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Original Article

FOC Controller Design for BLDC Motor with Torque Ripple Minimization Using SVPWM in MATLAB/Simulink

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Abstract - *Brushless DC motors are most utilized in areas of aerospace and electric vehicles. They offer great efficiency, compact size, and superior power density. However, the BLDC motor's torque output ripples provide significant challenges. Torque ripple causes undesirable vibrations, acoustic noise, and reduced performance. The main problem addressed in this article is minimizing torque ripple while achieving precise speed control. The proposed solution to the problem stated here is the Field-Oriented Control (FOC)-based speed control strategy. FOC enables smooth torque production and improved dynamic performance as opposed to typical trapezoidal control methods. The paper involved mathematical modeling of the BLDC motor using Clarke-Park transformations. Space Vector Pulse Width Modulation (SVPWM) is utilized to produce pulses to excite the stator coil. The FOC algorithm was executed in MATLAB/Simulink, and the system has been tested for differing load conditions. Important parameters, such as speed and current response, were analyzed. The ripple percentage of the torque output was compared against the IEEE std. 1812-2023 to prove the effectiveness of the FOC control loop. The results displayed that the FOC system significantly reduced ripple in torque output and thus improved the efficacy of the motor. In conclusion, the FOC strategy proved to be highly effective. It outperformed the six-step commutation strategy with respect to the torque ripple reduction and overall performance. Hence, proving the value of this method of control in applications like electric vehicles*.

Keywords - *Field-Oriented Control, BLDC motor, SVPWM, Torque ripple mitigation, Matlab/Simulink*.

1. Introduction

Brushless DC (BLDC) motors are highly utilized in industrial, automotive, and high-performance systems because of their high efficiency, reliability, and power density when compared to traditional brushed motors. Despite these advantages, BLDC motors often have higher ripples in their torque output, which can lead to unnecessary vibrations, elevated noise levels, and reduced overall system performance. Hence, reduction of torque ripples can improve motor efficiency and also achieve smooth, stable maneuverability-particularly in the fields of Electric Vehicles (EVs), robotics, and industrial automation. BLDC motors require a precise speed control loop that produces pulses for the inverter topology to control the electronic commutation of the stator phases. Numerous methods have been recorded to be used as a control for the BLDC motor, trapezoidal control being the most used in markets. Direct Torque Control (DTC) is one among such methods that is commonly used; however, it requires complex calculations, and it has a poor response at low speeds. Another such method is the Artificial Neural Network method (ANN), though this particular method is very useful, implementing it can be difficult due to its complex computational algorithms, and hence, field-oriented control provides a midway between cost and efficiency, despite the difficulty of placing rotor sensors in the wrong positions, which could give unreliable results [1].

Field-Oriented Control (FOC) is a developing control strategy that can perform precise regulation of motor parameters such as torque and speed while significantly reducing torque ripple. Unlike conventional trapezoidal control methods, FOC operates in a rotating reference frame, allowing autonomous control of flux and torque-producing components. This results in better motor operation with respect to noise levels, improved dynamic response, and improved overall efficiency [1-3].

One of the main reasons for using FOC is to reduce the torque ripple, a well-known issue in BLDC motors that creates vibrations, acoustic noise, and reduced efficiency. That is proven to be comparatively more in the trapezoidal method of control due to abrupt current changes and high torque pulsations. On the other hand, FOC provides a smooth operation and sinusoidal control of motor currents.

FOC provides an added advantage of better speed regulation and faster dynamic response, allowing the adaptation of the motor to changing load conditions [3-9].

The energy efficiency of the motor significantly improves with the usage of FOC as a control loop since this method controls stator current in the dq frame of reference, thus enabling the motor to draw just the required current. This prolongs the motor's life by reducing heat production and power loss.

Additionally, it prevents cogging torque and improves low-speed torque consistency, which makes it very useful in high-precision applications like servo-based systems, robotics, and CNC machinery. FOC, in its basic structure, is used to garner the parameters to produce the pulses for the inverter system that, in turn, controls the stator winding's excitation; hence, it is also important to choose the modulation techniques to produce the gate pulses with fewer harmonics so as to improve the performance of the motor.

Amongst ample modulation techniques, the most common and easy method is the Sinusoidal Pulse Width Modulation (SPWM). This is a technique wherein the sinusoidal signal with a triangular reference signal generates pulses required by the inverter. This method is easy to implement and use; however, as shown in [15], harmonics are more pronounced in SPWM compared to Space Vector Pulse Width Modulation (SVPWM), as explained in section 2.

As seen in [14], SPWM not only produces more harmonics but also causes more ripple in the torque output. Additionally, the terminal voltage in the motor is sinusoidal instead of trapezoidal, as it should be in a BLDC motor. Hence, given its clear advantages, SVPWM was chosen for this paper to be used with FOC for minimizing torque ripples.

This paper is structured as follows: Section I introduces the methodology used in studying the motor and its modelling in the simulation tool; it also explains the control loop structure. Section II presents the simulation techniques and the various parameters of the control loop simulation. Section III outlines the results of the said study and the conclusion that can be drawn from the same.

2. Methodology

Section II outlines the study's methodology and the parameters used to simulate the control loop for the BLDC motor.

2.1. Block Diagram

The architecture of FOC as a technique to solve torque ripples is shown in Figure 1, a widely used technique for controlling three-phase motors, such as BLDC.

Independent control of components responsible for torque and flux is the key to optimum performance of motor control in various load conditions; this is obtained by implementing a series of transformations of the stator currents from the ABC reference frame to the dq reference frame.

The FOC method relies on a few key components: PI controllers, Clarke/Park transformations, three-phase inverters, and feedback mechanisms. These elements work to dynamically adjust the current input to the motor, ensuring a smoother operation and higher energy efficiency.

2.2. BLDC Motor-Mathematical Modelling

A BLDC motor can be operated only using an electronically commutated logic rather than with mechanical brushes, making it more efficient and durable. The motor consists of a permanent magnet rotor, and the stator is made up of electrically induced coils.

The calculated model of the BLDC motor is essential for designing the FOC loop. The following equations are used to define the important parameters of the BLDC motor.

Equations from (1) to (11) introduce the mathematical model of the BLDC motor in the static ABC reference frame. It begins with voltage equations for each phase winding-A, B, and C-denoted as V_{an}, $V_{bn,}$ and V_{cn}.

These equations incorporate the resistive drop R_s, the self-inductance L, mutual inductance M, and the derivative of phase currents, along with the induced EMF components e_a, e_b, and e_c. Equations (1) to (3) are as shown:

$$V_{an} = R_s i_a + L\frac{d}{dt}(i_a) + M\left[\frac{d}{dt}(i_b) + \frac{\mathrm{d}}{\mathrm{d}t}(i_c)\right] + Ea \quad (1)$$

$$V_{bn} = R_s i_b + L\frac{d}{dt}(i_b) + M\left[\frac{d}{dt}(i_a) + \frac{\mathrm{d}}{\mathrm{d}t}(i_c)\right] + \mathrm{Eb} \quad (2)$$

$$V_{cn} = R_s i_c + L\frac{d}{dt}(i_c) + M\left[\frac{d}{dt}(i_b) + \frac{\mathrm{d}}{\mathrm{d}t}(i_a)\right] + \mathrm{Ec} \quad (3)$$

This expression is the foundation for a matrix-based dynamic model of the BLDC motor, V_{an}, V_{bn}, and V_{cn}. Equation (4) represents Equations (1)- (3) in the form of a matrix.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

The back-emf is represented in other ways too, in terms of the back-emf constant and speed, as explained in Equation (5).

$$e_a = K_a \omega_r \quad e_b = K_b \omega_r \quad e_c = K_c \omega_r \quad (5)$$

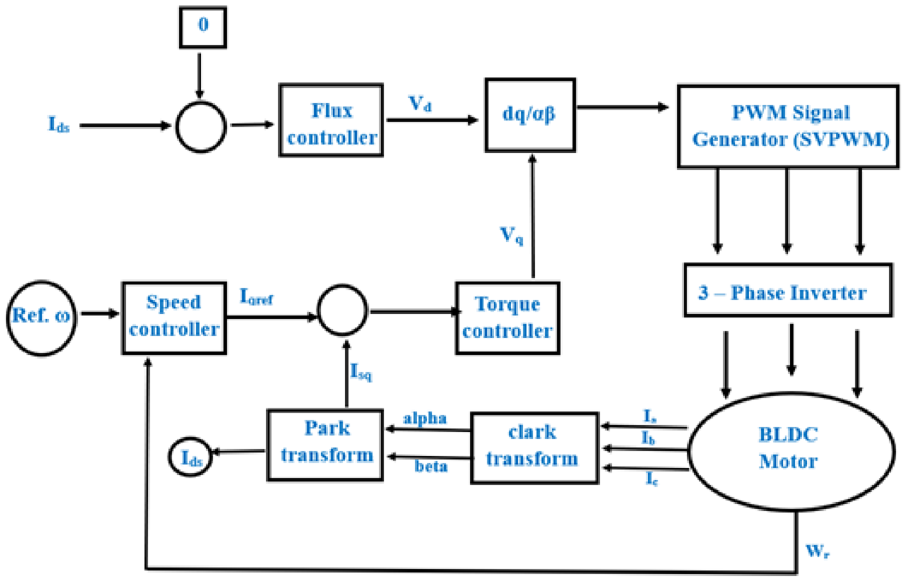

Fig. 1 Block diagram of FOC-based BLDC motor

Stator currents are rewritten as shown in Equation (6), assuming that the stator is star-connected.

$$i_a + i_b + i_c = 0\,,\ \text{so}\ \ i_b + i_c = -\,i_a \tag{6}$$

With the new considerations, Equations (1)-(3) are rewritten as shown in Equations (7)-(9).

$$V_{an} = R_s i_a + L\frac{\mathrm{d}i_a}{\mathrm{d}t} + M\frac{\mathrm{d}}{\mathrm{d}t}(i_b + i_c) + e_a$$

$$= R_s i_a + L\frac{\mathrm{d}i_a}{\mathrm{d}t} - M\frac{\mathrm{d}}{\mathrm{d}t}(i_a) + e_a$$

$$= R_s i_a + \frac{\mathrm{d}i_a}{\mathrm{d}t}(L - M) + e_a$$

$$V_{an} = R_s i_a + L_s\frac{\mathrm{d}i_a}{\mathrm{d}t} + e_a \tag{7}$$

Here, Ls = L-M (also called the total stator inductance), similarly,

$$V_{bn} = R_s i_b + L_s\frac{\mathrm{d}i_b}{\mathrm{d}t} + e_b \tag{8}$$

$$V_{cn} = R_s i_c + L_s\frac{\mathrm{d}i_c}{\mathrm{d}t} + e_c \tag{9}$$

Hence, the Equations (1)-(3) can also be rewritten using some specifications.as shown in Equation (10).

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{L_s}\left\{\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} - \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}\right\} \tag{10}$$

The final torque equation would be as follows, as shown in Equation (11), in terms of electrical parameters. The torque equation can be rewritten using the mechanical parameters as shown in Equation (12); here J denotes rotor inertia, B denotes the damping constant, and T_l represents the load torque.

$$T = \frac{P}{2}[K_a i_a + K_b i_b + K_c i_c] \tag{11}$$

Here, P is power, and K_a, K_b, and K_c are back-emf constants.

$$\frac{J}{\left(\frac{P}{2}\right)} \cdot \frac{\mathrm{d}w_r}{\mathrm{d}t} + \frac{B}{\left(\frac{P}{2}\right)} \cdot w_r + T_L = T \tag{12}$$

2.3. Space-Vector Pulse Width Modulation

The key aim in using a technique for modulation is to attain gate pulses with minimum harmonics. One among such techniques is SVPWM, as stated in [14]. SVPWM has a higher DC voltage utilization factor and produces minimal harmonics; hence, it can be considered as a superior technique to SPWM. The reduction in harmonics improves the efficiency of the motor and would improve its performance.

Only six of the eight common topologies that a voltage source inverter can adopt are positive switching states, which are distinguished by their unique output voltage; the remaining topologies are zero-value switching states, which are distinguished by their nil output voltage.

Figure 2 shows how the SVPWM uses two abutting effective vectors: a null vector of the eight-state space voltage vectors and its unique act time to create the identical space voltage vector needed by the motor.

In contrast with conventional SPWM, which produces distinct PWM signals for every phase, SVPWM maximizes switching sequences to attain improved torque control and increased efficiency. SVPWM is extensively utilized in FOC-based motor control, electric vehicles, and industrial drives due to its large reduction of harmonics, smoother motor operation, and increased torque efficiency [9].

2.4. Field-Oriented Control

The FOC technique, based on the vector control principle, wherein currents tapped from the stator are mathematically converted into a rotational reference frame (d-q frame) by implementing Clarke and Park transformations, is the center of importance in solving the stated problem. In this frame, the motor's currents are split into two independent components: i_d (direct-axis current), which influences flux, and i_q (quadrature-axis current), which influences torque. By keeping $i_d = 0$, the motor operates at maximum efficiency with smooth torque generation. A Proportional-Integral (PI) controller is the realistic choice for amending the stator currents. Here, SVPWM generates optimized switching signals for the inverter, guaranteeing continuous power delivery. FOC also provides superior low-speed and high-speed performance compared to conventional trapezoidal commutation methods, making it the ultimate choice for applications such as high-performance robotics, where precise and efficient motor control is essential.

According to theory, torque ripples get minimized when stator fields are aligned exactly 90 ° to rotor magnetic fields. Hence, it is essential to maintain the magnetic field of the stator exactly perpendicular with respect to the magnetic field of the rotor at all times. This is the main aim of using FOC, so it controls the stator's field by Clark-Park conversions [8].

The Park to Clarke transformation in Equations (12), (13), (14), (15) and Inverse Clarke to Park transformations in Equations (16), (17), (18), (19) and (20) are as follows:

2.4.1.Clarke Transformation (ABC to αβ Frame)

$$I_\alpha = I_a \tag{13}$$

$$I_\beta = \frac{I_a + 2I_b}{\sqrt{3}} \tag{14}$$

2.4.2. Park Transformation (αβ to d-q Frame)

$$I_d = I_\alpha \cos\theta + I_\beta \sin\theta \tag{15}$$

$$I_q = -I_\alpha \sin\theta + I_\beta \cos\theta \tag{16}$$

2.4.3. Inverse Park Transformation (d-q to αβ Frame)

$$V_\alpha = V_d \cos\theta - V_q \sin\theta \tag{17}$$

$$V_\beta = V_d \sin\theta + V_q \cos\theta \tag{18}$$

2.4.4. Inverse Clark Transformation (αβ to ABC frame)

$$V_a = V_\alpha \tag{19}$$

$$V_b = -\frac{1}{2}V_\alpha + \frac{\sqrt{3}}{2}V_\beta \tag{20}$$

$$V_c = -\frac{1}{2}V_\alpha - \frac{\sqrt{3}}{2}V_\beta \tag{21}$$

2.5. Torque Ripple Minimization

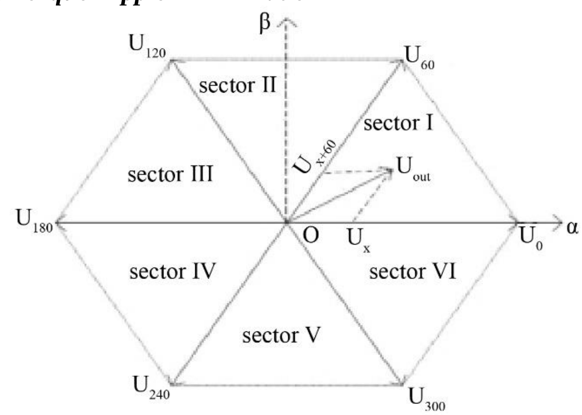

Fig. 2 The six sector diagram of the SVPWM [14]

Torque ripple minimization is achieved by optimizing the current waveform and reducing harmonics. Torque ripple percentage is calculated using Equation (22).

$$TRF = \frac{T_{\max} - T_{min}}{T_{avg}} X\ 100\% \tag{22}$$

3. Simulation

The mathematically modeled BLDC motor was simulated using MATLAB/Simulink with two control loops to test the effectiveness of the chosen control method, i.e.,field-oriented control loop. It was tested against the conventional control method, also called trapezoidal control. Table 1 details the values of different parameters needed for the simulation.

Table 1. Parameters of the BLDC motor

Considerations for Motor	Values
R_s	2.98Ω
L	7mH
P	2
V_{dc}	240V
J	0.47 *10^{-4} kgm^2
B	11* 10^{-5}
K_e	0.375
P_m	0.125

The overall view from the Simulink software of the mathematically modelled BLDC motor is as presented in Figure 3. Perfect verification of the model would be to check the generated back-emf waveform from the simulation of the motor. This is epitomised in Figure 4.

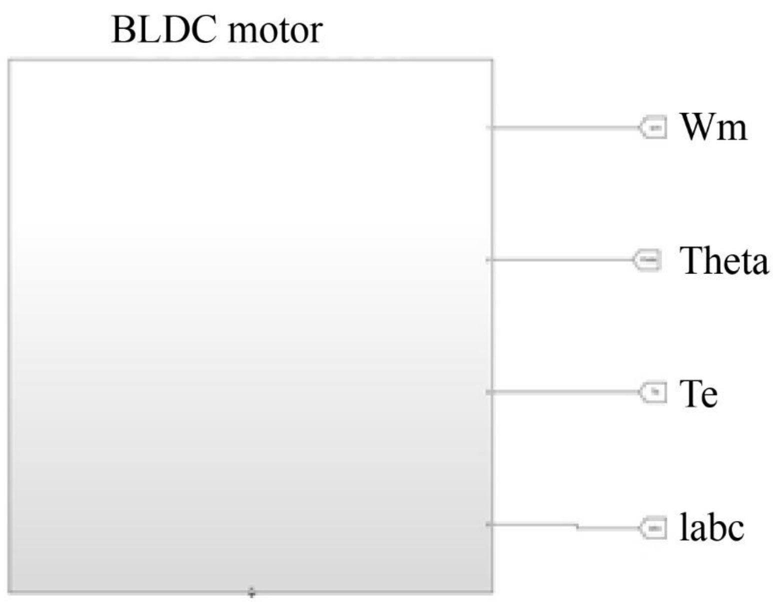

Fig. 3 Simulink model of a BLDC motor

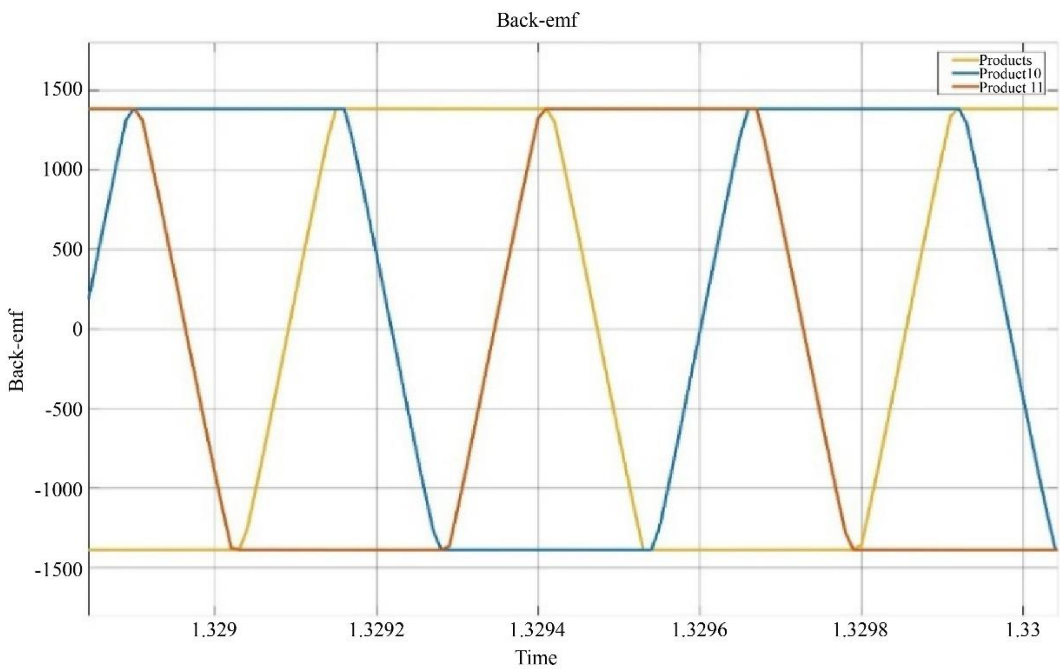

Fig. 4 Back-emf of the BLDC motor

3.1. Trapezoidal Control

The trapezoidal control, also acknowledged as the six-step commutation method, is a conventional practice used for control of the motor in the present-day market. This method is cheaper compared to field-oriented control but does not reduce ripple in the torque output as seen in the simulation results; therefore, this method is unreliable to use. Here, the rotor angle is taken as a feedback parameter from the position angle of the rotor, as obtained from the Hall position sensor block. This is then converted in the Hall decoder block to a sector for SVPWM, and output from this block regulates the switches in the inverter module based on the logic of gates in the gate driver block. Hence, by comparing the desired speed and rotor speed, motor control was obtained. Figure 5 represents the program blocks written for the trapezoidal control loop execution in Simulink software.

3.2. Field-Oriented Control Simulation

The model shown in Figure 6 consists of multiple interconnected subsystems that facilitate the conversion of input signals into appropriate control actions for the motor. At the core of the circuit, the BLDC motor is driven by a universal bridge that serves as an inverter. The inverter receives switching signals that control the commutation process, ensuring proper phase excitation for the rotor movement. The motor's electrical and mechanical parameters, including stator currents, rotor speed, torque, and rotor position (theta), are extracted for further processing and analysis.

The control mechanism comprises an FOC block that is responsible for generating appropriate voltage references based on the operating conditions of the motor. The reference voltage signals (V_{ref}) are used to regulate the inverter switching, ensuring smooth operation of the motor. Additionally, the torque, speed, and motor current are measured by utilizing a measurement block.

These parameters act as the feedback signals to the control loop, allowing accurate adjustments and corrections. The simulation model provides a comprehensive framework for analysing BLDC motor behaviour under controlled conditions, aiding the evaluation of FOC application in reducing ripples in torque and improving overall motor efficiency. The FOC technique enhances motor performance by converting the stator currents into a rotating frame of reference, thereby simplifying control and improving efficiency. The control process begins with the input speed reference being compared to the actual rotor speed (Omega); the difference between the two, also referred to as the error value, is input to the PI controller to generate the reference quadrature-axis current (iqref), which directly affects the stator current's torque-producing component. The direct-axis current (i_d)is set to zero for achieving optimal motor operation, ensuring that the flux remains unchanged. The inner current loop consists of a PID block that converts error values to V_d and Vq, which essentially goes through the Park-to-Clarke transformation to produce V_α and V_β for SVPWM. The PWM modulation technique chosen then produces the gate pulses for the inverter, generating the required currents to drive the BLDC motor.

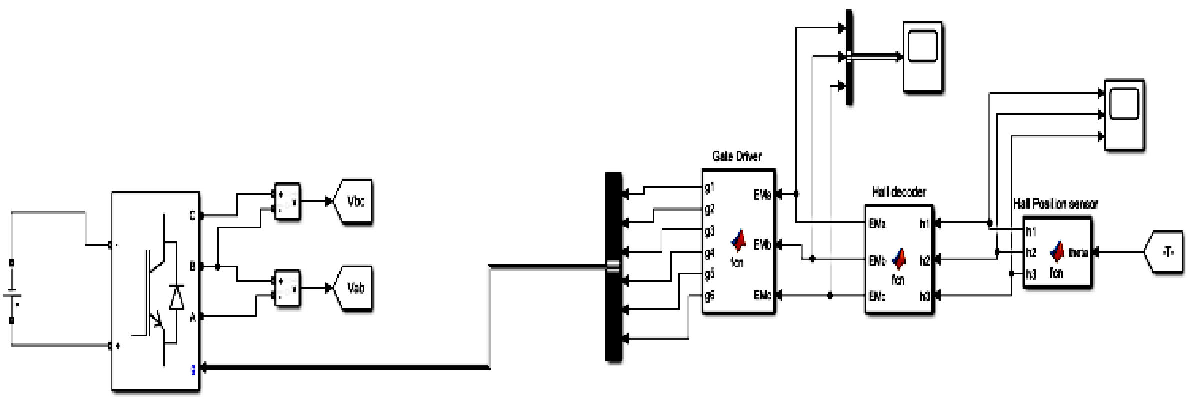

Fig. 5 Trapezoidal control loop

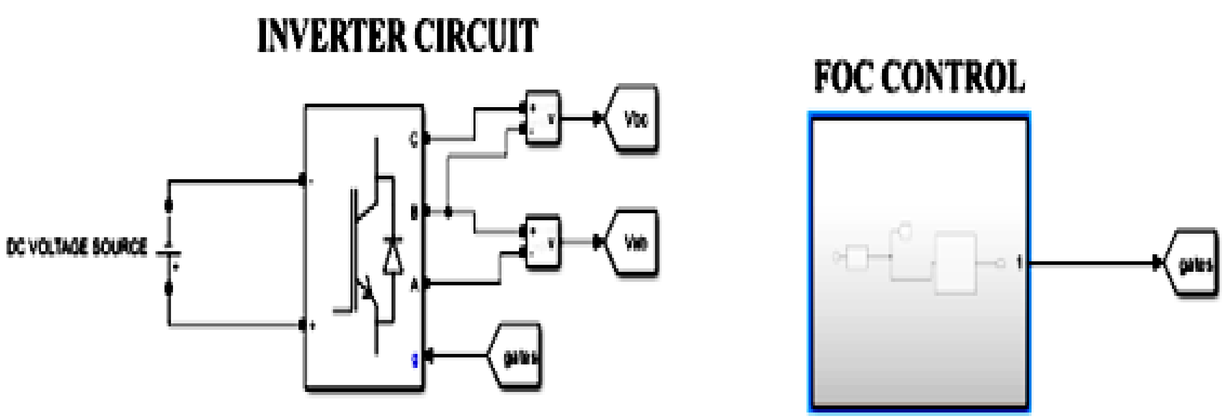

Fig. 6 Field-oriented control loop

4. Results and Discussion

The ultimate objective of the paper is to minimize torque ripple; hence, the torque ripple percentage was calculated for both control loops to decide the best control for the motor.

Table 2 compares the IEEE Std. 1812-2023 with the obtained results from the simulation. Here, various reference speeds were used to test the FOC loop. The output speed, torque, and line currents affected by FOC are as shown in Figures 7, 8, and 9, respectively, for a step change of 600 to 750 rpm in the reference speed. Figures 10, 11, and 12 detail the line currents, speed, and torque output of the motor for negative speed, i.e., -300 rpm to 0 to +300 rpm as the reference speed of the motor, while Figures 13, 14, and 15 depict the zoomed-in version of speed, line currents, and output torque of the motor during a load change. Negative speed represents braking in actual scenarios, and the FOC loop was able to control the system even during this scenario.

Table 2. Simulation results

Type of ref.speed	Torque Ripple Percentage		
	Control Loop	Ripple %	IEEE Criteria
Step change of 650 to 700 rpm	Trapezoidal control loop	10	10-15
Step change of 650 to 700 rpm	Field-oriented control loop	1.67	1-5
Negative speed	Field-oriented control loop	2	1-5

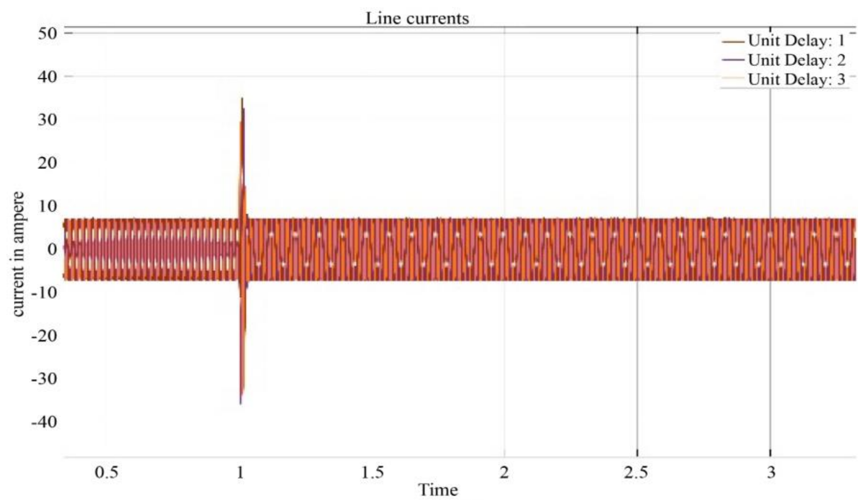

Fig. 7 Line currents during step change from 600 to 750 rpm

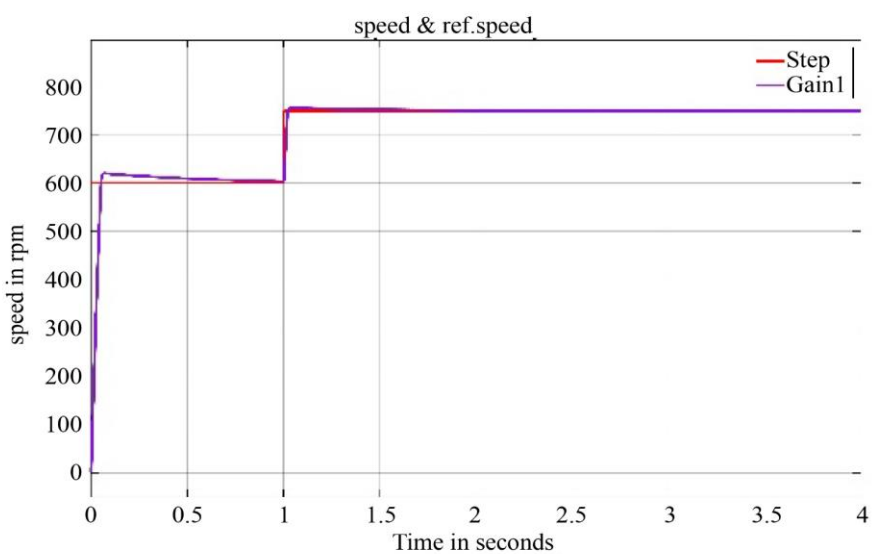

Fig. 8 speed & step change ref. speed of the motor from 600 to 700 rpm

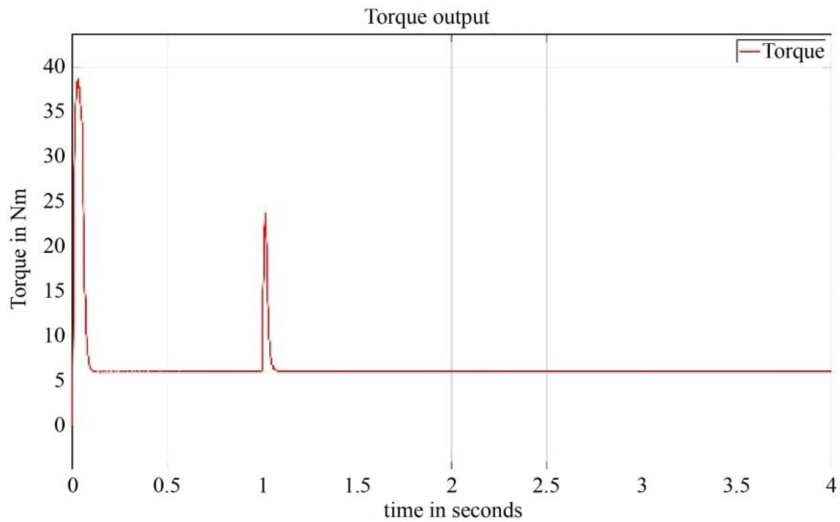

Fig. 9 Torque output of the motor during step change from 600 to 750 rpm

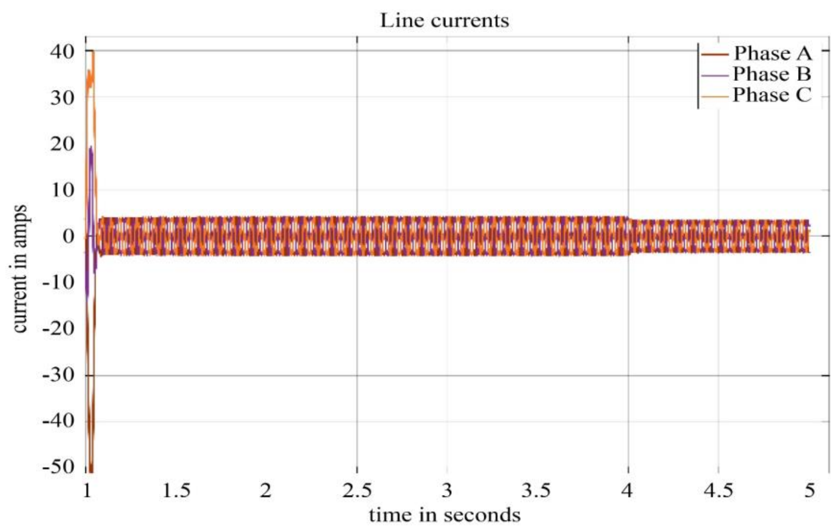

Fig. 10 Line currents during negative speed of 300 rpm with a change in load

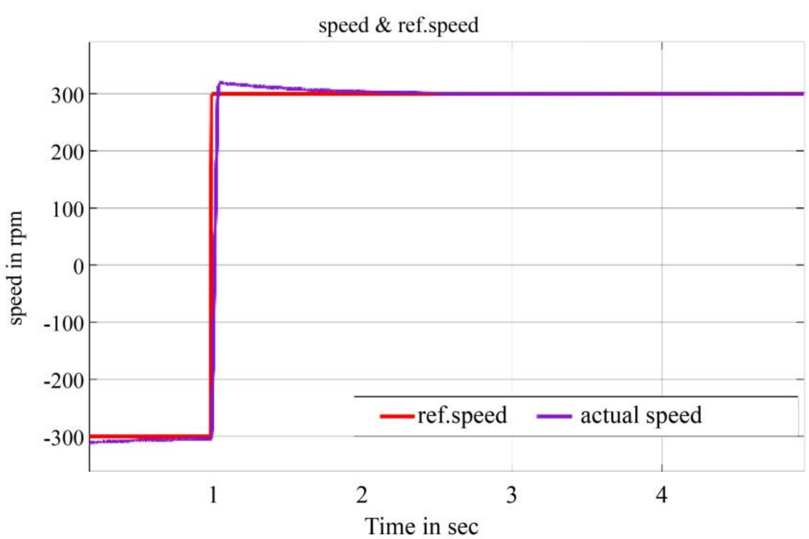

Fig. 11 speed & negative ref. speed changing from -300 to +300 rpm with a change in load

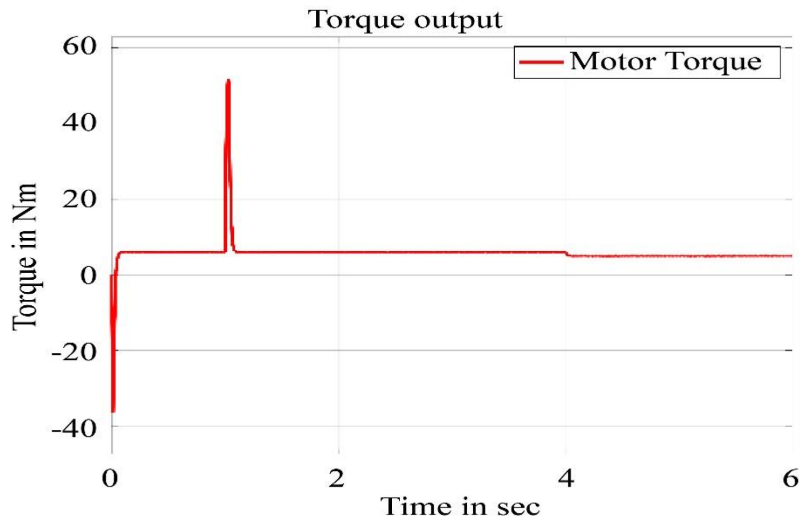

Fig. 12 Torque output during negative ref speed from -300 to +300 rpm with a change in load

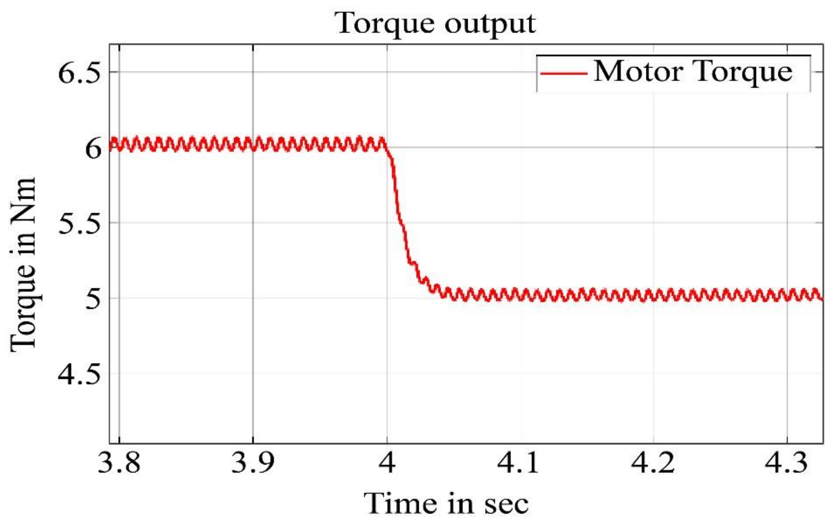

Fig. 13 Closer view of torque output during load change at t=4 sec

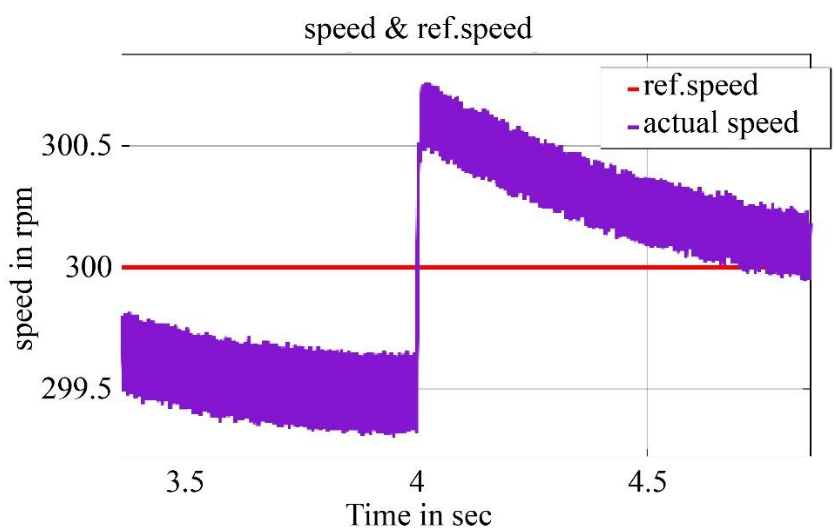

Fig. 14 Closer view of speed during load change at t=4 sec

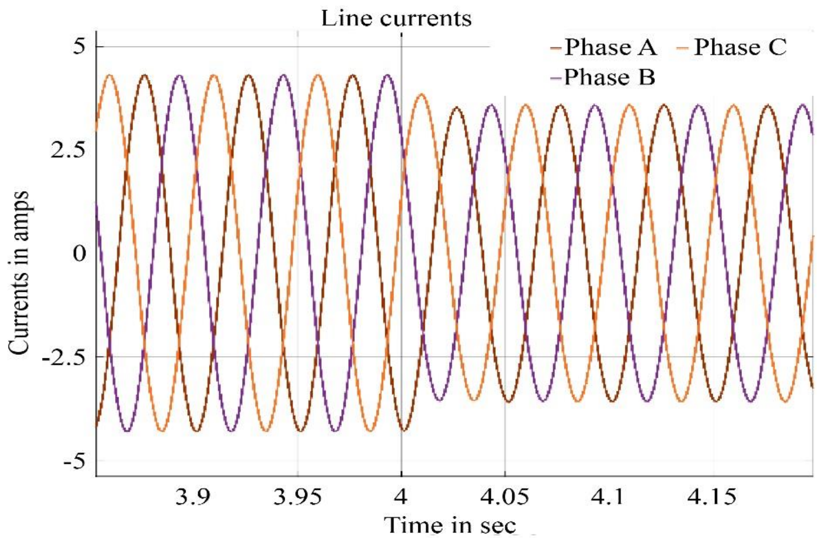

Fig. 15 Closer view of line currents at load change at t=4 sec

5. Conclusion

The paper's objective of designing and simulating the FOC loop for the mathematically modelled BLDC motor was successfully accomplished. The results demonstrated a staggering improvement in performance, as the torque ripple was reduced by 83.3% compared to conventional trapezoidal control. This clearly shows that implementing the FOC loop provides much smoother torque output and more precise speed control. Furthermore, the integration of SVPWM effectively reduced harmonic distortion, enhancing overall system efficiency and stability. These outcomes confirm that the proposed FOC with SVPWM strategy meets the research goal of minimizing torque ripple while obtaining precise speed regulation. The paper has validated that this advanced control method is well-suited for use in the advanced fields. For future research, the implementation of adaptive FOC algorithms can be proposed. These would function dynamically to adapt control parameters in real-time varying operating conditions and load disturbances, further enhancing robustness and efficiency in practical, unpredictable environments.

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