engineers who want to develop the current technology of the BLDC motors to achieve sustainable electric mobility systems.

Keywords: Brushless DC Motor; Closed Loop Control; EV Application; MATLAB; Motor Control Strategies

Introduction

With the progress of the world to a more environmentally friendly and sustainable future, a combination of renewable sources of energy and electric cars becomes more and more important (Roy *et al.*, 2024). The shift to sustainable transport has been an impulse to create energy-saving

technologies, one of the crucial solutions is electric vehicles (EVs) (Roy *et al.*, 2023). An extensive modelling of load-frequency control in hybrid power plants has shown that the integrated contribution of renewable generation, traditional plants, electric vehicles, and superconducting

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magnetic energy storage is effective in improving the stability of the entire grid and dynamic response (Nagendra *et al.*, 2024). Also, analyses on the concept of bidirectional power-flow control of EVs in photovoltaic-based grids emphasise the possibility of onboard AC charging to provide grid flexibility and also permit efficient vehicle-to-grid (V2G) functionality (Bharti *et al.*, 2024). This development is supported by an extremely efficient motor that is considered to be the best in the field: the Brushless Direct Current (BLDC) motor, which is compact in design and reliable in operation (Yaz & Cetin, 2021). Recent studies on solar-powered EV charging have demonstrated that the CTF method, based on the TOSSI, can be utilised to improve the performance of charging stations considerably to enhance the efficiency and reliability of renewable-integrated transportation systems (Pattnaik *et al.*, 2024). The present paper is devoted to the optimisation of the BLDC motor system in order to achieve an increased energy efficiency, especially in the case of electric mobility. The conversation includes basic features of the BLDC motors, mathematical modelling of the motors, as well as the control measures whose purpose is to obtain the optimal performance.

Working Principle of the BLDC Motor

In this configuration, the stator windings serve as the heart of the motor, while the permanent magnets orbit around it. Unlike traditional motors that rely on mechanical brushes for commutation, BLDC motors utilise advanced electronic circuits.

The rotor position plays a pivotal role in controlling the motor. Rotor position detection is achieved through two methods:

- **Sensor-Based Control:** Hall-effect sensors are the most commonly used type to detect rotor position. These sensors work on the theory that any conductor carrying a current placed within a magnetic field will induce a voltage proportional to the strength of the field. When the rotor's magnetic poles pass the sensor, it detects the polarity change, triggering the controller to energise the appropriate stator winding (Kumhar *et al.*, 2025b).

- **Sensorless Control:** The sensorless control bases its estimate of the rotor position on the back electromotive force (BEMF) produced in the stator windings. The scale of the BEMF, which is directly proportional to rotor speed, dictates the time during which the windings can be energised. BLDC motors usually produce a trapezoidal BEMF waveform, which makes them the best in certain

applications (Kumhar *et al.*, 2025a). With a three-phase BLDC, the windings in a motor are only energised in two, while the third is not energised. Such selective energisation reduces energy wastage, and maximum torque is produced. Electronic commutation is carried out with the help of a voltage-source inverter that uses switching devices, including MOSFETs or IGBTs, to switch the current in the stator windings (Iov *et al.*, 2007).

Importance of BLDC Motors in Electric Mobility

The use of BLDC motors in EV applications has been encouraged by the fact that they perform better compared to traditional motors like brushed DC motors and induction motors. These motors have a higher power-to-weight ratio, lower maintenance requirements, and better torque-speed abilities, making them acceptable to energy-limited automotive systems (Cai *et al.*, 2021). Literature highlights their significance, particularly in reducing energy losses and improving overall drivetrain efficiency. The absence of brushes and commutators in BLDC motors eliminates frictional losses, thereby ensuring durability and reducing maintenance requirements. A study by Yadlapalli *et al.* (2022) emphasised the impact of electronic commutation on minimising energy losses, thereby enhancing motor performance. Moreover, the integration of BLDC motors into electric mobility systems has been identified as a key driver for achieving low-carbon transportation solutions (Kumhar *et al.*, 2024). In electric vehicles, the efficiency of energy conversion from electrical to mechanical power is paramount. BLDC motors achieve this through their unique design, utilising permanent magnets and advanced control strategies. Studies by Prabhu *et al.* (2023) highlighted the role of rotor and stator configurations in optimising energy utilisation. Further, the ability to achieve high torque at low speeds aligns BLDC motors with the dynamic requirements of EVs.

The relevance of BLDC motors extends beyond operational efficiency to their adaptability to advanced control mechanisms. Modern vehicles demand precise control over speed and torque under varying load conditions (He *et al.*, 2021). Literature demonstrates that incorporating control strategies, such as PID controllers and sensorless techniques, can significantly enhance motor efficiency (Krishnakumar *et al.*, 2023). These advancements position BLDC motors as indispensable components in next-generation electric mobility systems.

Major Components of a BLDC Motor

The key components facilitating BLDC motor operation include (Anshory *et al.*, 2023):

- **Controller:** Determines the desired motor performance by comparing actual and reference values, subsequently generating control signals. Commonly used controllers include P, PI, and PID types.
- **Inverter:** The converter changes the direct current into alternating current and regulates the output signal to make sure the motors operate efficiently. The use of pulse-width modulation (PWM) is common in the regulation of the inverter output.
- **Sensors:** Other devices like Hall-effect sensors are used to detect the position of the rotor and pass the information to the controller so that right commutation is achieved. As a result, building and working of the BLDC motors is highly engineered to ensure maximum efficiency and performance. The combination of strong rotor-stator systems, the development of electronic commutation, and the accurate control system makes the BLDC motors a coherent part of modern energy-efficient operations, especially in the sphere of electric mobility.

Research Landscape and Objectives

The optimisation of BLDC motor systems for EV applications has been extensively explored in recent years. Research has primarily focused on three key areas: mathematical modelling, control strategy development, and integration with power electronic systems (Thomas & Shanmugam, 2022; Zhang *et al.*, 2022). The modelling of BLDC motors, particularly in the d-q reference frame, simplifies complex phase interactions, enabling the analysis of dynamic behaviour and performance characteristics. (Saiteja and Ashok, 2024) provided a comprehensive framework for modelling BLDC motors, showcasing the effectiveness of d-q transformations in achieving accurate simulations.

Another critical area of research involves control strategies. Traditional controllers such as Proportional-Integral-Derivative (PID) controllers have been widely studied for their simplicity and effectiveness (Borase *et al.*, 2021). However, recent advancements have introduced adaptive and machine learning-based controllers to enhance response times and minimise energy losses. Studies indicate that optimised controllers not only improve performance but also extend the lifespan of motor components by reducing thermal stress and electrical noise (Hajihosseini *et al.*, 2020).

The integration of power electronics, including inverters and pulse-width modulation (PWM)

techniques, is another cornerstone of BLDC motor research. (Hasan *et al.*, 2020) demonstrated that the use of three-phase inverters significantly improves the efficiency of BLDC motors by ensuring precise current control. In addition, PWM methods have been found to improve the use of energy by cutting down the switching losses.

In spite of these developments, there are still problems that surround the perfect fit of the BLDC motors in EVs. Such issues as transient response, dynamic stability, and energy management of different operational conditions have to be explored further. This paper will fill this gap and provide an in-depth investigation of BLDC motor systems and their optimisation for electric mobility that is energy-efficient. These goals are as follows:

- i. Design and modelling of BLDC motors.
- ii. Control strategies toward optimal speed torque regulation are discussed.
- iii. Examining the integration of power electronics to enhance energy efficiency.

Through this study, the paper aims to provide insights into the role of BLDC motors in promoting sustainable transportation and to contribute to the ongoing discussion on energy-efficient technologies in the field of electric mobility.

Materials and Methods

Mathematical Modelling of BLDC Motor

A three-phase BLDC Motor is constructed with sinusoidal distributed windings, featuring a 120° phase shift between the three stator windings. In the stator frame of reference, phase abc seems like a fixed angle, but with a time-varying magnitude. The three-phase system makes the calculation unnecessarily complex, so we transform it into a two-vector orthogonal system, which significantly simplifies the necessary calculations.

Transformation

A three-phase BLDC motor is constructed with stator windings displaced by 120°. In the stationary abc frame, these phase quantities vary with time and are interdependent, making the analysis complex. To simplify the modelling, the abc system is transformed into a two-axis orthogonal system (d-q frame) using Park's transformation. This reduces the number of variables and converts sinusoidal quantities into DC quantities in the synchronous reference frame, thereby simplifying controller design. The abc to dq0 transformation is expressed as:

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (1)$$

For the first 60°, switching

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} +1 \\ -1 \\ 0 \end{bmatrix} \begin{bmatrix} V_{dc} \\ 2 \end{bmatrix} \quad (2)$$

$$\text{Thus, } \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = C \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\text{Then, } \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = C^* \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

So once I_d , I_q , and I_0 components are evaluated, the phase current values can be obtained easily.

Voltage equations in the d-q winding

Let us denote the abc to dq0 transformation as $[T_r]_{abc \rightarrow dq}$ and dq0 to abc as $[T_r]_{dq \rightarrow abc}$

$$[T_r]_{abc \rightarrow dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \quad (3)$$

$$[T_r]_{abc \rightarrow dq} = [T_r]_{dq \rightarrow abc} \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & -\sin \theta \\ \cos\left(\theta + \frac{4\pi}{3}\right) & -\sin\left(\theta + \frac{4\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \quad (4)$$

The general KVL equation for the three stator phases can be expressed compactly as shown in Eq. (5).

$$[\mathbf{v}]_{abc} = R[\mathbf{i}]_{abc} + \frac{\partial}{\partial \theta} [\boldsymbol{\Psi}]_{abc} \quad (5)$$

By applying the abc to dq0 transformation (Eq. 1), the corresponding voltage equations in the dq0 reference frame are obtained (Eqs. 9-10).

$$[T_r]_{abc \rightarrow dq} [\mathbf{v}]_{abc} = [T_r]_{abc \rightarrow dq} R[\mathbf{i}]_{abc} + [T_r]_{abc \rightarrow dq} \frac{\partial}{\partial \theta} [\boldsymbol{\Psi}]_{abc} \quad (6)$$

$$[\mathbf{v}]_{dq} = R[\mathbf{i}]_{dq} + [T_r]_{abc \rightarrow dq} \frac{\partial}{\partial \theta} ([T_r]_{dq \rightarrow abc} [\boldsymbol{\Psi}]_{dq})$$

$$[\mathbf{v}]_{dq} = R[\mathbf{i}]_{dq} + [T_r]_{abc \rightarrow dq} [T_r]_{dq \rightarrow abc} \frac{\partial [\boldsymbol{\Psi}]_{dq}}{\partial \theta} + [T_r]_{abc \rightarrow dq} \frac{\partial [T_r]_{dq \rightarrow abc}}{\partial \theta} [\boldsymbol{\Psi}]_{dq}$$

$$[T_r]_{abc \rightarrow dq} \cdot [T_r]_{dq \rightarrow abc} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$[T_r]_{abc \rightarrow dq} \cdot \frac{\partial}{\partial \theta} ([T_r]_{dq \rightarrow abc}) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

$$\therefore [\mathbf{v}]_{dq} = R[\mathbf{i}]_{dq} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{\partial [\boldsymbol{\Psi}]_{dq}}{\partial \theta} + \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} [\boldsymbol{\Psi}]_{dq} \quad (7)$$

$$\therefore [\mathbf{v}]_{dq} = R[\mathbf{i}]_{dq} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{\partial [\boldsymbol{\Psi}]_{dq}}{\partial \theta} + \omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} [\boldsymbol{\Psi}]_{dq} \quad (8)$$

from which it can be written that,

$$V_d = Ri_d + \rho(\psi_d) - \omega \psi_q \quad (9)$$

$$V_q = Ri_q + \rho(\psi_q) - \omega \psi_d \quad (10)$$

These equations show that the d-axis and q-axis voltages are interdependent, with cross-coupling terms such as $\omega_e L_q i_q$ and $\omega_e L_d i_d$. These coupling terms are crucial in determining the dynamic performance of BLDC motors, highlighting the importance of controller design in decoupling the flux- and torque-producing components.

Torque (Te) equation

The electromagnetic torque is derived from the interaction between stator currents and rotor flux, and is expressed in Eq. (11).

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} r + L_d \rho & -\omega L_q \\ \omega L_d & r + L_q \rho \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (11)$$

Substituting the flux linkages and current components yields the final torque expression, as shown in Eq. (12).

$$\therefore [\mathbf{v}] = [\mathbf{z}][\mathbf{i}] = ([\mathbf{R}] + [\mathbf{L}]\rho + [\mathbf{G}]\omega)[\mathbf{i}] \quad (12)$$

Where,

$$[\mathbf{R}] = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \rightarrow \text{Resistance Matrix}$$

$$[\mathbf{L}] = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \rightarrow \text{Inductance Matrix}$$

$$[\mathbf{G}] = \begin{bmatrix} 0 & -L_q \\ L_d & 0 \end{bmatrix} \rightarrow \text{Motional inductance matrix}$$

or torque matrix

Electrical power input,

$$P_i = V_d i_d + V_q i_q \quad (13)$$

$$P_i = \begin{bmatrix} i_d & i_q \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} = [\mathbf{i}_t][\mathbf{v}] \quad (14)$$

$$P_i = [\mathbf{i}_t]([\mathbf{R}] + [\mathbf{L}]\rho + [\mathbf{G}]\omega) \quad (15)$$

$$P_i = [\mathbf{i}_t][\mathbf{R}][\mathbf{i}] + [\mathbf{i}_t][\mathbf{L}]\rho[\mathbf{i}] + \omega[\mathbf{i}_t][\mathbf{G}][\mathbf{i}] \quad (16)$$

The first term on the RHS is given by;

$$[\mathbf{i}_t][\mathbf{R}][\mathbf{i}] = i_d^2 r + i_q^2 r = \text{Ohmic loss in the two windings} \quad (17)$$

Similarly,

$$[\mathbf{i}_t][\mathbf{L}]\rho[\mathbf{i}] = I_d L_d \rho I_q + I_d L_q \rho I_d \quad (18)$$

The energy W_1 stored in a magnetic field due to self-inductance L

$$\text{and current } i \text{ is given by } = (iL\rho i) \quad (19)$$

The rate at which energy is stored in the magnetic field changes

From conservation of energy, Energy input = Energy output

$$\therefore P = \text{Power is being converted from electrical to mechanical form} = \omega[\mathbf{i}_t][\mathbf{G}][\mathbf{i}] = \text{Electromagnetic torque} \quad (20)$$

$$= \frac{P}{\omega} = [\mathbf{i}_t][\mathbf{G}][\mathbf{i}] \quad (21)$$

$$= L_d i_q i_d - L_q i_d i_q \quad (22)$$

$$= \psi_d i_q - \psi_q i_d \quad (23)$$

For the P pole machine

$$T_e = \frac{P}{2} (\psi_d i_q - \psi_q i_d) \quad (24)$$

Design of controller for the proposed model

The design of controllers for the BLDC motor is crucial for achieving precise control of speed and current, ensuring the system operates efficiently under varying load and environmental conditions. This section explores the design process for the current controller and the speed controller, focusing on their mathematical modelling, transfer function derivation, and parameter optimisation. Figure 1 shows a basic schematic of the proposed motor controller system.

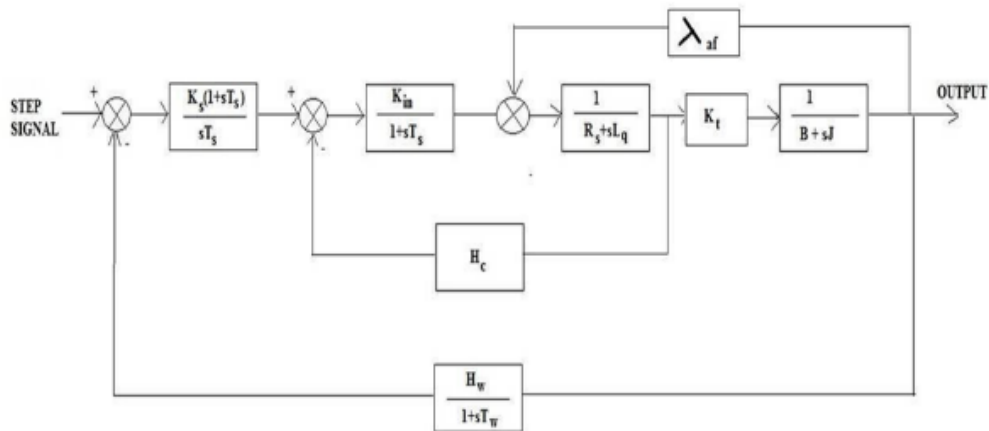


Figure 1. Optimised controller design for BLDC motor speed and current regulation

Designing the Current Controller

The stator current is adjusted to the desired amount by the current controller of the BLDC motor system to achieve the desired torque in the device. This type of control assumes the d-axis current is zero, but this is a simplification that makes it easier to eliminate the cross-coupling between the d-axis and the q-axis components. Based on this assumption, the behaviour of a motor is effectively linearised and therefore allows easier implementation in both simulation and hardware models. The voltage equation associated with the q-axis obtained after this assumption is as follows:

$$V_{qs} = (R_s + L_q p)i_{qs} + \omega_r \phi_{af} \quad (25)$$

The electromechanical equation is given by:

$$\frac{p}{2}(T_e - T_l) = j p \omega_r + B_l \omega_r \quad (26)$$

The expression for electromagnetic torque is given by:

$$T_e = \frac{3}{2} \cdot \frac{p}{2} \phi_{af} i_{qs} \quad (27)$$

Furthermore, if the load is considered to be fractional, then...

$$T_l = B_l \omega_m \quad (28)$$

This substitution leads to the resulting electromechanical equation, which is expressed as:

$$(J_p + B_t)\omega_r = \left\{ \frac{3}{2} \left(\frac{p}{2} \right)^2 \cdot \phi_{af} \right\} i_q = K_t i_q \quad (29)$$

$$\therefore B_t = \frac{p}{2} B_l + B_l$$

$$\therefore K_t = \frac{3}{2} \left(\frac{p}{2} \right)^2 \cdot \phi_{af}$$

When the induced EMF loop intersects the q-axis current loop at the crossover frequency, it can be simplified by moving the pick-off point to the right of the current controller block. After solving the block, we find the transfer function.

$$\frac{i_{qs}^r(s)}{i_{qs}^{*r}(s)} = \frac{K_{in} K_a (1 + s T_m)}{H_c K_a K_{in} (1 + s T_m) + (1 + s T_m) + (1 + s T_{in}) \{ K_a K_b + (1 + s T_a) (1 + s T_m) \}} \quad (30)$$

Where, $K_a = \frac{1}{R_s}$, $T_a = \frac{L_a}{R_s}$, $K_m = \frac{1}{B_t}$, $T_m = \frac{j}{B_t}$, $K_b = K_t K_m \phi_{af}$

We make an approximation that holds in the vicinity of the crossover frequency:

$$1 + s T_r$$

$$1 + s T_m \cong s T_m$$

$$(1 + s T_a)(1 + s T_{in}) \cong 1 + s(T_a + T_{in}) \cong 1 + s T_{ar} \quad (31)$$

Where, $T_{ar} = T_a + T_{in}$

Using this, the transfer function of the current loop is approximately given by:

$$\frac{i_{qs}^r(s)}{i_{qs}^{*r}(s)} \cong \frac{(K_a K_{in} T_m) s}{K_a K_b + (T_m + K_a K_{in} T_m H_c) s + (T_m T_{ar}) s^2} \cong \left(\frac{T_m K_{in}}{K_b} \right) \frac{s}{(1 + s T_1)(1 + s T_2)} \quad (32)$$

It is observed that $T_1 < T_2 < T_m$; thus, upon further simplification, $1 + s T_2 \cong s T_2$. The approximate transfer function of the current loop can be expressed as:

$$\frac{i_{qs}^r(s)}{i_{qs}^{*r}(s)} \cong \frac{K_i}{(1 + s T_1)}$$

$$K_i = \frac{T_m K_{in}}{T_2 K_b}$$

$$T_i = T_1$$

This simplified current loop transfer function is integrated into the speed controller block diagram design.

Speed Controller Design

The speed controller adjusts the motor's reference current to match the desired rotor speed, using feedback from the current controller. The design incorporates a cascading speed loop with a simplified current loop, resulting in a hierarchical control structure.

The Transfer Function of the Speed Loop, derived from the simplified current loop, is expressed as:

$$GH(s) \cong \frac{K_i K_m K_t H_\omega K_s}{T_m} \cdot \frac{(1 + s T_s)}{s^2 (1 + s T_{\omega i})}$$

From which the closed-loop speed transfer function can be determined.

$$\frac{\Omega_r(s)}{\omega_r^*(s)} \cong \frac{1}{H_\omega} \left\{ \frac{K_g \frac{K_s}{T_s} (1 + sT_s)}{s^3 T_{\omega i} + s^2 + K_g \frac{K_s}{T_s} (1 + sT_s)} \right\}$$

$$\text{Where, } K_g = \frac{K_i K_m K_t H_\omega}{T_m}$$

Setting this transfer function equal to the asymmetric-optimum function with a damping ratio of 0.707 results in the closed-loop speed transfer function:

$$\frac{\Omega_r(s)}{\omega_r^*(s)} \cong \frac{1}{H_\omega} \left\{ \frac{(1 + sT_s)}{1 + (T_s)s + \left(\frac{3}{8}T_s^2\right)s^2 + \left(\frac{1}{16}T_s^3\right)s^3} \right\}$$

By equating the coefficients of equations (6.15) and (6.16), solving for the constants provides the time and gain constants of the speed controller as follows:

$$T_s = 6T_{\omega i} \nu$$

$$K_s = \frac{4}{9K_g T_{\omega i}}$$

As a result, the proportional gain (K_{ps}) and integral gain (K_{is}) for the speed controller are determined as follows:

$$K_{ps} = K_s = \frac{4}{9K_g T_{\omega i}}$$

$$K_{is} = \frac{K_s}{T_s} = \frac{27}{K_g T_{\omega i}^2}$$

Comparison of Controllers

A comparison of different controller types based on performance characteristics is summarised in Table 1.

Proposed Controller for BLDC Motor

The BLDC motor's speed and current controllers are implemented using PI or PID configurations, depending on the application requirements. The motor parameters, including resistance (R_s), inductance (L_d , L_q), and flux

linkage (ϕ_{af}), are integral to determining the controller gains.

Key Parameters for the BLDC Motor:

- **Stator Resistance:** (R_s) = 1.4 Ω
- **Inductances:** (L_d , L_q): 0.0056 H, 0.009 H
- **Flux Linkage:** (ϕ_{af}) = 0.1546 Wb-Turn
- **Mechanical Time Constant:** (T_m) = 0.6 s
- **Transfer Functions for the Controller Design:** The inverter gain and time constant are expressed as:

$$K_{in} = 0.65 \frac{V_{dc}}{V_{cm}} = 18.525 \text{ v/v}$$

$$T_{in} = \frac{1}{2f_c} = 0.00025 \text{ s}$$

Thus, the inverter transfer function can be written as:

$$G_r(s) = \frac{K_{in}}{1 + sT_{in}} = \frac{18.525}{(1 + 0.00025s)}$$

The electrical time constant is given by,

$$T_a = \frac{L_q}{R_s} = 0.0064s$$

$$\text{Gain, } K_a = \frac{1}{R_s} = 0.7143$$

Motor (electrical) transfer function,

$$G_a(s) = \frac{K_a}{1 + sT_a} = \frac{18.525}{(1 + 0.00025s)}$$

Induced emf loop: Torque Constant,

$$K_t = \frac{3}{2} \left(\frac{p}{2}\right)^2 \cdot \phi_{af} = 2.087 \text{ N} \cdot \frac{\text{m}}{\text{A}}$$

Mechanical Gain,

$$K_m = \frac{1}{B_t} = 100 \text{ rad/s/Nm}$$

Table 1. Comparison of controller types highlights key performance characteristics

Characteristic	PI	PD	PID
Rise Time	Increases	Decreases	Decreases (with K_p)
Overshoot	Moderate	Decreases	Decreases (with K_d)
Steady-State Error	Eliminates	May remain	Eliminates (with K_i)
Transient Response	Moderate	Improved	Highly improved
System Stability	Improved	Improved	Balanced

Mechanical transfer function,

$$G_b(s) = \frac{K_t K_m \phi_{af}}{1 + sT_m} = \frac{32.26}{1 + 0.6s}$$

Here, the mechanical time constant is defined as:

$$T_m = \frac{J}{B_t} = 0.6s$$

Motor (mechanical):

$$G_m(s) = \frac{K_m K_t}{(1 + sT_m)} = \frac{208.7}{(1 + 0.6s)}$$

The equivalent electrical time constant of the motor

$$as^2 + bs + c = 0$$

$$\begin{aligned} \text{Let } a &= T_m T_{ar} \\ b &= T_m + K_a K_{in} T_m H_c \\ c &= K_a K_b \end{aligned}$$

By substituting the values of the in the equation. (5.21) from the above eq. (5.22)

$$\begin{aligned} a &= 0.6 * 0.0064 = 0.00384 \\ b &= 0.6 + (0.7143 * 18.525 * 0.6 * 0.8) = 6.95 \\ c &= 0.7143 * 32.267 = 23.049 \end{aligned}$$

Putting the values in the equation, we get
 $0.00384s^2 + 6.95s + 23.049 = 0$

Roots of the following Equation

$$\begin{aligned} S_1 &= 1806.57 \\ S_2 &= 3.322 \end{aligned}$$

Then the inverse roots will give T_1 and T_2

$$\begin{aligned} T_1 &= 0.0005775 \text{ sec} \\ T_2 &= 0.301 \text{ sec} \end{aligned}$$

The simplified transfer function for the current loop is expressed as:

$$\begin{aligned} G_{is}(s) &= \frac{K_i}{1 + sT_i} \\ T_i &= T_1 = 0.0005775 \text{ s} \\ K_i &= \frac{T_m K_r}{T_2 K_b} = 1.1443 \end{aligned}$$

Precise transfer function of the current loop:

$$G_i(s) = \frac{G_r(s).G_a(s)/\{1+G_a(s).G_b(s)\}}{1+H_c.G_a(s).G(s)/\{1+G_a(s).G_b(s)\}}$$

Speed controller:

$$\begin{aligned} K_g &= K_i K_m K_t \frac{H_\omega}{T_m} = 19.90 \\ T_{\omega i} &= T_\omega + T_i = 0.0025775 \text{ sec} \\ T_s &= 6T_{\omega i} = 0.0155 \text{ sec} \\ T_s &= \frac{4}{9K_g T_{\omega i}} = 8.6638 \end{aligned}$$

Simplified transfer function for the speed loop:

$$G_{ss}(s) \cong \frac{1}{H_\omega} \left\{ \frac{K_g \frac{K_s}{T_s} (1 + sT_s)}{s^3 T_{\omega i} + s^2 + K_g \frac{K_s}{T_s} (1 + sT_s)} \right\}$$

Exact speed-loop transfer function:

$$\begin{aligned} G_{se}(s) &= \frac{G_m(s).G_i(s).G_s(s)}{1 + G_\omega(s).G_m(s).G_i(s).G_s(s)} \\ \text{Where, } G_s(s) &= \frac{K_s}{T_s} \cdot \frac{(1+sT_s)}{s} = 560.2 \frac{1+0.0155s}{s} \\ G_\omega(s) &= \frac{H_\omega}{1 + sT_\omega} = \frac{0.05}{1 + 0.002s} \end{aligned}$$

The transfer functions that have been implemented in the PID controller have been designed to optimise the transient and steady-state behaviour of the BLDC motor, thus ensuring that it can be operated successfully under various load conditions.

MATLAB/Simulink Model Environment and Setup

The model of the proposed BLDC motor and controllers was developed and tested in MATLAB/Simulink. MATLAB R2024b, Simulink toolbox, and Simscape toolbox have been used. To focus on the high-frequency switching effects, namely, the parameters of the BLDC motor, stator resistance and inductances, flux linkage, and mechanical time constant, the simulation was set up with a fixed-step solver with a step size of 1/105 -s to provide numerical stability. An inverter stage was driven by a constant DC-link voltage, and modelled with ideal MOSFET switches and anti-parallel diodes. PWM was implemented. The transient response was assessed by load torque as a step input under the various operating conditions of 1000 rpm, 1500 rpm and 1650 rpm. The controllers (I, PI, PID) were set based on the obtained transfer functions, and the gains were set into Simulink control blocks. The scope blocks were used to measure motor speed, torque, and stator current to be analysed. The simulation model developed in this paper provides a repeatable platform for performance evaluation of different controller configurations.

Representation of Closed Loop System

BLDC motors have closed-loop systems that cannot be compromised in the quest to provide accuracy, efficiency and stability in various applications such as automotive, HVAC, and industrial systems. The BLDC motors have greater reliability and durability by replacing the traditional mechanical commutator with an electronic management system. The paper will look at the constituent components and working principles of the closed-loop system, which include Hall-effect

sensors, pulse-width modulation (PWM) generation, inverter setups, and speed control systems.

Overview of the Closed-Loop System

The closed-loop system uses the feedback based on the rotation and current of the motor to control the input of the stator so that the required speed and torque can be maintained. The schematic block diagram of Figure 2 in the closed-loop system of the BLDC motor is shown in the figure below (Figure 2), in which the Hall-effect sensors are placed in the stator, which identifies the position of the rotor. The rotor magnetic poles move past these sensors to provide high or low signals to allow the commutation and energisation of stator windings. The feedback signals are processed by the electronic controller, which combines them with reference signals and then gives out the outputs that stabilise the performance of the motor. The feedback loop constantly regulates current and voltage in the motor in real time to maintain the speed with changing loads and conditions. The inverter is a significant element of the system, and it is utilised as a conduction mode to alternate the stator phases one after another. Every inverter switch provides a certain period of time during which the commutation cycle can be accomplished: 120 or 180.

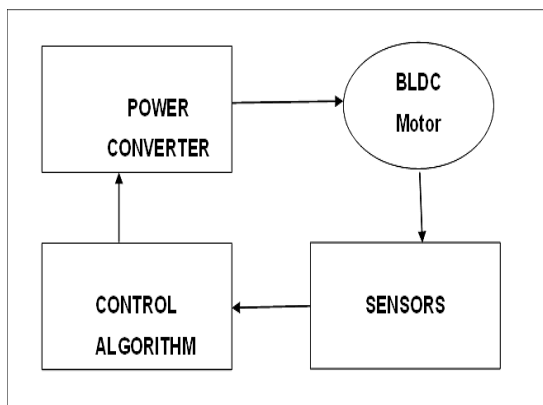


Figure 2. Closed-loop BLDC motor system with feedback-based control

Hall-Effect Sensors in Closed-Loop Operation

Hall-effect sensors are very important in the process of determining rotor position. These sensors follow the Hall-effect principle, whereby the current-carrying conductor charge carriers are caused to undergo a Lorentz force under the influence of a magnetic field, and as a result of this, a voltage is induced across the sides of the conductor. In the case of BLDC motors, a strategic position of the Hall-effect sensors is provided in the

stator to detect the rotor positioning through magnetic poles. The magnetic poles on the rotor generate a low or high signal when they come close to the sensors, thus signalling the existence of a North(N) pole or a South (S) pole. This data determines which winding of a stator is going to receive the power at a particular moment. To produce the necessary commutation sequence required, most BLDC motors use three Hall sensors positioned at angular offsets (60 or 120 degrees) to create the necessary commutation, and consequently enable precise control of the motor operation and efficient and stable operation in the dynamic conditions.

Pulse-Width Modulation (PWM) Generation

Pulse-width modulation (PWM) is an important method that is used in the controller block of a closed-loop system to control the amount of power to BLDC motors. It produces pulses of different widths in sequence, which regulate the average power supplied to the windings of the motor as shown in Figure 3. The circuit produces these pulses by varying the duty cycle to ensure that the voltage transitions are smooth enough to propel the motor.

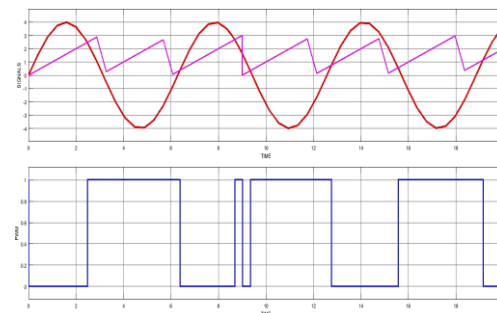


Figure 3. PWM output ensuring precise speed and torque control

The PWM output waveform shown in dark blue provides a high level of voltage and current fine-tuning control, which can be used to accurately control the speed and torque in different load scenarios. PWM also improves the motor energy efficiency by minimising the motor's unnecessary power losses.

Inverter Configurations in Closed-Loop Systems

Inverters are required to change a DC input to the AC output needed to power the BLDC motor. Different inverter configurations, including half-bridge, full-bridge, and three-phase inverters, are used in closed-loop systems. In the proposed work, a half-bridge inverter topology has been modelled as depicted in Figure 4. Figure 5 shows the effectual

output generated by the half-wave inverter, where the pink-coloured waveform represents the inverted voltage output. In contrast, the dark red line shows the current inverted production.

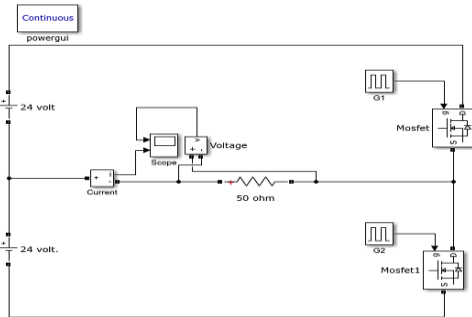


Figure 4. Half-bridge inverter circuit for DC to AC conversion in BLDC motors

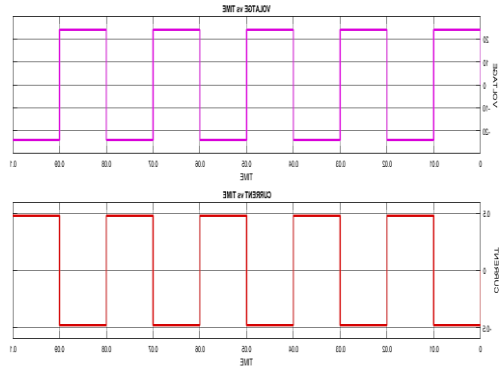


Figure 5. Half-bridge inverter output for stable voltage and current control

Figure 6 depicts a full-bridge inverter, consisting of two switches that alternately conduct to produce an AC output, and is suitable for low-power applications due to its simplicity and cost-effectiveness. A similar and more accurate full inverted waveform has been generated, which is applicable for both voltage and current.

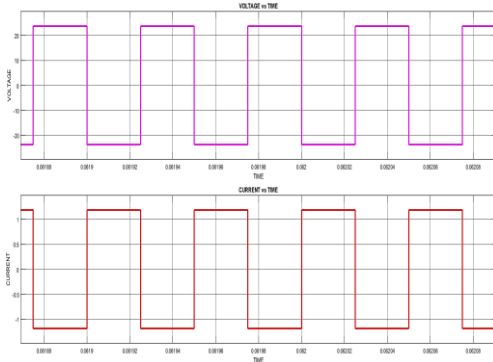


Figure 6. Half-bridge inverter output for stable voltage and current control

A Simulated model of a full-bridge inverter includes four switches arranged to deliver higher output voltage and power, making it ideal for medium- to high-power motor drives. A proposed model is illustrated in Figure 7, using MATLAB.

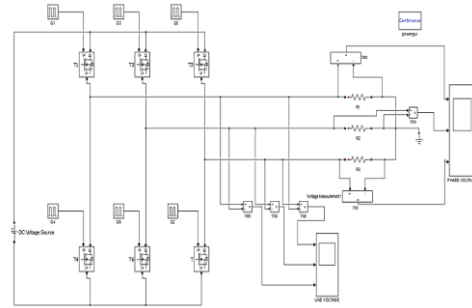


Figure 7. Three-phase inverter circuit for balanced power distribution

Figures 8 to 11 give different configurations of a three-phase inverter circuit that will offer stable voltage and current regulation to give efficient power regulation. The three-phase inverter shown in Figure 8 is connected to a resistive (R) load to ensure that dynamic operation remains constant. Figures 8 and 9 show the 180-degree phase and line voltage outputs, which are necessary to deliver power across all phases and achieve the best performance. On the same note, Figures 10 and 11 show the output of the 120-degree phase and line voltage of the inverter, which shows that the three phases are balanced and operating efficiently, therefore giving the inverter the ability to manage power efficiently within all the phases. The THI is essential to BLDC motors, which involves energisation of windings in a motor sequence to provide a rotating field of magnets since the proposed model will work in two configurations, the 180 mode, where all three switches conduct at once to increase torque and the 120 mode, where two switches conduct at once to maximise efficiency, such inverter designs will be critical to have an accurate and efficient control of the motor.

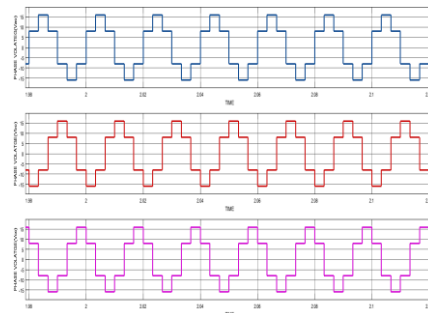


Figure 8. 180° phase voltage output of a three-phase inverter

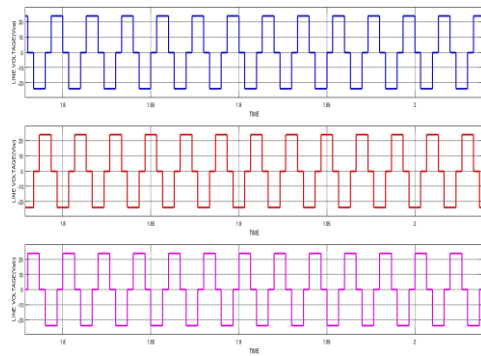


Figure 9. 180° line voltage output ensuring balanced three-phase operation

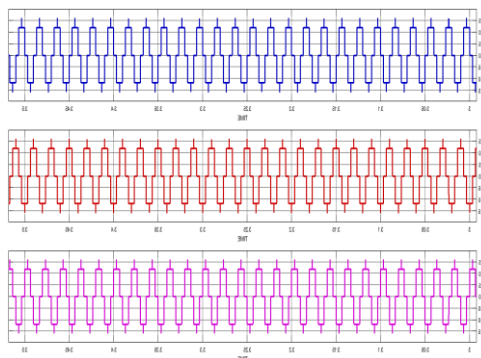


Figure 10. 120° phase voltage output for three-phase inverter performance

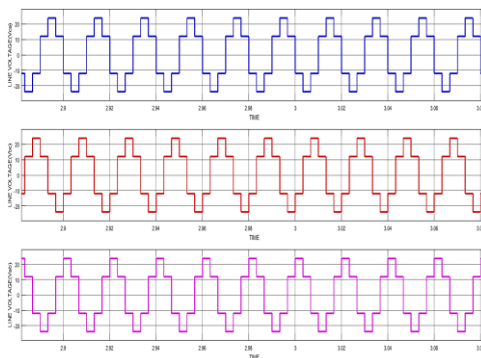


Figure 11. 120° line voltage output for efficient three-phase operation

Sine Wave Pulse-Width Modulation (SPWM)

Figure 12 explains the circuit of the SPWM, which is aimed at allowing the control of the voltage precisely and minimising harmonics with the purpose of providing power regulation. A more modern variant of PWM is sine-wave pulse-width modulation (SPWM) that produces smoother voltage signals in closed-loop systems by varying the pulses in synchronisation with a sinusoidal reference signal. The modulation process significantly reduces the harmonic distortion in the output, which improves the quality of power and

efficiency of the system. The SPWM method finds extensive use in both inverter and motor drive applications, where it has a better fidelity to a waveform than standard PWM. Its ability to attain proper voltage control makes it suitable for modern power electronics systems.

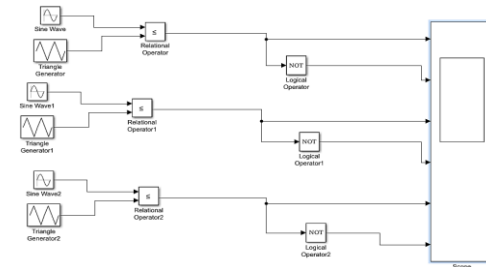


Figure 12. SPWM circuit for voltage control and harmonic minimisation

Figure 13 shows the output signal of a sine-wave pulse-width modulation (SPWM) circuit. The waveform represents smooth sinuoidal voltage and current waveforms through modulating pulse widths at a sinuoidal reference signal. This method greatly minimises the harmonic distortion, improves the quality of power and efficient use of energy, which is particularly applicable in high-accuracy and stable motor operation, power control and low electrical noise systems.

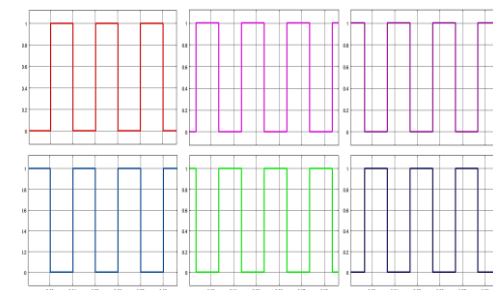


Figure 13. SPWM output for precise voltage and current regulation

Speed Control in Closed-Loop Systems

A brushless DC (BLDC) motor is closed-loop controlled as shown in Figure 14, demonstrating how the precision of the speed and position feedback is obtained. The coordination of the motors is done by the use of a system that combines the Hall-effect sensors and a feedback loop to monitor the rotor position and provide the motor with variable inputs in real time. This is a fine-tuning control mechanism that will guarantee the motor will work at the desired speed and torque at different load conditions. The closed-loop circuit ensures the efficiency and reliability of the BLDC motor are maximised, and it is therefore most

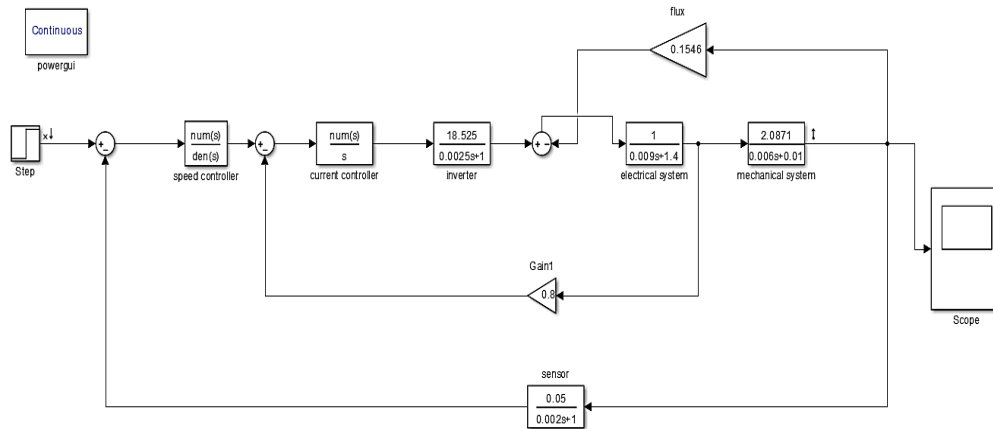


Figure 14. Closed-loop BLDC motor system for speed and position control

suitable in dynamic and various other applications that require high precision, hence its usefulness in these applications.

Figure 15 shows the closed-loop control structure of a brushless DC (BLDC) motor with a focus on the ability to precisely control both velocity and position variables. The structure incorporates sensor feedback, such as rotor position sensors and controllers, to dynamically adjust motor excitation to maintain desired performance measures. This is an error correcting approach that ensures that the system is free of instability, the overshoot is reduced, and that the system will settle quickly despite changing loads and operating perturbations. Therefore, performance optimisation and precision improvement make the closed-loop configuration an indispensable one when it comes to applications that require stable and reliable performance of the motors.

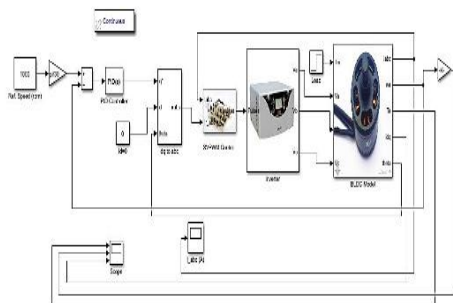


Figure 15. Closed-loop BLDC motor control ensuring performance stability

Figure 16 displays the step-response properties of a BLDC motor forced by a proportional-integral-derivative (PID) controller. The presented curve indicates the ability of the controller to produce smooth, unsteady output with the nearest negligible overshoot and accelerated settling after sudden changes in input. The PID scheme has the benefit of enabling a close control of the speed as well as the torque in a synergistic manner by incorporating proportional, integral and derivative actions and still maintaining system stability. These characteristics demonstrate the stability of the PID controller in a dynamic and changing working regime, which makes it a good choice in high-precision, highly efficient uses.

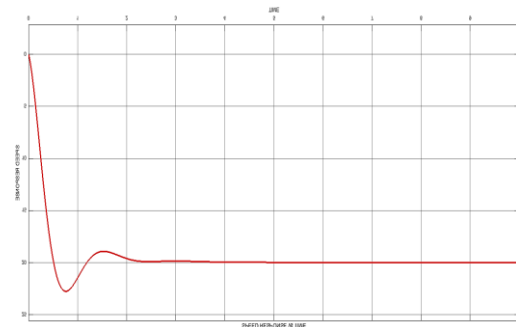
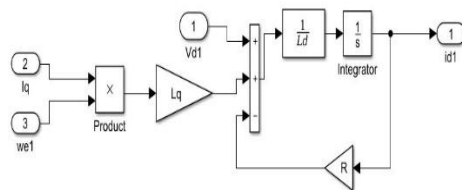


Figure 16. Step response of BLDC motor with PID controller

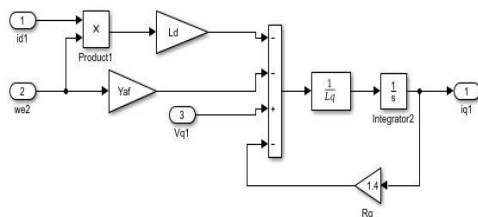
dq-Transformation in BLDC Motors

To simplify the analysis and control of BLDC motors, the closed-loop system employs the dq-transformation.

Figure 17 presents a closed-loop control system of a BLDC motor with a clear focus on the D-axis and Q-axis systems. The D axis controller (Figure 17 i) arbitrarily controls the current to the flux, and the Q axis controller (Figure 17 ii) arbitrarily controls the current to the torque. This two-axis design is based on dq-transformation, and therefore separates the dynamics of flux and torque so that the torque and position variables can be tuned independently and accurately. The closed-loop feedback ensures efficient performance and high accuracy, which makes the configuration suitable in the case of applications that require excellent dynamic performance and strong stability.



(i): Closed-loop control of BLDC motor D-axis for accurate torque and position tracking



(ii): Closed-loop control for the Q-axis of the BLDC motor ensures optimal performance and precise regulation of torque

Figure 17. (i) D-axis, (ii) Q-axis, dq-axis closed-loop control for BLDC motor torque tracking

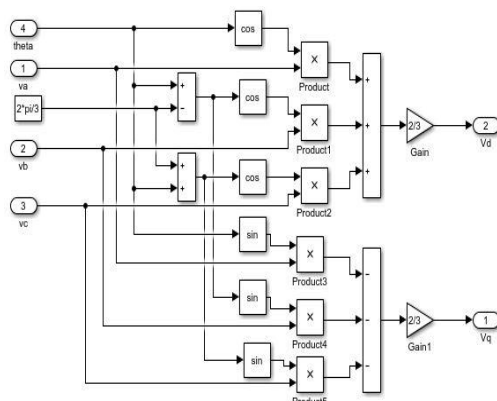


Figure 18. abc-to-dq transformation for simplified BLDC motor control

Figure 18 shows how three-phase currents and voltages, in an abc coordinate system, can be converted to two orthogonal components (the D-axis and Q-axis) in a dq coordinate system. This mathematical reformulation simplifies the complexity of the time-varying three-phase formulation by reworking the system to a two-axis (stationary) representation. As a result, dq - transformation simplifies the process of analysis and control design, allowing computation of the torque and flux parameters of the BLDC motor to be much more economically. It is a necessary strategy to achieve high performance by carefully optimising the process of torque and flux control.

Figure 19 represents the inverse transformation of dq coordinates to the abc coordinates, and thus, transforms the simplified two-axis control variables back into usable three-phase signals that can be used in practice. This inversion enables the BLDC motor to run freely since there is a correspondence between the controller outputs and the real three-phase windings of the motor. The dq-to-abc transformation ensures a seamless torque generation, energy saving, and critical contribution in maintaining stability and optimum operation in dynamic operating cycles.

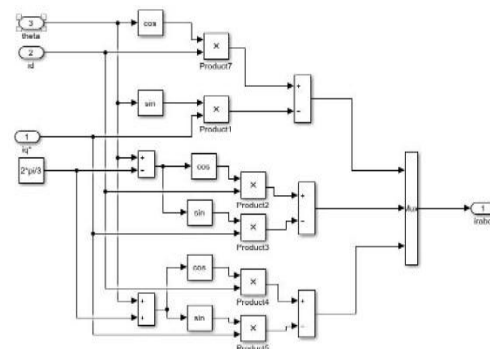


Figure 19. dq-to-abc transformation for seamless BLDC motor operation

Performance Metrics

Figure 20 illustrates the optimal torque and speed characteristics of the BLDC motor, which highlights that it is able to maintain an effective working operation under different load conditions. The speed profile plotted shows a very regulated curve with little deviations, which demonstrates the effectiveness of the control measures put in place in creating a balance. The torque curve demonstrates the capability of the motor to provide steady power output and simultaneously react to the changes in dynamic loads. The results support the fact that the BLDC motor is highly efficient and can be used in

applications that require fine control and energy efficiency.

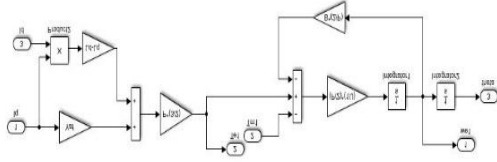


Figure 20. Optimised torque-speed characteristics of BLDC motor

The nature of the closed-loop architecture of the BLDC motors is that the advanced control modalities and dedicated hardware, including Hall-effect sensors, pulse-width-modulation (PWM) circuits, and inverter subsystems, are integrated to provide the high-performance operation of the motors. Figure 21 is an integrative view of optimised sub-systems that boost the performance of BLDC motors. It previews the integrative action of the main elements, controller, inverter, and feedback loops, which are synergistically working towards giving the perfect speed and torque regulation, as already mentioned. The figure also details the careful fine-tuning of every subsystem to reduce energy losses and increase system stability in changing conditions. Such a comprehensive approach guarantees dependable performance, making the BLDC motor a perfect choice in those cases when the need is to have high efficiency and adaptability in its dynamics.

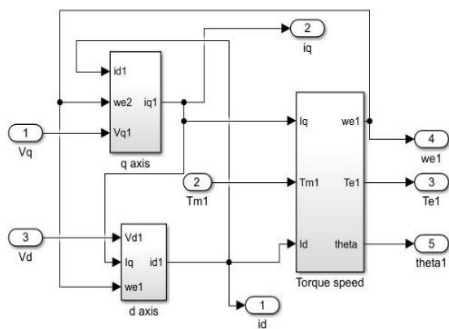


Figure 21. Sub-system optimisation for efficient BLDC motor operation

Results and Discussion

Result Analysis

The motor performance of the BLDC was studied using various controller settings, viz. Integral (I), Proportional-Integral (PI), and

Proportional-Integral-Derivative (PID) at varying reference speed settings. This part is an evaluation of the resulting motor behaviour based on simulation results, as shown in Figures 22-26. The comparative evaluation indicates the relative merits as well as the drawbacks of all controller architectures in maintaining the desired motor behaviour.

Figure 22 also shows the speed response of the BLDC motor when a reference speed of 1000 RPM was applied using a proportional (P) controller. The red curve, which is the desired operating point, is the reference speed and is fixed at 1000 RPM. The blue curve, or actual motor speed, quickly approaches the reference, but does not hit it exactly, a sign of a steady-state error. This continuous difference between the blue and the red curves underscores the failure of the P controller to remove the steady-state error. The green curve, which represents the signal error, indicates a downward trend with time, but never attains a value of zero again, bringing out the steady-state offset. Green curve oscillations are minor, implying that the damping ability of the system is limited. In general, the figure shows that the I controller is strong in terms of quick reaction, yet reveals that it is not as precise and stable as it should be.

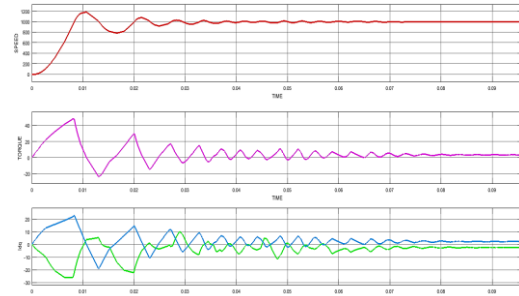


Figure 22. BLDC motor speed response with P controller at 1000 RPM

Figure 23 shows the output of the BLDC motor under control using a proportional -integral -derivative (PID) controller at 1000 RPM. The red curve, which is the reference speed, is constant at 1000 RPM, and this is the value of the motor target. The blue curve, indicating the actual motor speed, will first have a smooth increase and will follow the reference speed with little steady-state error, and that illustrates how the integral action is effective in eliminating the offset. The blue curve also approaches the reference value more closely with fewer oscillations as compared to the I controller. The green curve, which is the signal of error, is quickly decreasing to zero, which proves the increased precision and stability offered by the PI

controller. The green curve has only a few changes in comparison with the I controller, meaning that its damping is more effective and it adapts to changes in the load better. In general, the figure demonstrates that the PI controller is able to establish a trade-off between speed response and steady-state performance, which means that it can be used in the field of applications that demand high accuracy in speed control.

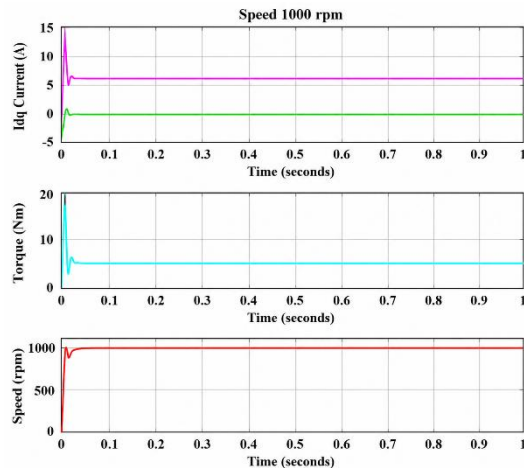


Figure 23. BLDC motor speed response with PID controller at 1000 RPM

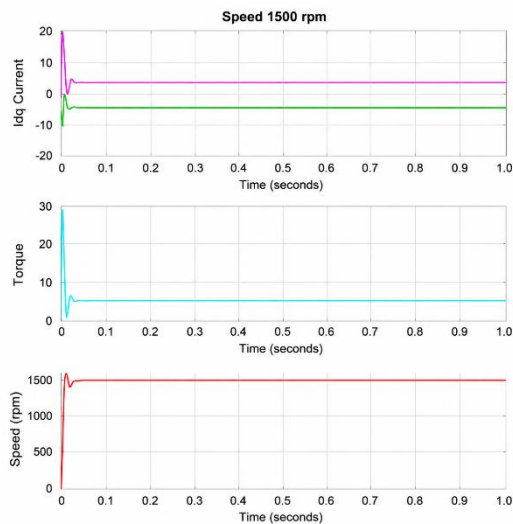


Figure 24. Performance of BLDC motor with PID controller at a 1500 rpm reference

The response of the BLDC motor, when driven by a proportional-integral-derivative (PID) controller, is shown in Figure 24 above at a reference speed of 1000 RPM. The red curve is the reference speed, which will be maintained at 1000 RPM as the desired target. The blue curve that displays the actual motor speed shows a high and

smooth increase, followed by attaining the reference speed with a high degree of accuracy and low overshoot. This shows that the PID controller is efficient in the regulation of accurate speed. The green curve, which is the signal of the error, rapidly drops to zero and is maintained in that position, which also shows the excellent performance of the controller in removing steady-state error and enhancing transient response. The PID controller gives the system superior damping and stability in comparison to the P and PI controllers, having no major oscillations in the green curve. This number demonstrates the capability of the PID controller to attain fast convergence, low overshoot, and strong operation, which is why it is the best option in cases when precision and dynamic adjustability are needed.

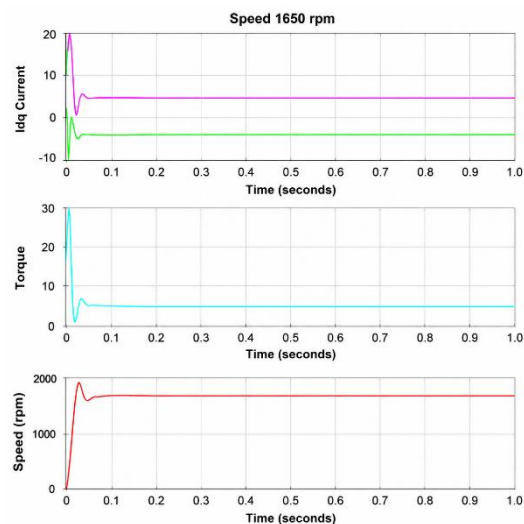


Figure 25. BLDC motor response with PID controller at 1650 rpm reference

As indicated in Figure 25 above, the performance of the BLDC motor using a proportional-integral-derivative (PID) controller (at a higher reference speed of 1500 RPM) is demonstrated above. The red curve, which is the speed at the reference point, is maintained at 1500 RPM, which is the point of operation desired. The blue curve is the actual motor speed, and it has a fast increase and is more accurate to the reference speed with a small overshoot and stable operation. This shows how well the PID controller can be used to stay accurate even when operating at slower reference speeds. The green curve, which is the error signal, will quickly reduce to a zero value, and this indicates that the controller can reduce steady-state error in an efficient manner. The green curve is smooth and stable, which means that the damping is excellent, the correction of errors is quick, and the

system is stable under dynamic conditions. The result compared with the previous ones provides affirmation that the PID controller is robust to different speeds, thus making it very effective to be used in harsh environments that need not only responsiveness but also precision.

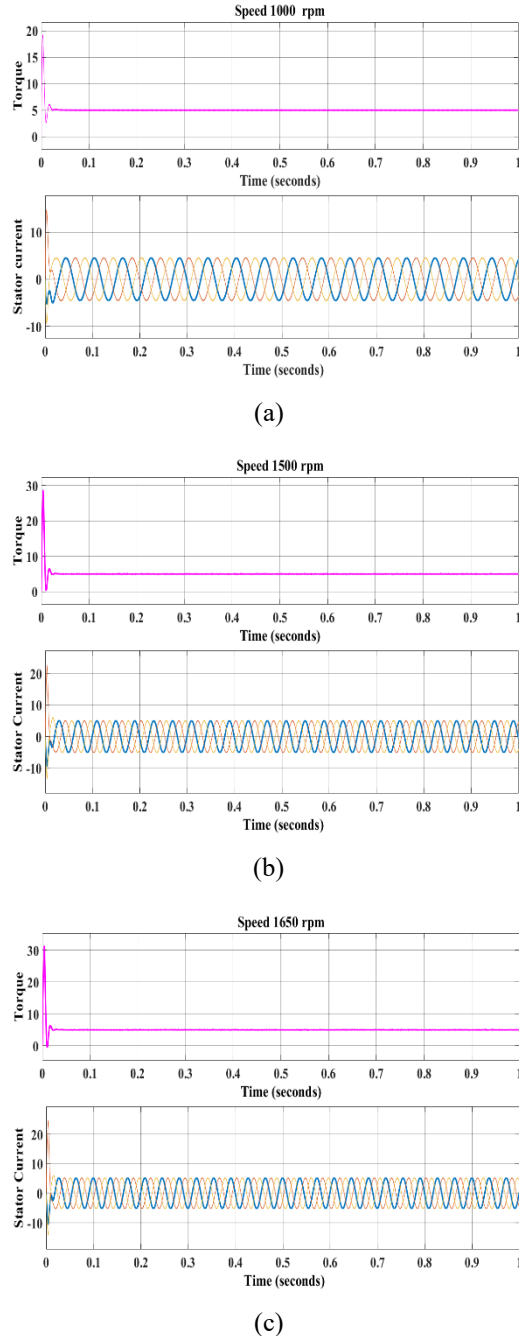


Figure 26. Stator current waveform for efficient torque delivery (a) 1000 rpm, (b) 1500 rpm, (c) 1650 rpm

The response of the stator current and the torque ripple condition of three cases, i.e., under-rated condition, rated condition and over-rated condition of the BLDC motor under closed loop control are demonstrated in Figure 26 (a), (b) and (c) as follows: As can be seen, the success of the implemented control strategy is that it guarantees the flow of torque and effective power transfer. The curves are the stator current waveform, whose pattern is more of a smooth sinusoid pattern, signifying a balanced and stable current waveform through the motor windings. Conversely, a torque linear waveform guarantees soft behaviour of the motor. The fact that there are no serious fluctuations or spikes in the curve indicates that there is not much electrical noise inside the system, and the control system is well-tuned. This profile of current assists in minimising torque ripple so that a constant mechanical output is obtained and the motor is more efficient. The figure shows that the closed-loop system is effective in the regulation of current to ensure that torque is kept constant; hence, this motor is ideal in applications that need accurate speed and load control.

The outcomes of the simulation identify the unique nature of various controllers:

- I Controllers: Rapid response, have steady-state error, and poor damping.
- PI Controller: Removes steady-state error and offers greater stability at the trade-off of slower rise time.
- PID Controller: This type of controller is a combination of P and PI controllers, with the advantage of rapid response, great stability, and zero steady-state error.

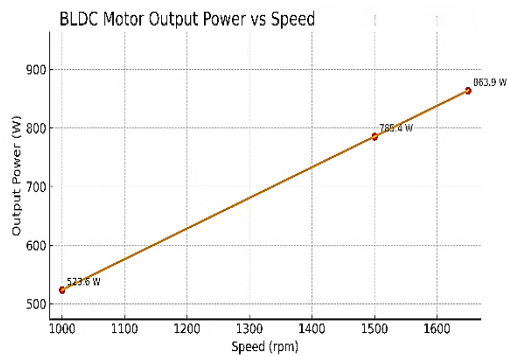
The PID controller proved to be more effective at different speeds, which qualifies it to be the most appropriate in controlling the BLDC motor in a situation where precision and dynamic adjustability are needed. The stator current analysis also supports the efficiency of the closed-loop system in ensuring efficient and stable operation of the motor.

Efficiency Comparison

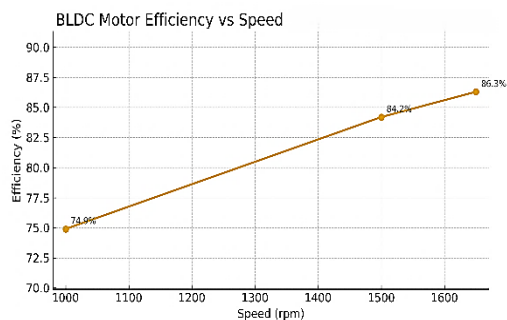
Figure 27 (a) demonstrates the BLDC Motor, Output Power Vs Speed. It shows the correlation between the speed of the motor and the output power. The motor draws 523.6 W at 1000 rpm, and it rises gradually after that, to 785.4 W at 1500 rpm, to a maximum of 863.9 W at 1650 rpm. The trend is almost linear, which means that the power of the output is proportionate to the speed in the conditions being tested. The ability of the motor to provide greater power at higher operating speeds, with the

linear characteristics being preserved even at over-rated operating conditions, is important in the dynamic operations of electric vehicles that demand flexibility in both torque and power demand.

Figure 27 (b) demonstrates the BLDC Motor, Output Power Vs Speed. It shows the correlation between the speed of the motor and the output power. The motor draws 523.6 W at 1000 rpm, and it rises gradually after that, to 785.4 W at 1500 rpm, to a maximum of 863.9 W at 1650 rpm. The trend is almost linear, which means that the power of the output is proportionate to the speed in the conditions being tested. The ability of the motor to provide greater power at higher operating speeds, with the linear characteristics being preserved even at over-rated operating conditions, is important in the dynamic operations of electric vehicles that demand flexibility in both torque and power demand.



(a)



(b)

Figure 27. BLDC motor efficiency comparison
(a) Output Power vs Speed and
(b) Efficiency vs Speed

Comparative Analysis

Table 2 shows the comparative analysis of the results of the simulation at various reference speeds. The system exhibits a small amount of overshoot (1.53%), moderate rise time of 4.13 ms, and settles in 25.77 ms with zero steady-state error at 1000 rpm, meaning its operation is smooth and stable. At a

higher reference speed of 1500 rpm, the overshoot is even higher (10.55 per cent), but the system is quicker, with a smaller settling time of 15.56 ms and smaller steady-state error (0.01 per cent). Overshoot becomes even higher at 1650 rpm to 13.06% and rise and settling times are also similar (3.73 ms and 14.64 ms, respectively) with a slight increment in the steady-state error (0.03%). These findings validate that a more dynamic response is achieved with higher speeds but with increased overshoot, which points out the trade-off between speed and stability in the BLDC motor control.

Table 2. BLDC speed comparison (1000, 1500, 1650 rpm)

Speed (rpm)	Overshoot (%)	Rise Time (ms)	Settling Time (ms)	Steady-State Error (%)
1000	1.531	4.136	25.771	0
1500	10.556	3.710	15.565	0.01
1650	13.068	3.737	14.645	0.03

Even though the current controllers like adaptive, fuzzy logic, sliding mode and model predictive control have advanced capabilities, they also add complexity, computational load and cost to the system, which is not always viable in real-time electric vehicle applications. Conversely, this paper shows, by a single MATLAB/Simulink model, that generalized classical controllers like I, PI and PID can provide high quality performance, with a steady state error that is negligible, rise time is fast and the torque ripple is controlled in under-rate (1000 rpm), rate (1500 rpm) and over-rate (1650 rpm) operating environments. Reproducibility and clarity are guaranteed by the integration of consolidated motor parameters, a well-defined simulation environment, and a tabular comparison of performance. Such simplicity and efficiency underscore the strength and usability of PID controllers for the control of BLDC motors, thus making the study a tutorial resource and an original contribution with simulation-based information to support the next-generation EV systems.

Future Scope

The proposed motor model and controller strategies of the BLDC motor will be applied to the hardware prototyping with the lab-scale in the future. The practical aspect will incorporate the real-time control using a DSP/FPGA platform, inverter hardware, and sensor integration as a way of confirming the simulation output. An analysis of torque ripple, efficiency, and dynamic performance will be given under real-world conditions. This proposed experimental validation shall not only prove the accuracy of the developed model but will

also reveal that the developed model can be applied in the real world in regard to electric vehicles.

Conclusion

The paper involved an elaborate research on the closed-loop control of the BLDC motors, design, and the analysis of different controllers, such as P, PI, and PID controllers. This was confirmed by the findings that the closed-loop system is able to improve the efficiency of the motor by keeping the desired speed, torque, and stability of the motor when operated under the conditions of different loads. Hall effectors, pulse-width modulation (PWM), and inverters are some of the core elements that were pointed out as important to attain efficient and accurate control. The comparative analysis showed that although the P controller gives a quick response, it has a tendency to exhibit steady-state errors. The PI controller removes these errors and enhances stability, but at a lower rise time. The PID controller was found to be the most robust configuration with a combination of low response time, good damping, and zero steady-state error, which was suitable for high-precision applications. Moreover, stator current profile analysis proved that the system will be able to reduce energy losses and provide smooth operation of the motor. The combination of sophisticated control algorithms and hardware devices highlighted by the closed-loop system is important in the contemporary use of the closed-loop system in electric cars, HVAC systems, industrial automation, etc. The future of controlling can be further enhanced by optimisation, and futuristic research can be aimed at enhancing the control strategies by employing adaptive or machine-learning-based approaches to achieve high levels of efficiency and scalability.

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