Model Predictive Control Of BLDC Motor For Electric Vehicles

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***Abstract*—**This paper presents the modeling, simulation and control of four-Quadrant Brushless DC (BLDC) motor for electric vehicle applications using Model Predictive Control (MPC). The proposed system comprises a Lithium-Ion battery, a bidirectional DC–DC converter, a three-phase voltage source inverter (VSI), and a BLDC motor to achieve efficient power conversion and four-quadrant operation with regenerative braking [1],[6]. A PI controller regulates the bidirectional converter to maintain the DC-link voltage, while Hall sensor feedback is processed within the MPC framework to predict the motor response and determine the optimal control action. The Model Predictive Controller output is applied to a discrete PWM generator, which produces the switching pulses for the VSI. The proposed control strategy enhances dynamic performance, reduces tracking error, and ensures smooth transitions between forward motoring, forward regenerative braking, reverse motoring, and reverse regenerative braking. MATLAB/Simulink results demonstrate effective speed regulation, satisfactory torque characteristics, stable back EMF and stator current, and effective battery voltage, battery current and State Of Charge (SOC) through regenerative braking, confirming the suitability of the proposed MPC-based BLDC drive for high-performance electric vehicle applications.

Keywords- BLDC Motor, Four-Quadrant Operation, Model Predictive Control (MPC), Bidirectional Converter, Lithium-Ion Battery, Regenerative Braking, Voltage Source Inverter.

I. INTRODUCTION

The rapid growth of electric vehicles (EVs) has increased the demand for efficient, reliable, and energy-efficient motor drive systems capable of meeting modern transportation requirements. Compared to the conventional internal combustion engine vehicles, EVs offer high energy efficiency, low emissions, and reduced maintenance, making them a promising solution for sustainable transportation. The performance of an EV largely depends on its electric drive system, which requires an efficient motor and an advanced control strategy to ensure smooth operation under varying driving conditions.

Among the various electric motors used in EVs, the Brushless DC (BLDC) motor has gained significant attention because of its high efficiency, compact size, high power density, excellent speed–torque characteristics, and low maintenance requirements. These features make the BLDC motor highly suitable for traction applications where rapid acceleration, deceleration, and frequent speed variations are encountered. In addition, four-quadrant operation enables the motor to operate efficiently in both forward and reverse directions under motoring and regenerative braking modes, thereby improving vehicle performance and energy utilization [1].

To achieve high-performance control under dynamic operating conditions, this work proposes a Model Predictive Control (MPC)-based BLDC motor drive for electric vehicle applications. The proposed drive system consists of a Lithium-Ion battery, a bidirectional DC–DC converter, a three-phase VSI, Hall sensors, PI controllers, an MPC, and a discrete PWM generator. The bidirectional converter maintains the DC-link voltage and enables bidirectional power flow during motoring and regenerative braking, while the MPC utilizes Hall sensor feedback to predict the system response and determine the optimal control action for accurate motor operation. This control strategy improves the dynamic response, minimizes tracking error, and enhances the overall stability of the drive system.

The proposed system is modeled and simulated in MATLAB/Simulink to evaluate its performance under four-quadrant operation. The simulation results are analyzed using motor speed, electromagnetic torque, back-EMF, stator current, battery voltage, battery current, and battery SOC. The obtained results demonstrate smooth transitions in all the four operating quadrants, effective speed regulation, efficient regenerative energy recovery, and reliable system performance, confirming the suitability of the proposed MPC-based BLDC motor drive for electric vehicle applications.

II. OPERATION OF BLDC MOTOR DRIVE

The BLDC motor drive employed in this work consists of a three-phase Voltage Source Inverter (VSI), a BLDC motor, and Hall-effect sensors, as shown in Fig 1. The three-phase VSI converts the regulated DC-link voltage into controlled AC voltages required for BLDC motor operation. It comprises six MOSFET switches connected in a three-phase bridge configuration, each provided with an antiparallel diode to facilitate current commutation and regenerative operation. Owing to their fast switching capability and low switching losses, MOSFETs are well suited for electric vehicle drive applications [1], [4].

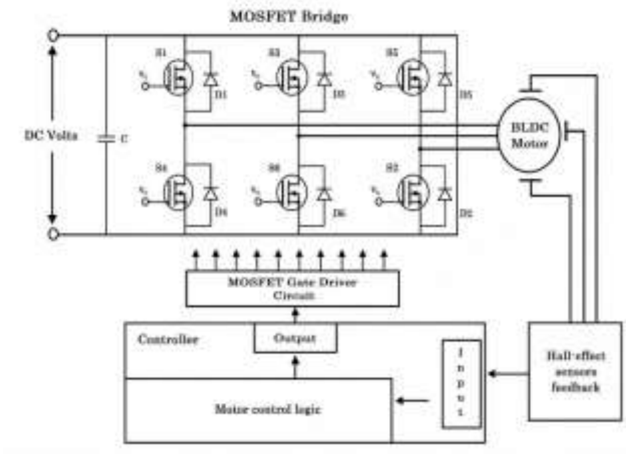


Fig 1 BLDC Motor Drive circuit

The BLDC motor operates with a trapezoidal back-EMF characteristic, where electronic commutation is achieved by synchronizing the stator phase currents with the rotor position. Hall-effect sensors continuously detect the rotor position and provide feedback signals to the controller, enabling the appropriate inverter switching sequence for smooth torque production over a wide speed range [1], [4], [6]. In this paper, the Hall sensor signals are utilized by the control system to ensure accurate electronic commutation and effective motor operation.

The inverter switching states corresponding to different rotor positions and Hall sensor signals are illustrated in Fig 2. Proper synchronization between the inverter output and rotor position enables reliable forward and reverse motoring, while regenerative braking allows the BLDC motor to operate as a generator, returning the recovered energy to the battery through the bidirectional DC–DC converter and thereby improving the overall energy efficiency of the electric vehicle drive system [6], Applying KVL to the Fig 1 at any instant of BLDC motor conducting only for the two phases as given in the equation (1) where I_c is the phase current and R_c is the per phase resistance.

$$V_d = 2(E_b + I_C R_c) \qquad (1)$$

Where, V_d is the dc-link voltage and E_b is per phase back EMF of the motor.

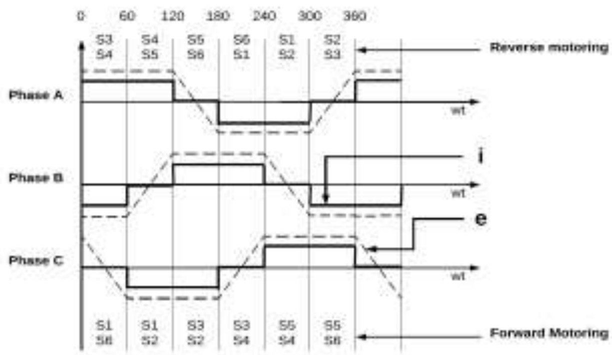


Fig 2 Back EMF, Phase current and switching sequence of switches with rotor electrical angle in degree.

III. BI-DIRECTIONAL DC-DC CONVERTER

The bidirectional converter [1] is illustrated in Fig 3. It consists of two switches (T1 and T2) and two diodes (D1 and D2) are connected in antiparallel with the two switches. It acts as a buck converter when the switch T1 and diode D2 conducts during motoring mode, and for regenerative braking the switch T2 and D1 conducts, thus the making the converter to work in boost operation by boosting the DC-Link voltage to charge the battery. Diode allow the flow of current in only one particular direction depending on the operation. During buck operation, the inverter side voltage (V_d) is α times of the battery voltage (V_b) where T_{ON} is the time period for which switch conducts and T is the total time period of operation.

$$V_d=\alpha V_b\ ; \qquad \alpha=\frac{T_{on}}{T} \tag{2}$$

In the boost operation the battery is charged by

$$V_b=\frac{V_d}{1-\alpha} \tag{3}$$

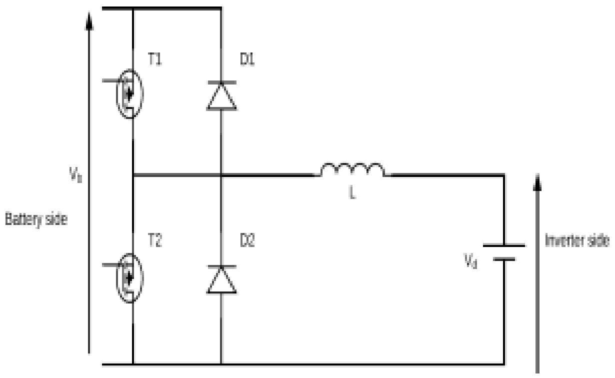
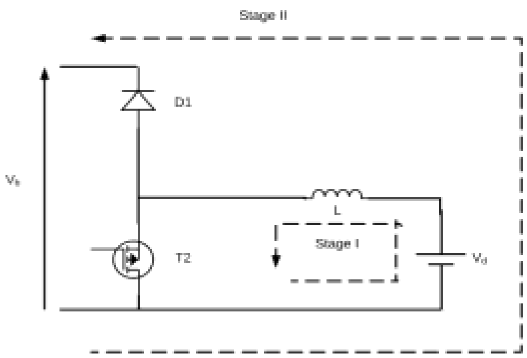


Fig 3 Bi-Directional DC-DC Converter

The operation of the two switches, T1 and T2 of the bidirectional converter is carried out using two different methods. During the motoring mode, switch T1 is triggered using voltage control, whereas during the braking mode, switch T2 is triggered using current control, as the DC-link voltage should remain constant during motoring, while the reverse DC-link current needs to be controlled during regenerative braking [2].

Fig 4 Circuit diagram during motoring.



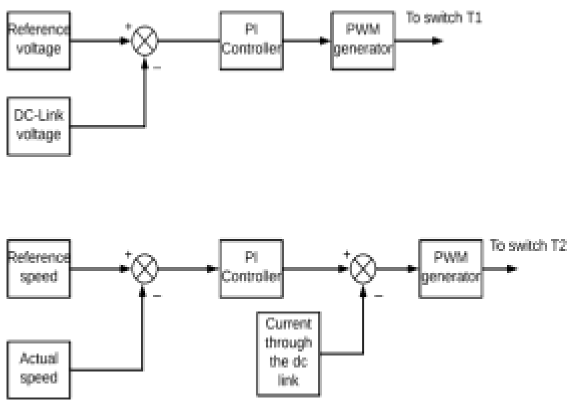


Fig 5 Circuit diagram during regenerative braking.

During the buck mode operation, switch T1 is turned ON (Stage I) and the energy is stored in the inductor (L). Whenever the gate pulse becomes zero (Stage II), the inductor discharges through diode D2 as shown in Fig 4. During the boost mode operation, T2 is turned ON and the inductor stores the energy from the inverter side (V_d). Similarly, when the gate pulse becomes zero, D1 provides the path for the current (Stage II) to flow back to the supply source V_d as shown in Fig 5.

IV. PI CONTROLLERS

The proposed BLDC motor drive employs two Proportional–Integral (PI) controllers to regulate the bidirectional DC–DC converter under motoring and regenerative braking conditions. The overall configuration of the PI controllers is shown in Fig 6.

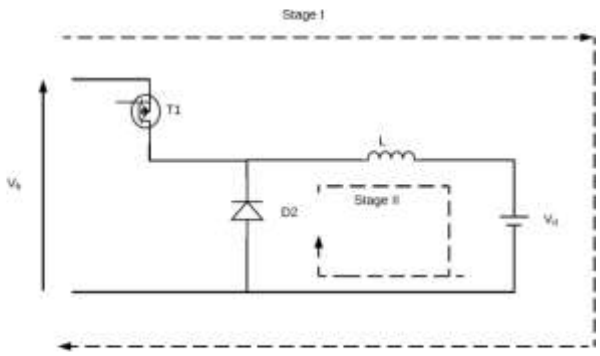


Fig 6 PI Controllers (Control logic for Bi-directional converter switches)

The first PI controller is used for motor speed regulation during motoring operation. It compares the reference speed with the actual motor speed and generates an appropriate control signal to drive the first switch (T1) of the bidirectional DC–DC converter. By adjusting the duty cycle of T1, the controller regulates the power supplied from the lithium-ion battery to the DC-link, thereby maintaining the desired motor speed and ensuring smooth acceleration [2].

The second PI controller is employed to regulate the DC-link voltage during regenerative braking. It compares the reference DC-link voltage with the measured voltage across the DC-link capacitor and generates the control signal required for the operation of the second switch (T2)
of the bidirectional DC–DC converter. This control action

maintains a stable DC-link voltage while enabling the recovered energy to flow back to the lithium-ion battery during braking.

Both PI controllers operate independently of the Model Predictive Controller (MPC). Their primary function is to regulate the operation of the bidirectional DC–DC converter, whereas the MPC is responsible for controlling the three-phase Voltage Source Inverter (VSI) to achieve accurate current tracking, effective speed regulation, and reliable four-quadrant operation of the BLDC motor.

V. MODEL PREDICTIVE CONTROLLER

The Model Predictive Controller (MPC) is employed to regulate the BLDC motor current and enhance the dynamic performance of the proposed drive system. As illustrated in Fig 7, the controller predicts the future behavior of the motor using its mathematical model and determines the optimal control action by minimizing a predefined cost function. The reference current generated by the speed control loop is compared with the predicted current, and the resulting control signal is supplied to a discrete PWM generator to produce switching pulses for the three-phase Voltage Source Inverter (VSI). Through continuous prediction, optimization, and feedback, the controller provides fast dynamic response, accurate current tracking, and improved system stability under varying operating conditions [6].

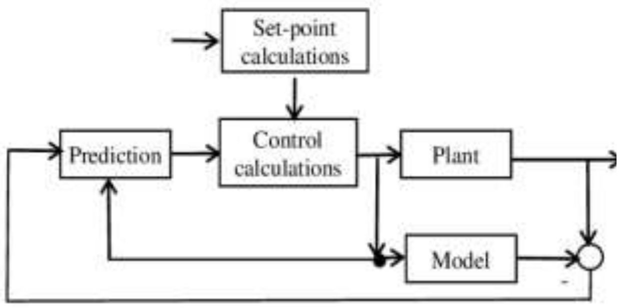


Fig 7 Block Diagram Of Model Predictive Controller

The predictive model is developed from the BLDC motor phase voltage equation,

$$V_s = Ri_s + L\frac{di_s}{dt} + e_s \quad (4)$$

Where, V_s, i_s, R, L and e_s denote the inverter output voltage, stator current, phase resistance, phase inductance and back-EMF, respectively.
Using the Forward Euler discretization, the future stator current is predicted as

$$i_s(k+1) = \left(1 - \frac{RT_s}{L}\right) i_s(k) + \frac{T_s}{L}\left(V_s(k) - e_s(k)\right) \quad (5)$$

Where, T_s is the sampling period, while $i_s(k)$ and $i_s(k+1)$ represent the present j is represented in state-space form as

$$x(k+1) = Ax(k) + Bu(k) + Ed(k) \quad (6)$$

Where, $A = \left(1 - \frac{RT_s}{L}\right)$, $B = \frac{T_s}{L}$, $E = -\frac{T_s}{L}$

Here, x(k), u(k) and d(k) denote the state variable, control input and disturbance (back-EMF), respectively.

At each sampling instant, the controller predicts the future motor current for all possible control actions and evaluates the cost function

$$J = \left(i^*(k) - i_p(k+1)\right)^2 \quad (7)$$

where i*(k) is the reference current, $i_p(k+1)$ is the predicted current and J is the cost function value.

The optimal switching action is selected by minimizing the cost function,

$$J_{min} = \min(J_1, J_2, \ldots, J_8) \quad (8)$$

$$S_{opt} = \operatorname{argmin}(J) \quad (9)$$

The above equations describe the prediction and optimization process of the proposed MPC. At every sampling instant, the controller predicts the future motor current for all possible switching states and evaluates the corresponding cost function. The switching state that minimizes the cost function is selected as the optimal control action and applied to the discrete PWM generator, which generates the gating pulses for the three-phase VSI. Consequently, the proposed controller achieves accurate current tracking, effective speed regulation, stable four-quadrant operation, and efficient regenerative braking, thereby improving the overall performance of the BLDC motor drive for electric vehicle applications.

VI. FOUR QUADRANT OPERATION

In the first and third quadrants, the torque and speed have the same sign, indicating motoring operation in the forward and reverse directions, respectively. Unlike a conventional DC motor, the direction of rotation of a BLDC motor cannot be reversed by simply changing the DC-link voltage polarity. Instead, reverse operation is achieved by changing the phase sequence of the inverter switching, while maintaining a positive DC-link voltage.

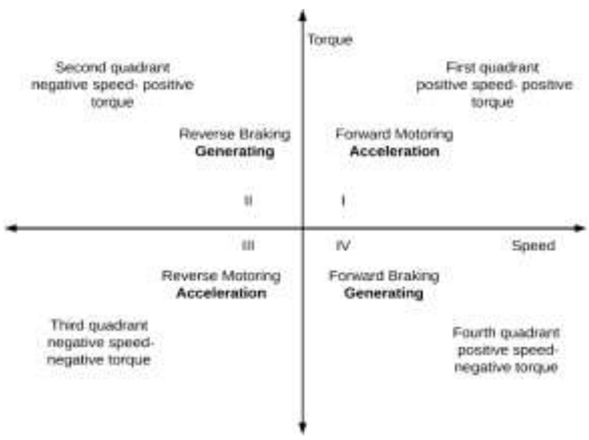


Fig 8 Four quadrant operation

During regenerative braking, the bidirectional DC–DC converter operates in boost mode, whereas buck mode is used during motoring operation. When braking is initiated, the inverter switches are turned off, allowing the antiparallel diodes of the VSI to conduct and rectify the back-EMF generated by the BLDC motor. The recovered electrical energy is boosted by the bidirectional converter and returned to the lithium-ion battery, thereby improving the overall energy efficiency of the drive system.

During downhill operation or deceleration, the excess kinetic energy of the vehicle is effectively converted into electrical energy and stored in the battery through regenerative braking.

Fig 9 Block Diagram of four quadrant operation.

VII. CLOSED-LOOP CONFIGURATION OF THE BLDC MOTOR DRIVE SYSTEM

The overall closed-loop configuration of the proposed BLDC motor drive system is shown in Fig 10. The system comprises a lithium-ion battery, bidirectional DC–DC converter, DC-link capacitor, three-phase VSI, BLDC motor, Hall sensor decoder, two PI controllers, a Model Predictive Controller (MPC), and a discrete PWM generator. The speed PI controller compares the reference speed with the actual motor speed and controls the first switch of the bidirectional DC–DC converter, while the DC-link voltage PI controller regulates the DC-link voltage by controlling the second switch during regenerative braking. The regulated DC-link voltage is supplied to the VSI for motor operation.

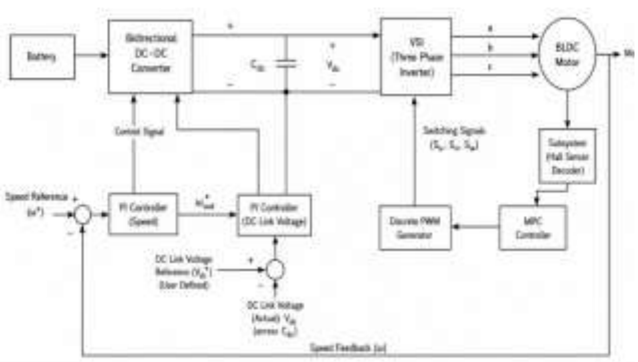
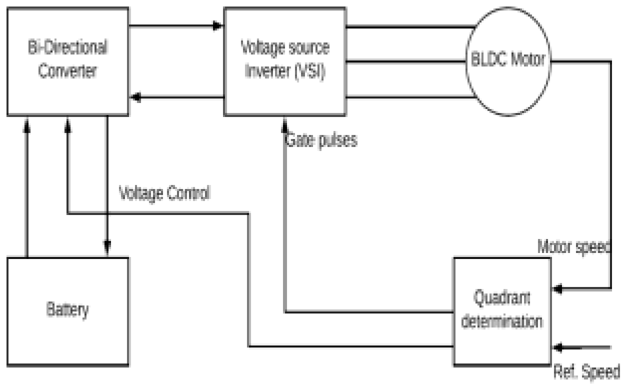


Fig 10 Closed-Loop Configuration of the BLDC Motor Drive System

The output of the BLDC Motor is applied to the Hall sensor and the Hall sensor decoder processes the Hall sensor and then it is applied to the MPC block. Using the motor model, the MPC predicts the future motor current and selects the optimal switching action by minimizing the cost function. The selected control signal is converted into switching pulses by the discrete PWM generator and applied to the VSI, which drives the BLDC motor. The actual motor speed and DC-link voltage are continuously fed back to their respective PI controllers, enabling accurate speed tracking, stable DC-link voltage regulation, effective four-quadrant operation, and efficient regenerative braking, thereby improving the overall performance of the proposed electric vehicle drive system.

VIII. RESULTS AND CONCLUSION

A. SIMULATION MODEL



The proposed simulation model, shown in Fig 11, consists of a lithium-ion battery, bidirectional DC–DC converter, DC-link capacitor, three-phase VSI, BLDC motor, Hall sensor decoder, two PI controllers, a Model Predictive Controller (MPC), and a discrete PWM generator.

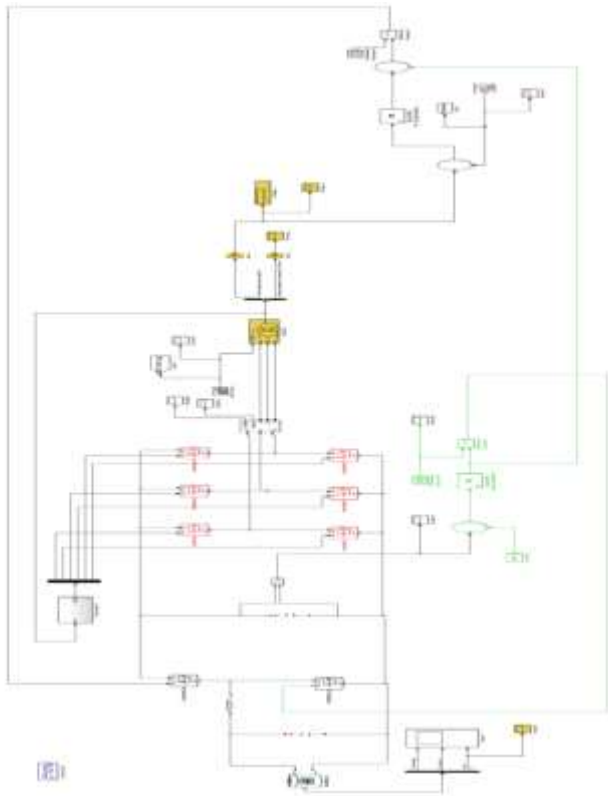
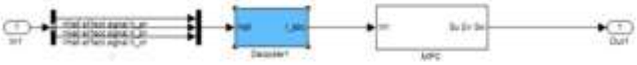
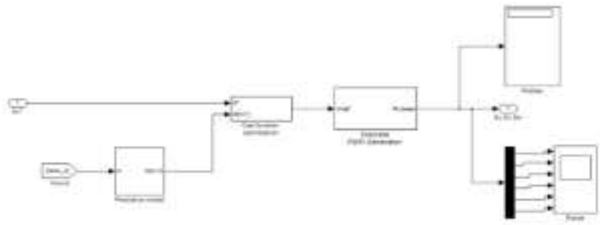


Fig 11 Proposed Simulation Model Of Model Predictive Control Of BLDC Motor For Electric Vehicles



(a)



(b)

Fig 12(a) Hall Sensor Decoder and MPC Control Subsystem (b) Model Predictive Controller (MPC) Subsystem

The supply from the battery is fed to the bidirectional converter which in turn regulates the DC-link voltage, while the VSI supplies the required three-phase voltages to the BLDC motor. The Hall sensor decoder provides rotor position information to the MPC, which predicts the future motor current and determines the optimal control action. The coordinated operation of the PI controllers and MPC ensures accurate speed regulation, stable DC-link voltage, reliable four-quadrant operation, and efficient regenerative braking for electric vehicle applications.

B. RESULTS

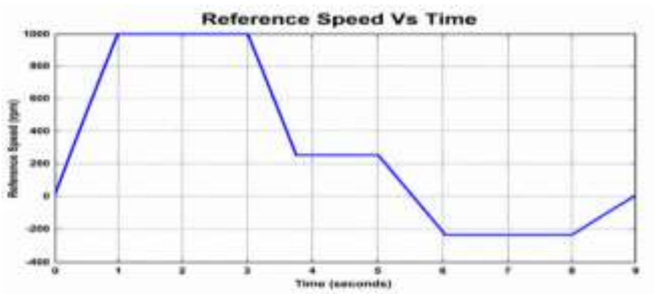


Fig 13 Reference Speed Vs Time

The reference speed profile used for simulation is shown in Fig 13. Initially, the reference speed increases from 0 to 1000 rpm during the interval of 0–1 s and is maintained at 1000 rpm until 3 s. The speed is then reduced to 250 rpm between 3 s and 3.5 s and held constant until 5 s. Between 5 s and 6 s, the reference speed changes from +250 rpm to −250 rpm to achieve reverse operation, after which the motor continues at −250 rpm until 8 s. Finally, the reference speed is gradually reduced to 0 rpm between 8 s and 9 s, bringing the motor to a controlled stop.

This reference profile enables the evaluation of acceleration, deceleration, speed regulation, direction reversal, and four-quadrant operation of the proposed BLDC motor drive.

Fig 14 Actual Speed Of a Motor Vs Time

Fig 14 shows the actual speed response of the proposed MPC-controlled BLDC motor during four-quadrant operation. The motor accelerates smoothly from 0 to 1000 rpm during 0–1 s and maintains this speed until 3 s. The speed is then reduced to 250 rpm and remains constant until 5 s. Between 5 s and 6 s, the motor successfully reverses its direction by transitioning from +250 rpm to −250 rpm, after which it operates steadily at −250 rpm until 8 s before decelerating smoothly to 0 rpm at 9 s. The actual speed closely follows the reference speed throughout the simulation with minimal transient deviations and fast settling time, demonstrating effective speed regulation, excellent tracking performance, and successful four-quadrant operation of the proposed MPC-based BLDC motor drive.

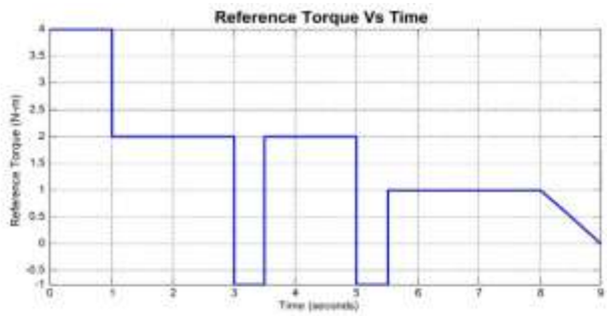


Fig 15 Reference Torque Vs Time

Fig 15 shows the reference torque profile applied to the proposed BLDC motor drive during four-quadrant operation. A reference torque of 4 N-m is initially applied during 0–1 s to accelerate the motor, followed by a constant torque of 2 N-m until 3 s for forward motoring. Regenerative braking is initiated by applying a torque of −1 N-m between 3 s and 3.5 s, after which the reference torque returns to 2 N-m until 5 s. A second regenerative braking interval occurs between 5 s and 5.5 s with a reference torque of −1 N-m, followed by a constant torque of 1 N-m until 8 s.

Finally, the reference torque is gradually reduced to 0 N-m between 8 s and 9 s, bringing the motor to a smooth stop. This reference torque profile facilitates the evaluation of motoring, regenerative braking, and four-quadrant operation of the proposed BLDC motor drive.

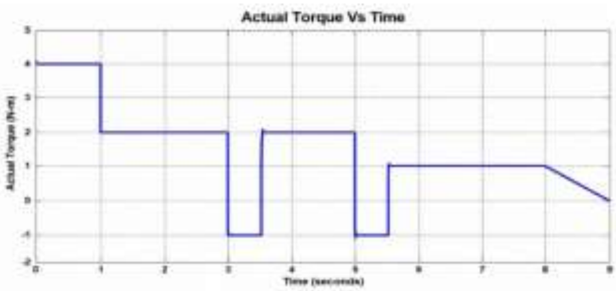


Fig 16 Actual Torque Of A Motor Vs Time

Fig 16 shows the actual electromagnetic torque response of the proposed MPC-controlled BLDC motor during four-quadrant operation. The motor initially develops approximately 4 N-m during 0–1 s to achieve rapid acceleration, followed by a steady torque of about 2 N-m during forward motoring. Negative torque is observed during 3–3.5 s and 5–5.5 s, indicating successful regenerative braking. Between these intervals, the motor operates with positive torque corresponding to the commanded operating conditions, and finally, the torque gradually decreases to zero between 8 s and 9 s, bringing the motor to a smooth stop. Although small torque overshoots are observed during commutation and operating-point transitions, the actual torque response follows the reference torque profile satisfactorily. From the waveform it is observed that stable motoring, effective regenerative braking and four-quadrant operation of the proposed MPC-based BLDC motor drive is achieved succesfully.

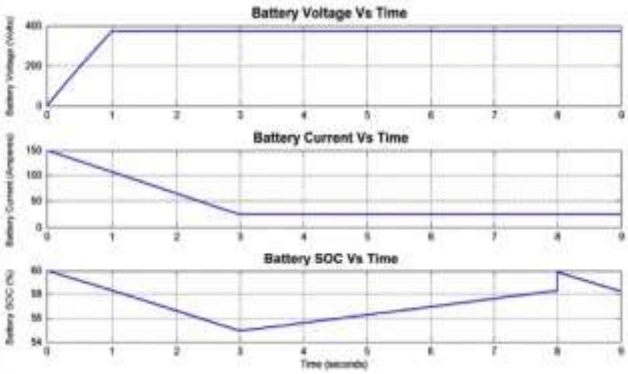


Fig 17 Battery Voltage, Current And SOC Vs Time

Fig 17 shows the battery voltage, battery current, and State of Charge (SOC) responses of the proposed BLDC motor drive during four-quadrant operation. During the initial acceleration period (0–1 s), the battery supplies a high current to meet the increased torque demand, resulting in a gradual decrease in SOC. During steady-state operation, the battery voltage remains nearly constant at approximately 375 V, while the battery current decreases with the reduced power demand.

During regenerative braking period, the battery voltage remains stable, whereas the SOC gradually increases, indicating successful recovery of braking energy and its storage in the Lithium-Ion battery. Overall, the proposed control strategy maintains a battery voltage stable, the battery current regulates according to the operating conditions, and battery energy utilization enhances through the effective regenerative braking.

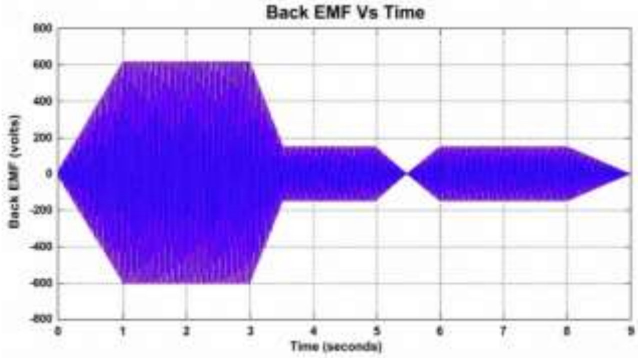


Fig 18 Back EMF Vs Time

Fig 18 shows the three-phase back-EMF of the proposed BLDC motor during four-quadrant operation. The back-EMF increases from zero during motor acceleration and remains nearly constant of ±620V during steady-state forward operation. As the motor speed decreases, the magnitude of the back-EMF also decreases around ±150V. During direction reversal, the polarity of the back-EMF changes, confirming successful reverse operation. Finally, the back-EMF gradually reduces to zero as the motor comes to rest. Since the back-EMF of a BLDC motor is directly proportional to rotor speed, the waveform closely follows the speed profile, thereby validating the effective speed regulation and successful four-quadrant operation of the proposed MPC-controlled BLDC motor drive.

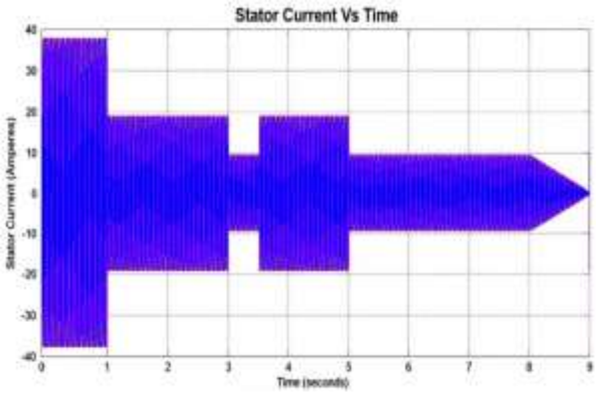


Fig 19 Stator Current Vs Time

Fig 19 shows the stator current of the proposed BLDC motor during four-quadrant operation. A high stator current is observed during the initial acceleration period around ±38A to produce the required starting torque. As the motor reaches steady-state operation, the current decreases to ±19A and remains nearly constant according to the load demand.

During deceleration and regenerative braking, the current magnitude reduces and reverses during the transition to reverse operation, confirming successful four-quadrant control. The stator current subsequently stabilizes during reverse motoring and gradually decreases to zero as the motor comes to rest. The waveform demonstrates effective current regulation and validates the stable operation of the proposed MPC-controlled BLDC motor drive under varying operating conditions.

C. CONCLUSION

This paper presented a Model Predictive Control (MPC)-based four-quadrant BLDC motor drive for electric vehicle applications. The proposed drive system integrates a lithium-ion battery, bidirectional DC–DC converter, Voltage Source Inverter (VSI), two PI controllers, and an MPC with a discrete PWM generator to achieve effective speed regulation and energy management. The PI controllers regulate the bidirectional DC–DC converter to maintain a stable DC-link voltage, while the MPC predicts the future motor current and determines the optimal switching action for the VSI.

Simulation results demonstrate successful operation of the BLDC motor in all four quadrants, including forward motoring, forward regenerative braking, reverse motoring, and reverse regenerative braking. The proposed controller provides accurate speed tracking with fast dynamic response, while maintaining stable DC-link voltage and effective current regulation under varying operating conditions. Although small torque ripples are observed during commutation and operating-point transitions, the overall torque response remains stable and satisfactory. Furthermore, regenerative braking enables the recovery of kinetic energy and improves battery energy utilization. These results confirm that the proposed MPC-based BLDC motor drive is an effective solution for high-performance electric vehicle applications.

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