International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

Check for updates

Direct torque control of three-phase brushless DC motor using PI controller

Hayder Yousif Abed *

Department of Electrical Engineering, College of Electrical Engineering, University of Technology, Iraq.

International Journal of Science and Research Archive, 2026, 20(01), 908–915

Publication history: Received on 13 June 2026; revised on 25 July 2026; accepted on 27 July 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.20.1.1507

Abstract

In this paper, in order to improve system performance, this study provides a thorough analysis of a three-phase brushless DC motor (BLDCM) and the use of Direct Torque Control (DTC) enhanced with a PI controller. An examination of the many kinds of electric motors and their history is the first step in the job. After that, it goes into detail regarding three-phase brushless DC motor, which are frequently utilized in industry due to their durability, effectiveness, and ease of maintenance. A thorough mathematical model of the three-phase brushless DC motor is provided, including key variables like torque, synchronous speed, and equivalent circuit representation. In order to understand the motor's dynamic behavior, the study also examines its properties, particularly the torque-speed relationships. The main focus of this research is DTC, a high-performance control strategy that directly controls stator flux and electromagnetic torque without needing complicated transformations. Different DTC methods are talked about, with their pros and cons. A Proportional-Integral PI controller is added to the DTC scheme to fix problems like torque ripple and make control more accurate. Using MATLAB/Simulink, we can simulate the proposed DTC-PI system. The results show that speed tracking has gotten better, dynamic response has gotten better, oscillations have gotten smaller, and stability has gotten better when the load changes. The study finds that using DTC with PI control makes induction motor drives work much better than using traditional methods.

Keywords: Three-Phase Brushless DC Motor; Direct Torque Control; Proportional-Integral; Active and reactive power; Direct and quadrature voltages.

1. Introduction

Brushless DC (BLDC) motors are extensively employed across various sectors, including industrial automation, electric vehicles, aerospace, and computing. These motors offer several distinct advantages over traditional brushed DC motors. Specifically, they require less maintenance due to the elimination of the commutator and exhibit a longer operational life by reducing friction and electrical losses. Their high-power density makes them ideal for applications necessitating a high electromagnetic torque-to-weight ratio [1]. Furthermore, compared to brushed DC motors and induction machines, BLDC motors possess lower inertia, which facilitates a faster dynamic response to reference commands. They also achieve higher efficiency through the use of permanent magnets, which result in virtually zero rotor losses [1]. Control science is vital for optimizing electric motor performance, efficiency, and stability. In BLDC motors, advanced control strategies manage electronic commutation and nonlinear dynamics to minimize disturbances, enhance speed tracking, and address challenges like torque ripple.

2. Importance of control in electric motors

Control science is fundamental to the operation of modern electric motors, as it enables the transformation of electrical energy into precise mechanical output [1]. By utilizing advanced circuitry and algorithms, control systems allow designers to manage the dynamic characteristics of motors, which is essential for creating successful, efficient, and

* Corresponding author: Hayder Yousif Abed

reliable industrial systems [2,3]. Effective control is particularly critical for motors that must operate across wide speed ranges or within sensitive applications where parameter variations and external disturbances can degrade performance [4].

3. Control science in BLDC motor operation

Brushless DC (BLDC) motors represent a significant evolution in drive technology, offering high efficiency, reliability, and superior torque-to-weight ratios [1,4]. Because they replace mechanical commutators with electronic commutation systems, their operation is fundamentally dependent on control science to dictate rotor position and current timing [5,6].

4. Performance and efficiency

Control algorithms are essential for maintaining the high-efficiency potential of BLDC motors across diverse operating conditions [6,7]. By employing techniques such as Field-Oriented Control (FOC) or Pulse Width Modulation (PWM), designers can optimize energy usage and ensure consistent speed regulation [6,8]. Advanced control methods, such as Fuzzy Sliding Mode Controllers (FSMC) or robust adaptive control, allow these motors to handle nonlinearities and load disturbances more effectively than traditional fixed-gain controllers [3,4,7].

5. Stability and tracking

Achieving precise speed tracking is a primary objective of BLDC control science, often verified through stability analysis methods like the Lyapunov direct approach [9]. Controllers such as the Higher-Order Sliding Mode Controller (HOSMC) are designed to provide:

- **Enhanced tracking:** Providing precise speed control with minimal or no overshoot [9,10].
- **Improved dynamics:** Offering quick rise and settlement times during transient phases [9,4].
- **System stability:** Maintaining consistent performance despite internal uncertainties or parameter variations [3,7].

6. Direct Torque Control

The DTC is a high-performance control technique for IM drives that directly regulates electromagnetic torque and stator flux. DTC does not require complicated coordinate transformations or current regulators, in contrast to vector control techniques. Rather, it uses instantaneous torque and flux errors to choose suitable voltage vectors. In this chapter study the DTC, its equations, its types, and how it controls on motor.

7. BLDC Motor Controllers

For effective and secure operation, induction motor controllers are utilized to control speed, torque, and current. where an BLDC motor can be driven in a variety of ways. The performance of the motor and the practicality and expense of its actual implementation are the primary distinctions between them.

7.1. Voltage/Frequency (V/F)

Despite being the most straightforward controller, (V/F) is the most widely used, appearing in most industrial applications. It imposes a consistent relationship between voltage and frequency and is referred to as a scalar control. It is typically used without speed feedback and has a fairly straightforward construction. Nevertheless, this controller is not very accurate in terms of speed and torque. responses mainly due to the fact that the stator flux and the torque are not directly controlled.

7.2. Soft Starter (Starting Controller)

Enables a smooth start for an electric motor. It will gradually raise the voltage rather than delivering the full voltage at away. Inrush currents are lessened by this regulated rise in supply voltage. It also lowers mechanical strain on the motor and linked equipment. Soft starters are frequently used in industrial environments where important processes are powered by motors. They assist extend equipment life, decrease downtime, and increase reliability. They are frequently found in compressors, mills, crushers, fans, pumps, and conveyors. They are particularly helpful when low power surges and seamless beginnings are crucial.

8. Principle of DTC

It enables electrical machines to have a precise and quick electromagnetic torque response by establishing a decoupled control of the stator flux and the electromagnetic torque in the stationary frame (α, β). It chooses a suitable voltage vector using a switching table. Changes in the torque and stator flux of the machine immediately affect the choice of switching states. The flux and torque magnitudes are limited to two hysteresis bands in order to make the decision. These controllers guarantee that these two quantities are independently regulated. The outputs of hysteresis controllers choose the proper voltage vector for each commutation period based on torque and flux errors as inputs. The main objective of DTC is to directly control the electromagnetic torque and stator flux linkage of the motor by selecting the optimum voltage vectors from a switching table, without the need for complex coordinate transformations (like in Field Oriented Control) or inner current control loops.

8.1. Main Components of the DTC-BLDC System

Here is how each block functions in the control loop:

- **3-Phase Permanent Magnet BLDC Motor**
- **Role:** The actuator/load of the system.
- **Characteristics:** Unlike induction motors, it uses permanent magnets (PM) on the rotor. It requires precise rotor position or flux information to switch the inverter phases properly.
- **3-Phase Voltage Source Inverter (VSI) & DC Link**
- **Role:** Converts the constant DC voltage (V_{dc}) into variable frequency and variable voltage AC power for the motor.
- **Operation:** It consists of 6 semiconductor switches (like IGBTs or MOSFETs). The switching signals (S_a, S_b, S_c) from the optimum vector selector dictate which switches open or close to feed the motor phases (U, V, W).
- **Clarke Transformation ($\boldsymbol{abc \to \alpha\beta}$)**
- **Role:** Simplifies the 3-phase currents (I_a, I_b, I_c) measured by the **Current Sensors (CS)**.
- **Operation:** It transforms the stationary 3-phase coordinates into a 2-phase stationary orthogonal coordinate system (α, β). This makes the calculation of flux and torque mathematically easier.
- **Stator Flux, Rotor Position, and Torque Estimator**
- **Role:** The "brain" of the feedback loop. Since we cannot easily place sensors inside the motor to measure torque and flux directly, this block mathematically estimates them in real-time.
- **Inputs:** Measured phase voltages (V_s) and transformed currents (I_α, I_β).
- **Outputs:** * Estimated Torque (T_e)
    - Estimated Stator Flux magnitude ($|\Psi_s|$)
    - The sector zone where the flux vector currently resides (k, typically divided into 6 sectors).
- **Hysteresis Comparators (Torque & Flux)**
- **Role:** They act as bang-bang controllers to keep the torque and flux within a narrow, acceptable error band.
- **Operation:** * The **Torque Hysteresis Comparator** compares the reference torque (T_e^*) with the estimated torque (T_e). It outputs a digital status (τ) indicating whether torque needs to be increased or decreased.
    - The **Flux Hysteresis Comparator** compares the reference flux ($|\Psi_s|^*$) with the estimated flux ($|\Psi_s|$). It outputs a digital status (ϕ) indicating whether the flux needs to be strengthened or weakened.
- **Optimum Switching Vector Selector (Look-up Table)**
- **Role:** Selects the best inverter switching state at any given microsecond.

8.2. Control of Stator Flux

Basing on the BLDC model in stationary frame, the stator flux can be expressed as equations (3-1) and (3-2). By integrating the stator voltage (VS) minus the voltage drop across the resistor ($Rsis$).

$\Psi\ S\alpha = \int (V_{S\alpha} - R_S i_{S\alpha})\ dt \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots\ (3-1)$

$\Psi\ S\beta = \int (V_{S\beta} - R_S i_{S\beta})\ dt \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots\ (3-2)$

The resulting flux is given by equation (3-3) and the flux angle by equation (3-4).

$\Psi s = \sqrt{\Psi^2{}_{s\alpha} - \Psi^2{}_{s\beta}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .\ (3-3)$

2.Electromagnetic Torque

$\Psi s = tan^{-1}\left(\frac{\Psi_{s\beta}}{\Psi_{s\alpha}}\right) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots\ (3-4)$

The general expression of electromagnetic torque is given by equation (3-5):

$T_e = \frac{3P}{2}\left(\Psi_{s\alpha} i_{s\beta} - \Psi_{s\beta} i_{s\alpha}\right) \dots \dots \dots \dots \dots \dots \dots \dots \dots\ (3-5)$

And
where:
p: is the number of poles pairs.
Ψ s, Ψ r: are stator and rotor flux vectors.
δ: angle between the stator and rotor flux vectors.
Controlling the Movement of Flux, the change in flux is directly proportional to the applied potential vector (Vs) and the sampling time period (At).

$\Delta\ \Psi\ S \approx VS.\Delta t \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots\ (3-6)$

This means that the end of the flux vector moves in the same direction as the applied voltage vector, allowing for instantaneous path control.

9. DTC Schematic

A potential design of DC is illustrated in figure 1, where the torque and stator flux magnitudes are represented by two distinct loops. The two-level and three-level hysteresis blocks receive the error values that come from comparing the reference values for the torque and flux stator modulus with the actual values. The position of the stator flux and the outputs of the torque error and stator flux error hysteresis blocks are utilized. Six distinct sectors make up the stator flux position; the torque errors and stator flux modulus are typically contained within their respective hysteresis bands.

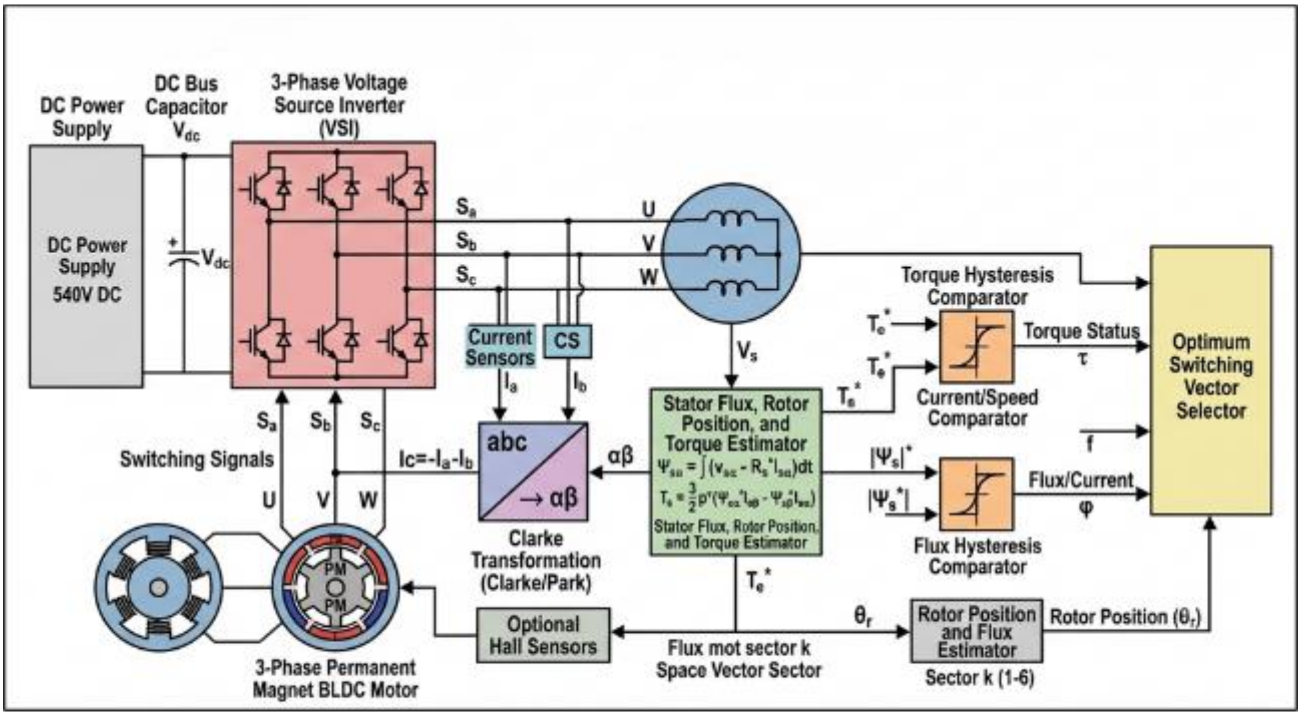

Figure 1 Direct torque control schematic

10. Simulation And Results

This section uses MATLAB/Simulink to provide the simulation model and evaluate the effectiveness of a DTC scheme used to a BLDC motor supplemented with a PI controller. demonstrated the outcomes of regulating the motor speed when the torque of the load is varied, where we used both less and more torque than the torque that was rated. add that displayed the current and voltage.

Based on the provided Simulink model in figure 2, this is a **Direct Torque Control (DTC)** and **Space Vector Pulse Width Modulation (SVPWM)** driven motor drive simulation, specifically configured for a **Brushless DC (BLDC) Motor** fed from a three-phase AC grid. Here is a comprehensive scientific breakdown of the system, divided into its core subsystems, the simulation begins on the far left with the electrical power source and initial conversion stage:

- **Grid Equivalent:** A 3-phase AC source (600 V, 60 Hz) models the main power grid.
- **Diode Rectifier:** An uncontrolled 3-phase diode bridge rectifier converts the incoming AC voltage into a rough DC voltage.
- **DC Link Cap & Braking Chopper:** * A parallel capacitor smooths out the DC voltage ripple, acting as an energy reservoir (V_{dc}).

A **Braking Chopper** (a resistor in series with a controlled switch) is included to dissipate excess regenerative energy when the motor decelerates, preventing destructive overvoltage on the DC link.

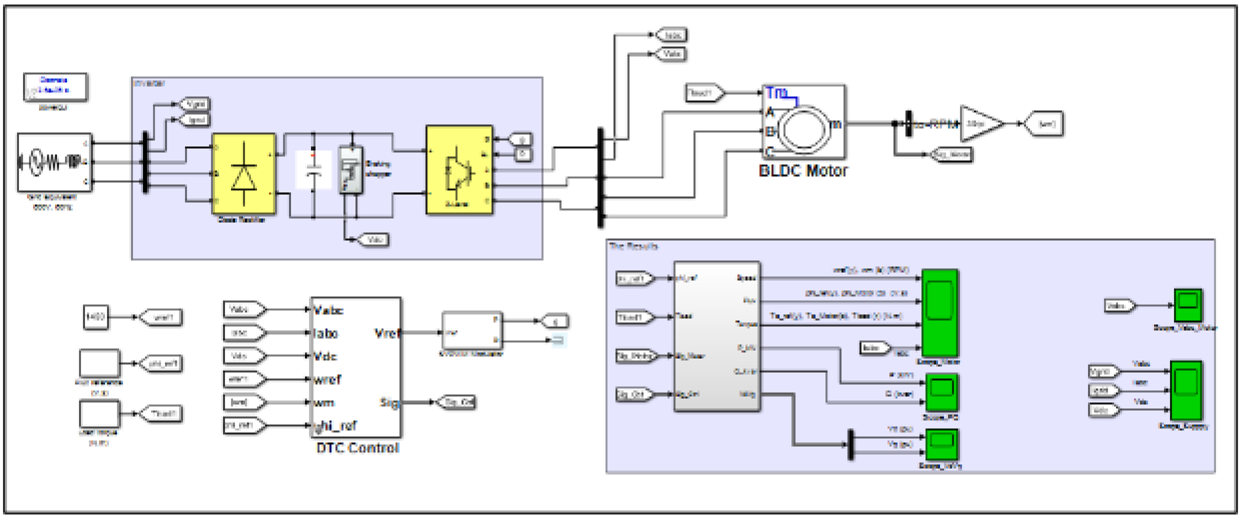

Figure 2 MATLAB/Simulink DTC system

10.1. Power Inversion Stage

- **Two-Level Converter:** This is a classic 3-phase Voltage Source Inverter (VSI) utilizing insulated-gate bipolar transistors (IGBTs) or MOSFETs. It takes the stable V_{dc} and converts it back into variable-frequency, variable-voltage AC power to drive the motor.
- **SVPWM Modulator:** The control pulses (g) driving this inverter are generated by a **Space Vector Pulse Width Modulation (SVPWM)** block. SVPWM treats the inverter's switching states as vectors in a complex plane. It optimizes the switching sequences to reduce total harmonic distortion (THD) and utilize the DC link voltage more efficiently than standard SPWM As shown in the figure 3.

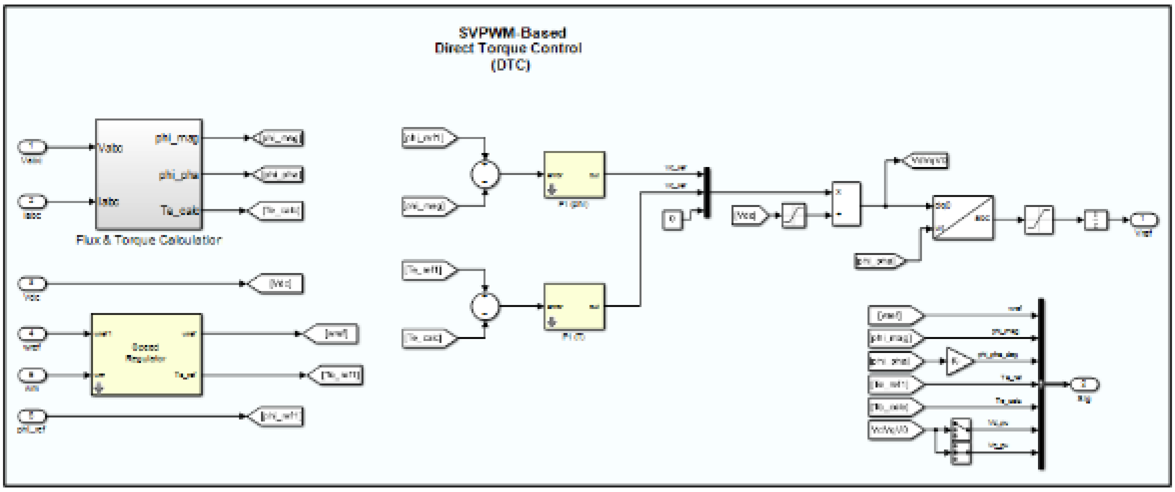

Figure 3 MATLAB/Simulink SVPWM Modulator system

10.2. The Control Core: Direct Torque Control (DTC)

At the bottom of the diagram, you can see two parallel control blocks labeled DTC Control and DTC Control1.

DTC is an advanced high-performance motor control strategy characterized by its rapid dynamic response. Instead of decoupling stator currents into field and torque components (like Field-Oriented Control), DTC directly regulates the motor's **stator flux linkage** and **electromagnetic torque**.

How the DTC Loop Functions:

1. **Feedback Inputs:** The block samples real-time system metrics: stator voltages (V_{abc}), stator currents (I_{abc}), DC link voltage (V_{dc}), and actual mechanical speed (ω_m).
2. **Reference Inputs:** It accepts a speed reference (w_{ref1} or ω_{ref}) and a flux reference (ϕ_{ref1}).
3. **Estimation:** Inside the block, mathematical models calculate the instantaneous stator flux magnitude (ϕ_s) and the electromagnetic torque (T_e) based on the measured currents and voltages.
4. **Hysteresis Comparators:** The estimated flux and torque are compared against their reference values using hysteresis controllers.
5. **Switching Table / Vector Selection:** Based on the errors and the current position of the stator flux vector in the space plane, the system determines the optimal voltage vector (V_{ref}) to feed into the SVPWM modulator to quickly eliminate the errors.

10.2.1. The Electromechanical System (The Load)

- **BLDC Motor:** The 3-phase power output from the inverter passes through a measurement block and drives a **Brushless DC Motor**. Despite its name, a BLDC motor behaves like a synchronous motor with permanent magnets on the rotor and trapezoidal (or sinusoidal) back-EMF waveforms.
- **Mechanical Dynamics:** The motor receives a dynamic load torque (T_{load1}) to simulate real-world physical resistance. The output shaft speed is measured in radians per second (ω_m) and converted to RPM via a gain block (to-RPM).

10.3. Signal Monitoring and Visualization (The Results)

The large box on the bottom right handles data aggregation and visualization:

- **Scope-motor:** Compares reference values against actual values for **Speed** (w_{ref} vs ω_m), **Flux** (ϕ_{ref} vs ϕ_{motor}), and **Torque** (T_{ref} vs T_{motor} vs T_{load}). This is where you verify if the DTC controller is successfully tracking its targets as shown in the figure 4,5.
- **Scope (PQ):** Monitors Active Power (P in kW) and Reactive Power (Q in kvars) drawn by the system as shown in the figure 6,7.
- **Scope (V_d and V_q):** Tracks the stator voltage components in the synchronous reference frame (V_d and V_q, in per-unit system) as shown in the figure 8,9.

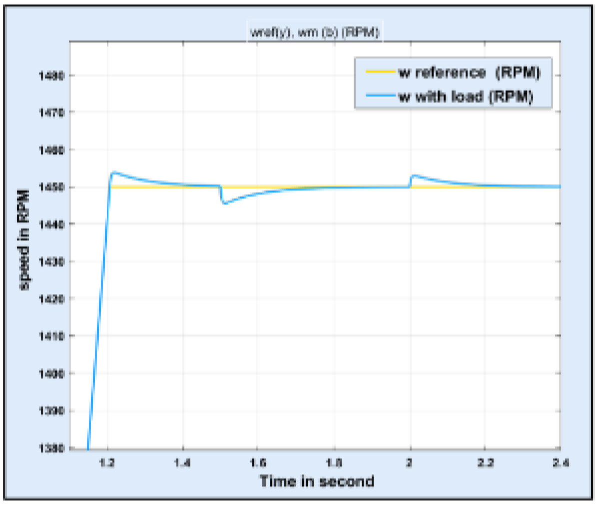

Figure 4 Speed of motor with load

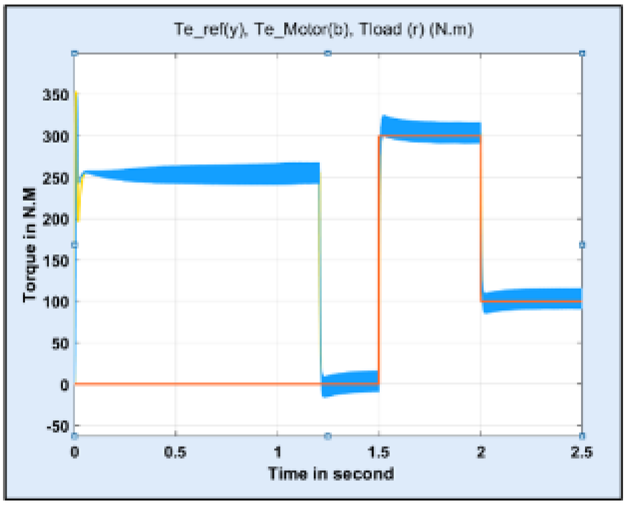

Figure 5 Torque of motor with load

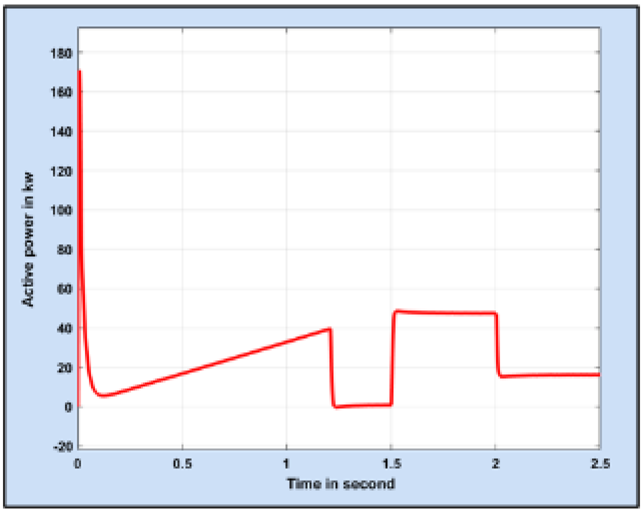

Figure 6 Active power

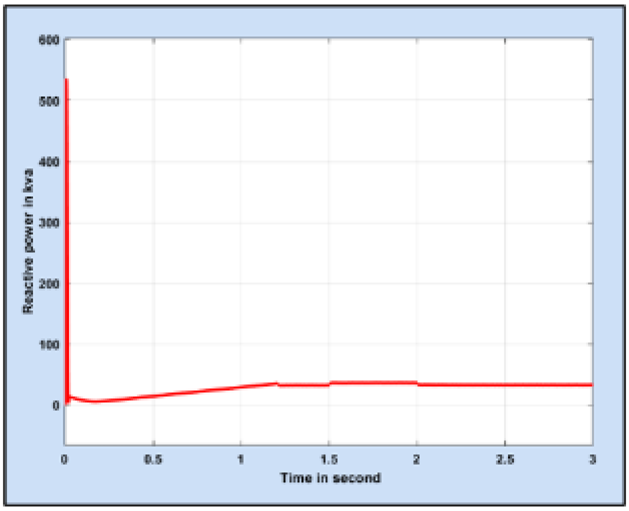

Figure 7 Reactive power

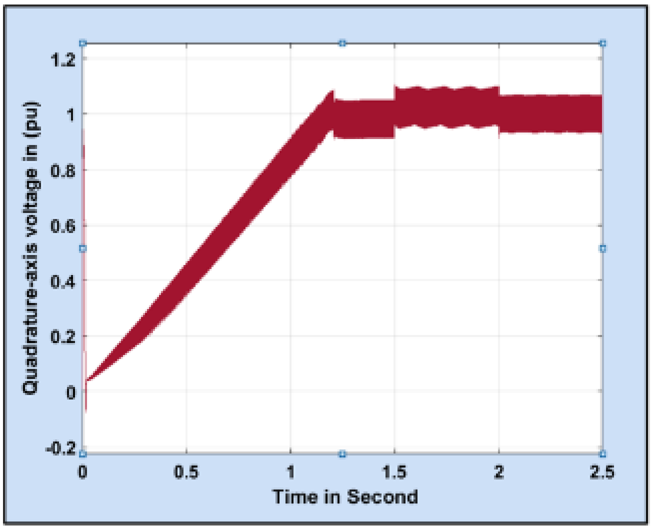

Figure 8 Quadrature axis voltage

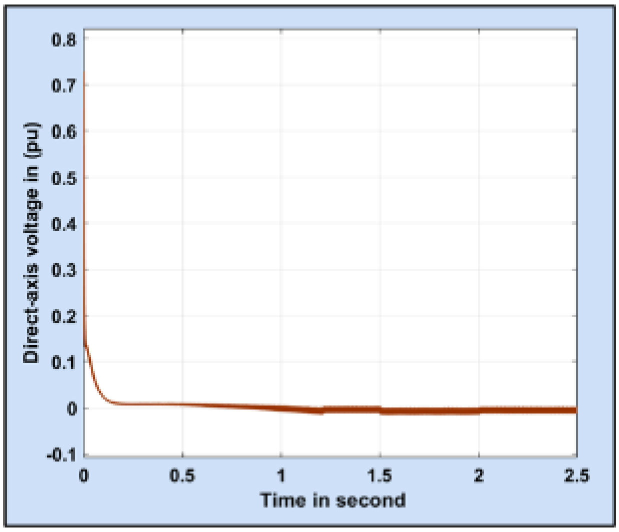

Figure 9 Direct axis voltage

11. Conclusion

This scientific study comprehensively investigates the Direct Torque Control (DTC) methodology for brushless DC (BLDC) motors, which has been enhanced and developed using a Proportional-Integral (PI) controller to optimize the overall performance of the entire electromechanical system. Through rigorous system simulations and deep analysis, several key fundamental conclusions explaining the operational differences were established. The conventional DTC method demonstrated its well-known advantages, including an exceptionally fast dynamic response, a simple control structure, and the complete elimination of complex coordinate transformations. However, it faced notable technical challenges, most prominent of which was the high level of generated torque ripples. To address these persistent limitations, integrating a PI controller into the direct control scheme proved highly effective. This integration contributed to the continuous, precise correction of control errors and facilitated exceptionally smooth speed and torque regulation. Consequently, the enhanced system achieved outstanding accuracy in tracking the reference speed under varying load conditions, improved steady-state performance by minimizing oscillations, and guaranteed an excellent dynamic response during sudden load disturbances. In conclusion, numerical simulation results clearly confirm that the proposed hybrid approach significantly outperforms the conventional standard method, particularly in terms of stability, accuracy, and operational robustness.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] D. D. Kumar, M. Rambabu, B. Yogesh, and G. Likhitha, “International Journal of Research Publication and Reviews Control Techniques for BLDC Motor: A Review”.

[2] K. Fatih, “DTC Control of BlAC and BLDC Motors for Pure Electric Vehicles,” Sept. 2018.

[3] A. R. A. Majid, “Enhancing BLDC Motor Speed Control by Mitigating Bias with a Variation Model Filter,” *International Journal of Advanced Computer Science and Applications*, vol. 15, no. 9, Jan. 2024.

[4] K. M. A. Prasad and U. Nair, “Intelligent fuzzy sliding mode controller based on FPGA for the speed control of a BLDC motor,” *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 1, pp. 477–486, Mar. 2020.

[5] H. A. Natvarlal and M. J. Modi, “Speed Control of Brushless DC Motor: A Review,” Jan. 2015.

[6] V. K. Awaar, S. Bannuru, and A. Abbas, “Position senseless field-oriented control of BLDC motor for EV applications,” *E3S web of conferences*, vol. 391, pp. 01176–01176, Jan. 2023.

[7] G. Morales, A. S. Lucena, E. A. G. Peñazola, C. G. da C. Neves, and P. J. D. de O. Evald, “Robust adaptive control for BLDC motor control: synthesis and experimental validation,” pp. 1–6, Oct. 2024.

[8] M. C. Ozgenel, “Analysis of the Effects of Three Various Current Control Methods on BLDC Motors,” vol. 12, no. 3, pp. 1550–1566, Dec. 2019.

[9] Z. Alqarni, “Higher Order Sliding Mode Control for Speed Control of BLDC Motor,” pp. 0212–0217, Mar. 2023.

[10] A. H. Mohamed and H. E. A. Ibrahim, “Comparative Study Between PID and Fuzzy PID Controller for Speed Control of BLDC Motor,” *International Journal of Engineering Research and*, vol. 7, no. 05, May 2018.