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Four-quadrant operations and control of a three-phase BLDC motor for an electric vehicle

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Abstract

This project demonstrates the control of a brushless direct current (BLDC) motor in all four quadrants (forward/reverse motoring/braking) using a universal bridge. The output of the universal bridge is fed to drive the motor. During the motoring mode, buck operation through the universal bridge of the battery takes place, and during regenerative mode, the mechanical energy is converted into electrical energy and is stored in the same chargeable battery through the boost operation. This concept could be applied in an electric vehicle downhill run by controlling the speed in the gravitational action, where the speed becomes more than the reference speed. As the electric vehicle operates with frequent start/stop, the scheme proposes the recovery of energy for every stopping operation through regenerative braking. Also, when an electric vehicle (EV) is going downhill, the controlled speed provides energy return to the battery. MATLAB/Simulink software is used to verify the above operations.

***Keywords**:* BLDC (Brushless Direct Current motor); PI (Proportional Integration Control); EV (electric vehicle); EMF (electromotive force); FLC (fuzzy logic controller).

1. Introduction

In electric vehicles (EVs), several motor types and control systems are used. These systems vary in efficiency, control, and complexity. Some of the pre-existing systems include:

Brushed DC Motors: Utilized a commutator and brushes to manage current flow. It has a Simple control system and is relatively inexpensive. It needs Higher maintenance due to brush wear. It has lower efficiency and less precise control compared to BLDC motors.

Single-Quadrant DC Motors: These motors could operate in one direction and control speed, but lacked reverse and braking capabilities. These motors are Simple and cost-effective for applications with minimal control requirements. These motors have Limited functionality, requiring additional systems for reversing or braking.

Stepper Motors: These motors are controlled by digital pulses, providing precise position control without feedback systems. They have precise position control and easy integration with digital control systems. It has Limited torque and speed, making it less efficient for continuous rotation applications.

Hybrid Systems: This combines different motor types and control strategies to achieve desired performance. It increases complexity, cost, and potential for integration issues.

Chopper Controller for DC Motors: It varies the voltage supplied to a DC motor, enabling speed control. It is an improved efficiency over simple resistive control. It is Limited to single-quadrant operation unless combined with additional circuitry.

To address this problem with electric vehicles, this project proposes a simple four-quadrant operation in which the motor's energy is used to charge the battery during braking. This method of efficient power utilization can be achieved through a universal bridge. There is just one energy source, which the motor efficiently utilizes.

The most commonly used topology for a three-phase BLDC motor. The BLDC motor has a trapezoidal back EMF waveform. To maintain a constant power output, the current is injected during the 120 ° period of constant back EMF.

The injection current is controlled by two switches on different legs in the universal bridge. Therefore, at a time, only two switches operate. Unlike a DC motor, commutation in this case is controlled by switches. The current injection in each phase should be appropriately aligned with the back EMF to get the rotor flux and stator flux angle close to 90° for maximum torque production. The switching sequences of the MOSFET switches are shown in Fig. 2 for both forward motoring and reverse motoring. These three phases produce a constant DC voltage for 360° during regenerative braking. It is important to know the rotor position so that the stator winding is energized in sequence.

The rotor position can be detected using internal and external position sensors, or without them. In this project, hall sensors are used to detect the rotor position. These sensors are embedded in the stator, and according to the sensor output, the switches are triggered (Singh & Mishra, 2019).

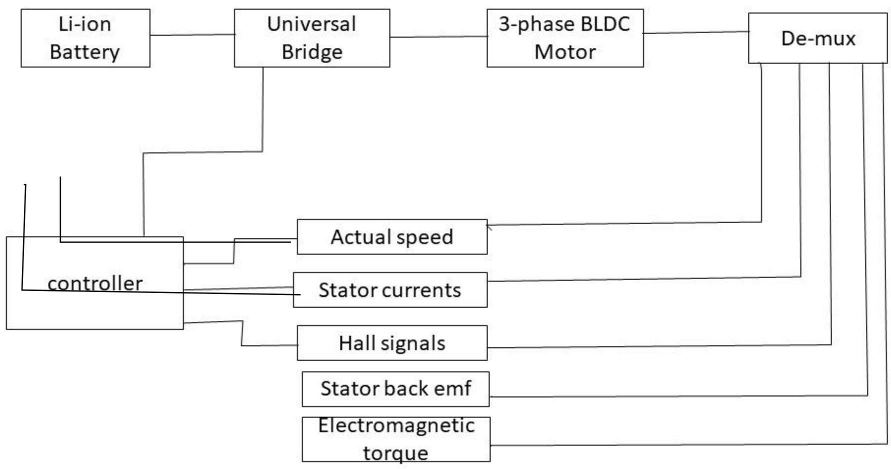

Figure 1: Block diagram representation of four-quadrant operation

The four-quadrant operation of the BLDC motor is depicted clearly in Fig. 1.1. In the first and third quadrants, both the torque and speed have the same sign, either positive or negative. The four-quadrant operation of the BLDC motor is slightly different, as the direction of rotation cannot be made opposite just by reversing the voltage polarity of the DC link, as in the case of the DC motor. To reverse the direction of rotation of the motor, the phase sequence of the BLDC motor has to change, as the voltage across the DC link is always positive, and therefore, the current is positive. To operate the motor in the third-quadrant phase sequence of a BLDC, the phase sequence should be reversed. This could be achieved by changing the switching sequence of the Universal bridge.

Braking is obtained through the universal bridge. The universal bridge operates in two modes: buck or boost mode. Motoring mode uses buck operation, and braking mode uses boost operation.

The logic diagram for the four-quadrant operation is shown in Fig. 1. When regenerative braking is required, the torque and speed commands are detected, and the gate pulses to the universal bridge switches are turned off (Abouseda et al., 2025; Nguyen et al., 2018).

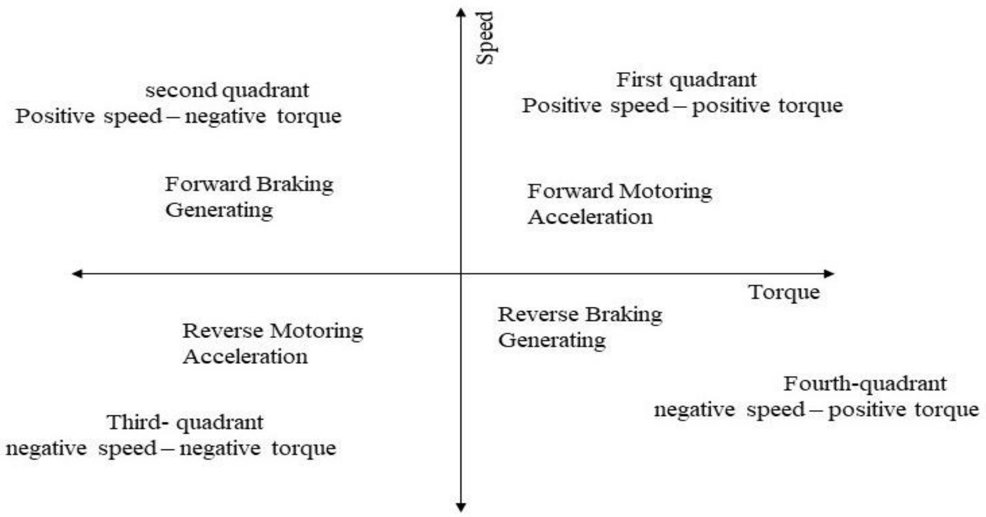

Figure 2: Four-quadrant operation

But this can happen only when the diodes (D) of universal bridge are forward biased this is achieved by reducing the dc-link voltage making it less than the rectified back EMF voltage which is an ideal case in absence phase resistance, with the presence of phase resistance the equation becomes, Once the diodes are forward biased, immediately the control is transferred to switch T2 which step up the voltage and charges the battery.

The control logic is elaborated. Switch T_2 is controlled via current control. During a vehicle's downhill run, the speed exceeds the reference speed (higher potential energy), which is converted to kinetic energy. To maintain the motor's reference speed, its kinetic energy could be returned to the battery.

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2. Modelling and Simulation

2.1 Three-Phase BLDC Motor

Brushless DC motors (BLDC) have been a much-focused area for numerous motor manufacturers as these motors are increasingly the preferred choice in many applications, especially in the field of motor control technology. BLDC motors are superior to brushed DC motors in many ways, such as the ability to operate at high speeds, high efficiency, and better heat dissipation. They are an indispensable part of modern drive technology, most commonly employed for actuation, machine tools, electric propulsion, robotics, computer peripherals, and electrical power generation. With the development of (Singh & Mishra, 2019) sensorless technology alongside digital control, these motors become more effective in terms of total system cost, size, and reliability (Ramu et al., 2025; Nguyen et al., 2018).

A brushless DC motor (known as BLDC) is a permanent magnet synchronous electric motor that is driven by direct current (DC) electricity, and it accomplishes electronically controlled commutation system (commutation is the process of producing rotational torque in the motor by changing phase currents through it at appropriate times) instead of a mechanically commutation system. BLDC motors are also referred to as trapezoidal permanent magnet motors.

Unlike a conventional brushed type DC motor, wherein the brushes make the mechanical contact with the commutator on the rotor so as to form an electric path between a DC electric source and rotor armature windings, a BLDC motor employs electrical commutation with a permanent magnet rotor and a stator with a sequence of coils. In this motor, the permanent magnet (or field poles) rotates, and the current-carrying conductors are fixed.

The armature coils are switched electronically by transistors or silicon-controlled rectifiers at the correct rotor position, so that the armature field is in space quadrature with the rotor field poles. Hence, the force acting on the rotor causes it to rotate. Sensors, or rotary encoders, are most commonly used to measure rotor position and are mounted around the stator. The rotor position feedback from the sensor helps to determine when to switch the armature current.

Hall sensors or rotary encoders are most commonly used to sense the rotor position and are mounted around the stator. The rotor position feedback from the sensor helps to determine when to switch the armature current.

This electronic commutation arrangement eliminates the commutator and brushes in a DC motor, resulting in more reliable, less noisy operation. Due to the absence of brushes, BLDC motors are capable of running at high speeds. The efficiency of BLDC motors is typically 85 to 90 percent, whereas brushed-type DC motors are 75 to 80 percent efficient. There is a wide variety of BLDC motors available, ranging from small power levels to fractional horsepower, integral horsepower, and large power levels.

2.2 Universal Bridge in Simulation

The Universal Bridge block implements the three-phase inverter in Simulink (up to 6 MOSFET/IGBT switches) (Ramu et al., 2025). It connects a DC source (or grid) to the BLDC motor model. In Ramu *et al.'s* model, the bridge "amplifies” the current delivered to the BLDC, and the speed regulator controls its switching frequency/firing pulses (Soni & Kumar, 2016). In practice, using the Universal Bridge block simplifies modelling various inverter topologies (diode or IGBT) in BLDC simulations.

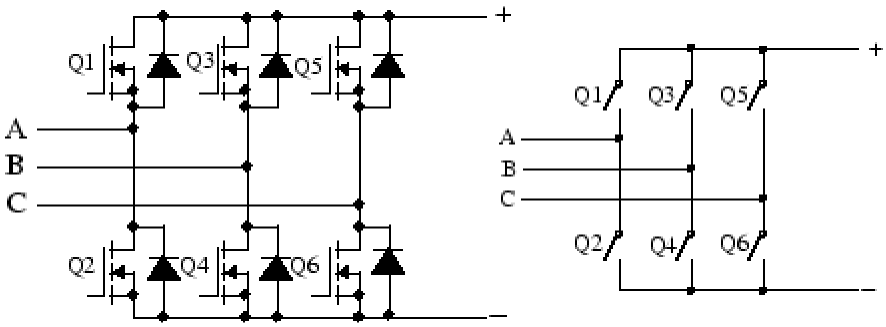

Figure 3: Block diagram of Universal Bridge

2.3 Gate driver

Amplify the control signals from the microcontroller or FPGA to drive the MOSFET or IGBT gates effectively. They ensure rapid switching and protect against voltage spikes.

2.4 Sensors

Position Sensors: Hall-effect sensors or encoder feedback to detect rotor position and commutation sequence.

Current Sensors: Measure motor phase currents to provide feedback for control algorithms and to protect against overcurrent conditions.

2.5 Modelling of Speed Controllers

The actual speed is compared with the reference speed, fed to the PID controller, and sent to output port 1 (gate). Output port 1 is a vector multiplier that multiplies the hall signals and feeds the current controller. Let this input be I^*_{abc}.

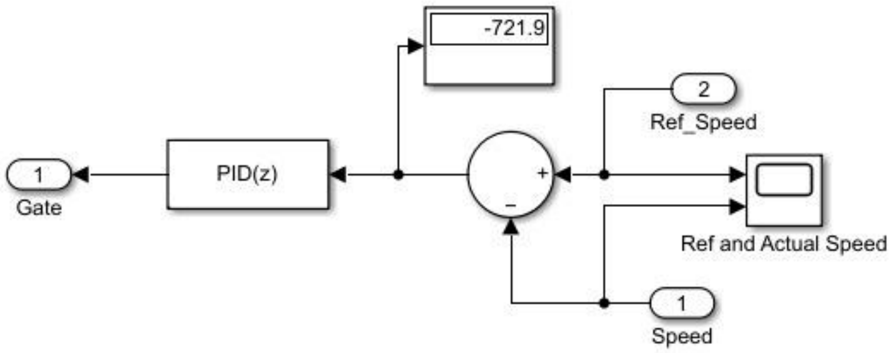

Figure 4: Simulation diagram of speed controller circuit

2.6 Modelling of the Current Controller

To regulate torque and limit currents, many BLDC systems use an inner current-control loop beneath the PID speed loop. Nguyen *et al.* (2018) describe a cascade control scheme: an inner PI current loop and an outer PI speed loop (Abouseda et al., 2025). In their Simulink design, DC-link current (sum of phase currents) is fed back as the control variable in the inner loop (Nguyen et al., 2018). The speed loop sets a torque (current) reference via a PI regulator, and the inner loop uses PWM switching (via the inverter) to track that current. This approach reduces the sensor count (using DC-link current instead of all phase currents) and is suitable for microcontroller implementation (Abouseda et al., 2025; Nguyen et al., 2018). The result is stable speed control with inherent current limiting. Other studies mention hysteresis or PWM current controllers, but the surveyed literature predominantly uses PI-type current regulators in the inner loop.

- Inner-Loop Current Control: The current controller ensures the actual motor current follows the torque command. Nguyen *et al.* implement this with PI control on the DC-link current (Nguyen et al., 2018). The PWM inverter (universal bridge) modulates the motor voltage to achieve the desired current.
- Cascade Architecture**:** These papers explicitly show a block diagram: DC source → Universal Bridge (PWM inverter) → BLDC motor; the speed PI controller outputs a

voltage (or torque) reference; the current PI controller (inner) drives PWM gating to regulate current (Abouseda et al., 2025; Nguyen et al., 2018).

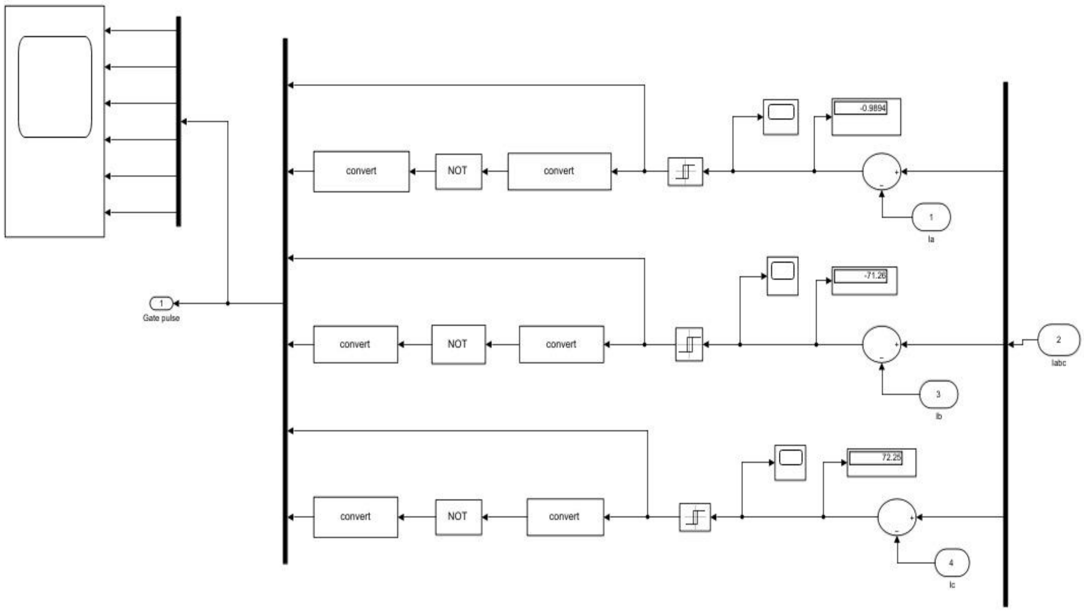

Figure 5: Simulation diagram of the current controller

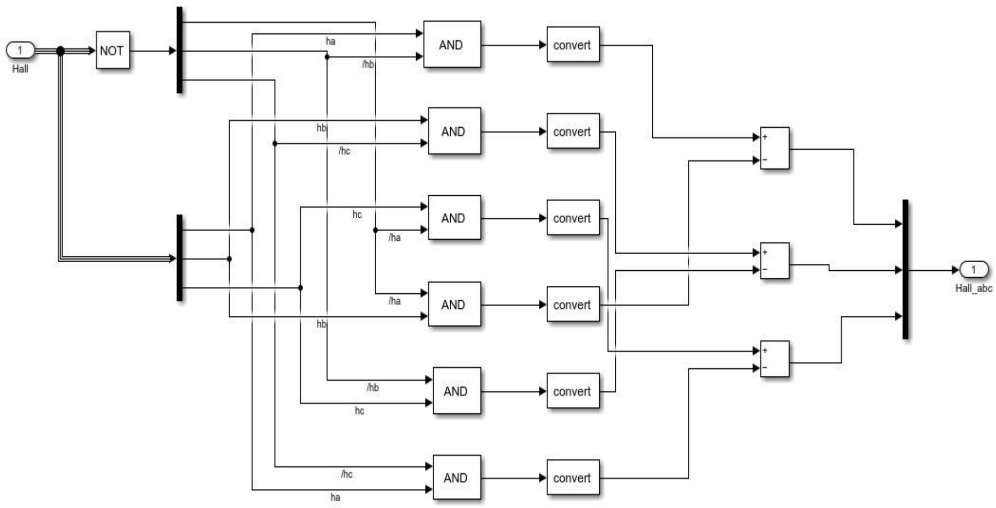

Figure 6: Simulation diagram of decoder circuit

The output I^*_{abc} is demuxed into three signals I*a, I*b, I*c, and compared with the stator back current Ia, Ib, Ic, respectively. The error signals are fed to relays, which generate 1 when the error is 0.001 and 0 when the error is -0.001. And NOT gates are used to generate a total of 6 signals, which are multiplexed to generate the gate signal.

2.7 Li-ion battery

A lithium-ion battery or Li-ion battery is a type of rechargeable battery. Lithium-ion batteries are commonly used for portable electronics and electric vehicles and are growing in popularity for military and aerospace applications. A prototype Li-ion battery was developed by Akira Yoshino in 1985, based on earlier research by John Goodenough, M. Stanley Whittingham, Rachid Yazami, and Koichi Mizushima during the 1970s–1980s, and then a commercial Li-ion battery was developed by a Sony and Asahi Kasei team led by Yoshio Nishi in the 1991s. In batteries, lithium ions move from the negative electrode through an electrolyte to the positive electrode.

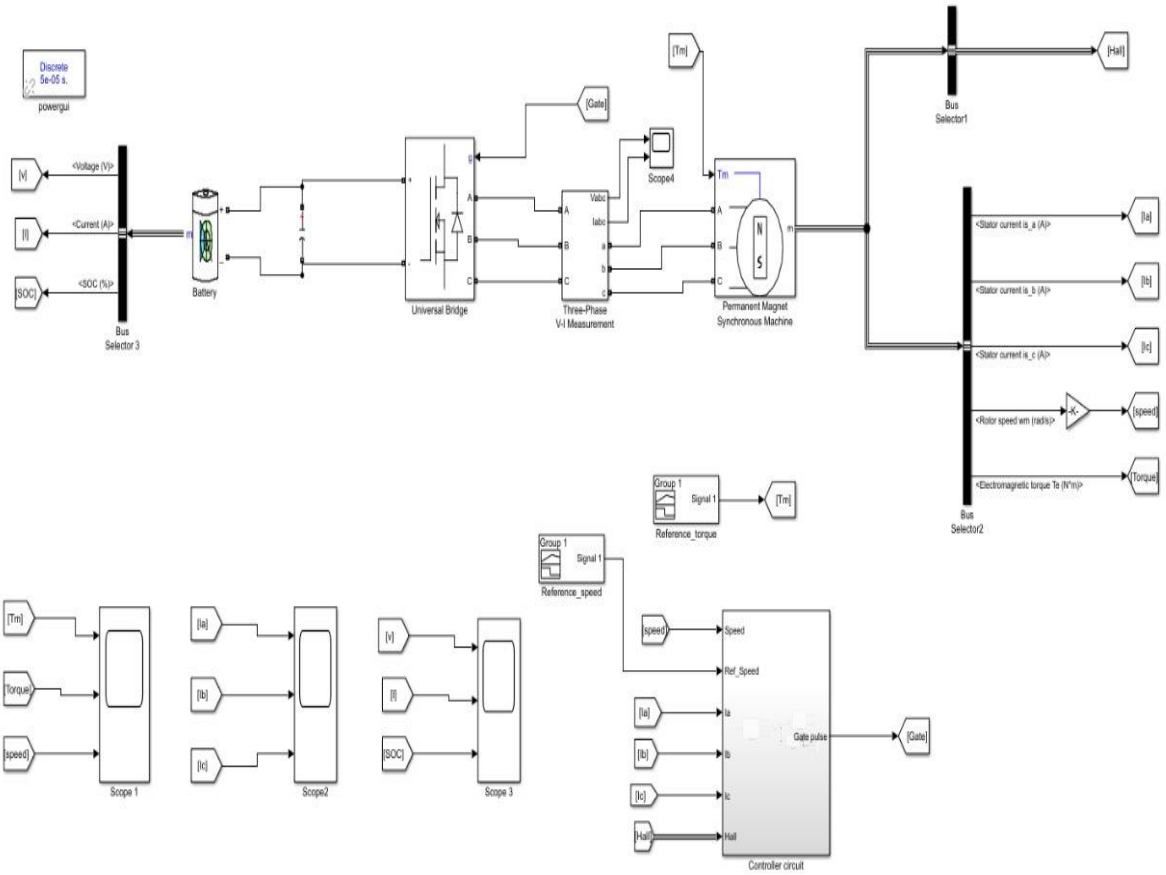

Figure 7: Overall simulation diagram

In the batteries, lithium ions move from the negative electrode through an electrolyte to the positive electrode during discharge, and back when charging. Li-ion batteries use an intercalated lithium compound as the positive electrode material and typically graphite as the negative electrode material. The batteries have a high energy density, no memory effect (except for LFP cells), and low self-discharge.

2.8 Overall Simulation Diagram

The figure below shows the overall simulation. We have provided the external torque and use the motor back emf and current for control. After 3 seconds of operation, the simulation results are displayed. The motor's steady-state operation in four quadrants is correctly depicted. The BLDC motor first operates in forward motoring mode for 0.1 to 0.75 seconds, followed by 0.75 to 1.25 seconds of forward braking to lower the speed from 2500 rpm to 1000 rpm. Then the motor runs in reverse monitoring mode for 1.25 to 1.75 seconds, and finally runs in reverse generating mode for 1.75 to beyond.

3) Result and Discussion

3.1 Current waveform

In the figure below, the current initially decreases due to the battery's internal resistance, then continues to rise during rheostatic acceleration in monitoring mode. During free-running time, there is less discharge due to the requirement for low torque. During breaking, the current flow from the motor to the battery is interrupted, so the graph goes down, and after some time, the battery gets charged again, and this goes continuously.

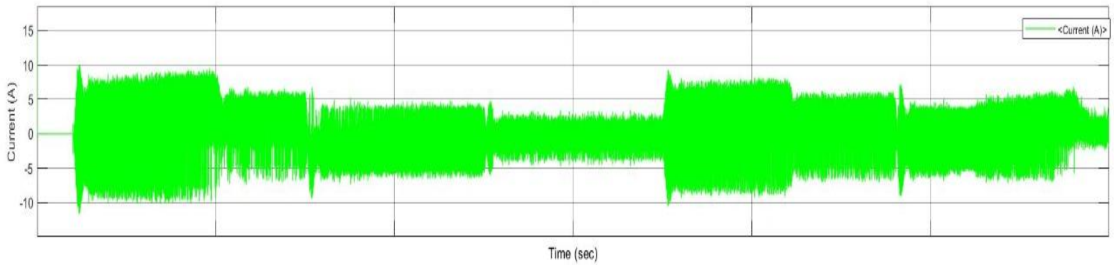

Figure 8: Waveform of current

3.2 Voltage waveform

This graph represents a waveform; a visual representation of how a signal changes over time. The horizontal axis (x-axis) indicates time in seconds, while the vertical axis (y-axis) represents voltage in volts. The blue waveform shows variations in the voltage amplitude (or strength) over the recorded time period. Initially, there is a burst of high activity with a dense, high-amplitude voltage, suggesting a strong or loud input. As time progresses, the voltage amplitude decreases, becoming flatter and less active. Later, there is another spike in activity, followed by a gradual decline again.

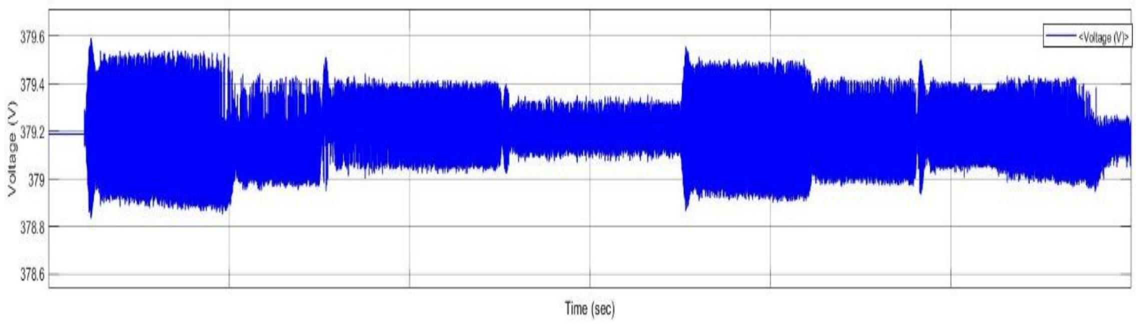

Figure 9: Waveform of voltage

3.3 Waveform of the SOC of the battery

In the figure below, in the first quadrant, the motor draws energy from the battery, so the battery's state of charge decreases. In second quadrant motor run in forward generating mode and generate the back emf and supplied the energy to the battery and the state of charge of battery increased, third quadrant, the motor run in reverse motoring mode and it consume the energy from the battery and soc of battery decreased and fourth quadrant the motor run in reverse braking generating mode and the soc of the battery increased.

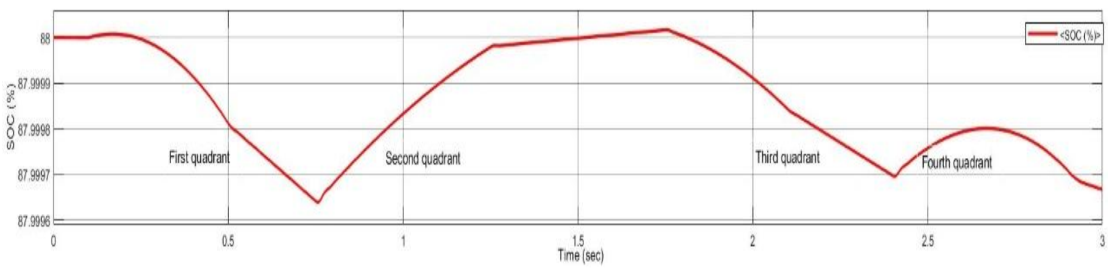

Figure 10: Waveform of the SOC of the battery

3.4 Waveform of speed and torque

Initially, the vehicle stops, and the speed and torque are zero. After the vehicle starts to run, the speed and torque of the motor increase and acquire a constant value. However, when the vehicle runs on a forward flat slope, the motor operates in forward generating mode, i.e., speed is positive and torque is negative, and both speed and torque decrease. When the vehicle moves in the backward direction, then the motor runs in the third quadrant, the speed and torque are negative, and the motor runs in reverse motoring mode. When the vehicle runs in a downward, backward direction, the motor runs in the fourth quadrant, i.e., speed is negative and torque is positive, and the speed decreases.

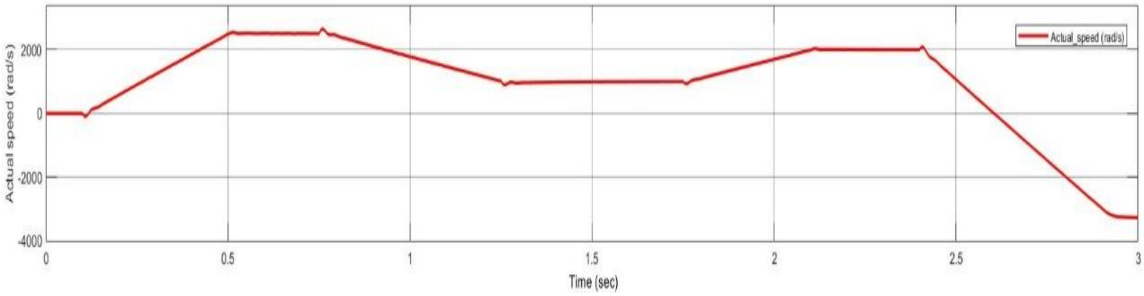

Figure 11: Waveform of actual speed

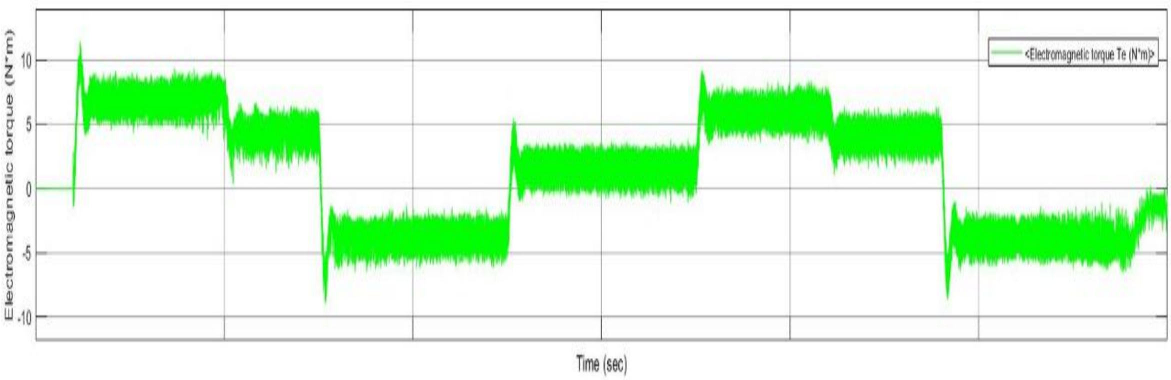

Figure 12: Waveform of actual torque

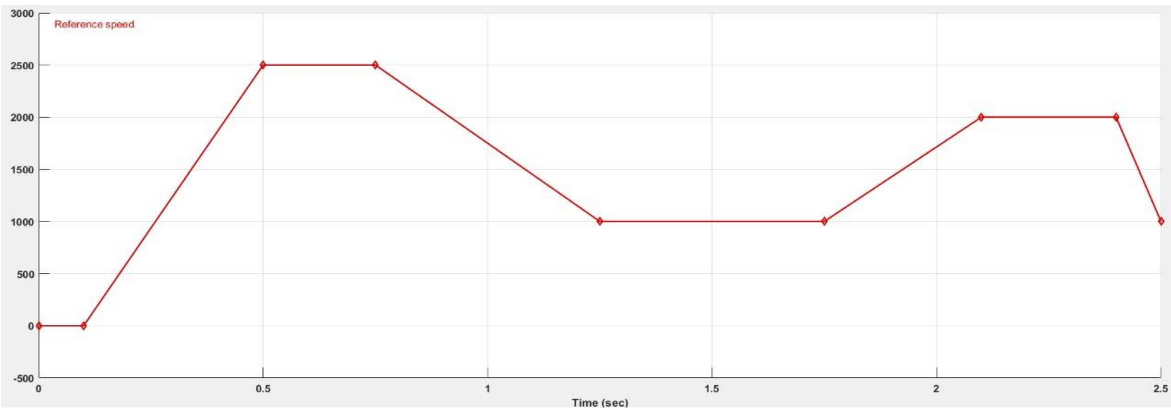

Figure 13: Waveform of reference speed

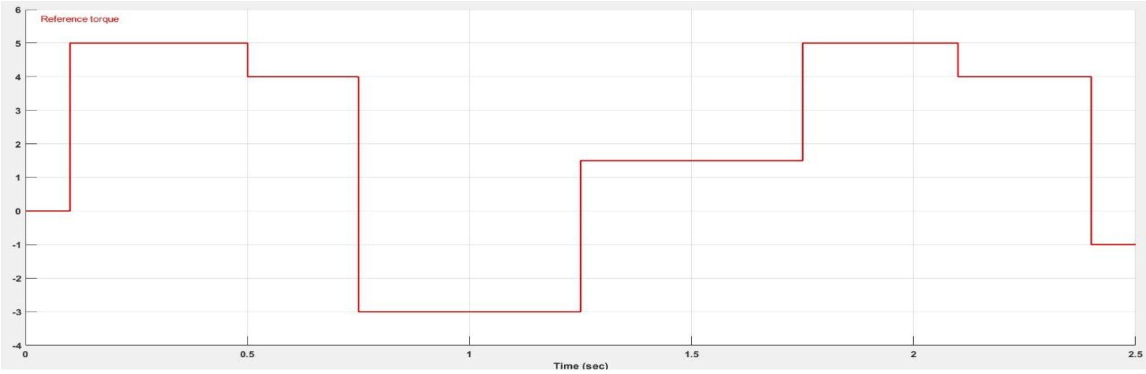

Figure 14: Waveform of reference torque

4. Conclusion

In this work, the four-quadrant operation of a three-phase BLDC motor was simulated for an electric drive system to achieve maximum efficiency while considering fuel constraints. The simulation showed that the motor could operate efficiently in all four quadrants using a simple closed-loop control system that required minimal hardware. During regenerative braking, the The motor successfully converted kinetic energy back into electrical energy, which was then used to recharge the battery through the universal bridge. This method proved particularly useful for electric vehicles operating on downhill slopes, helping control vehicle speed under gravity while simultaneously charging the battery. The simulation results from MATLAB/Simulink clearly showed the variations in voltage, current, state of charge (SOC), reference torque, electromagnetic torque, and actual speed, confirming the effectiveness of the proposed system. Overall, the study demonstrated that using a BLDC motor can significantly improve efficiency and energy recovery compared to conventional engines. Practical implementation of this system is currently underway to validate these findings under real-world conditions.

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Appendix-Data

Table A.i: Battery parameters

Battery Type	Lithium Ion
Nominal Voltage	350V
Maximum Capacity	100Ah
Exponential Voltage	378V
Initial State of Charge	88%
Cut-Off Voltage	262.5V
Fully Charge Voltage	407.4V
Nominal Discharge Current	44.5A

Table A.ii: PID controller parameters

Proportional	0.0855
Integral	0.471
Derivative	-0.00072
Filtration Coefficient	117.319

Table A.iii: Parameters of the motor

DC- link Voltage(V)	350
Rated Speed(rpm)	2500
PM Flux-linkage (Wb)	0.1194
Pole pair number	4
Phase Resistance(Ω)	0.0485
Phase Inductance(mH)	8.5