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Regenerative Braking of BLDC Motor in Electric Vehicle

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***Abstract*— This paper explores the implementation of regenerative braking in Brushless DC (BLDC) motors for electric vehicle (EV) applications. Regenerative braking harnesses the back electromotive force (EMF) of the motor during deceleration to recharge the battery, thereby extending the vehicle's range and improving overall efficiency. The study presents a detailed investigation into the development and testing of a control system for a BLDC motor operating in both motoring and regenerative braking modes. Utilizing a trapezoidal commutation strategy and a three-phase, two-level voltage source inverter, the system demonstrates efficient operation and energy recovery capabilities. Simulation results illustrate the transition between motoring and regenerative modes, highlighting the significant impact on torque, power, and current. The findings underscore the potential of regenerative braking in BLDC motors to enhance the performance and sustainability of electric vehicles.**

***Keywords*—Electric Vehicles (EVs), Regenerative Braking, BLDC Motor (Brushless DC Motor), PI Controller**

I. Introduction

The surge in electric vehicles (EVs) as eco-friendly transportation solutions has spurred interest in improving their efficiency and range. “Regenerative braking, a pivotal feature in EVs, efficiently converts kinetic energy into electrical energy during deceleration, extending driving range and reducing energy consumption”[8]. Brushless DC (BLDC) motors have gained popularity for EV propulsion due to their efficiency, reliability, and compact design, operating via electronic commutation for precise speed and torque control. “This paper investigates regenerative braking implementation in BLDC motors without dedicated DC-DC boost converters or ultra-capacitors. It begins with an overview mathematical modelling, and controller design for precise closed-loop speed and current control. Simulation results demonstrate smooth transition between motoring and regenerative modes, indicating regenerative braking's effectiveness for energy recovery and potential to enhance EV performance and sustainability”[8].

II. Modelling of BLDC Motor and Controller Design Page Layout

To achieve precise closed-loop control of the BLDC motor, the switching sequence of the semiconductor power devices is meticulously regulated so that it follows two phase conduction technique with trapezoidal commutation. Figure I illustrates a block diagram of this closed-loop speed and current control system for the BLDC motor. The control system employs a cascaded, dual closed-loop architecture for precise speed regulation. “The outer loop, designated as the speed control loop, functions at a slower rate. Here, the actual motor speed is measured and compared to the desired reference speed. This resulting speed error signal is fed into a proportional-integral (PI) controller. The output of the PI speed controller establishes the reference current for the inner current loop”[8]. This loop regulates the motor’s current to achieve the desired speed. The actual stator current is then compared to the reference current, generating a current error signal. This error is then processed by a hysteresis current controller. The hysteresis controller’s output generates the necessary gate pulses for the inverter’s MOSFETs, ultimately controlling the motor’s current based on the reference provided by the outer speed loop [7].

A. *Mathematical Modelling and Controller Design:*

The following sections delve into both the mathematical modelling of the BLDC motor and the design considerations for the PI speed controller and the hysteresis current controller. “At a time only two phases will be conducted out of three phases let phases A and C be conducted, applying KVL in this loop and writing equations in the s-domain (refer to Fig 2) .”[8]

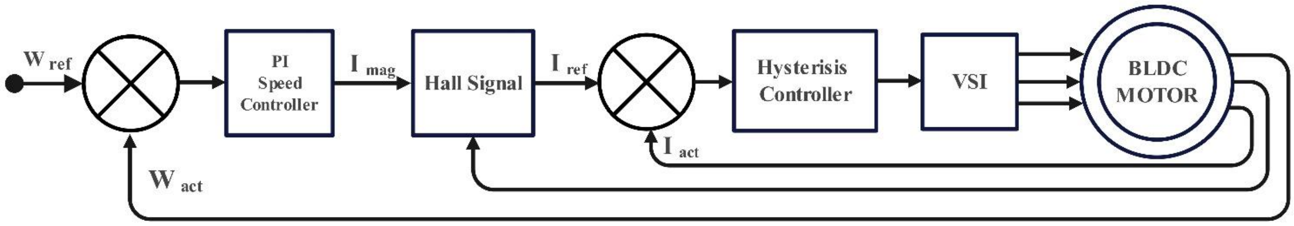

Figure 1Block Diagram of BLDC Motor Speed current Control System[8]

"In the s-domain, the input voltage of a BLDC motor is typically referred to as ' v_s', Applying Kirchhoff's Voltage Law (KVL) in a loop."[8]

$$v_s = (R_s + sL_s)I_{as} + e_{as} - e_{cs} \tag{1}$$

Assuming a Symmetrical motor i.e., $R_a = R_b = R_c = R$ and $L_a = L_b = L_c = L$.
Here $R_s = 2R$, $L_s = 2L$;

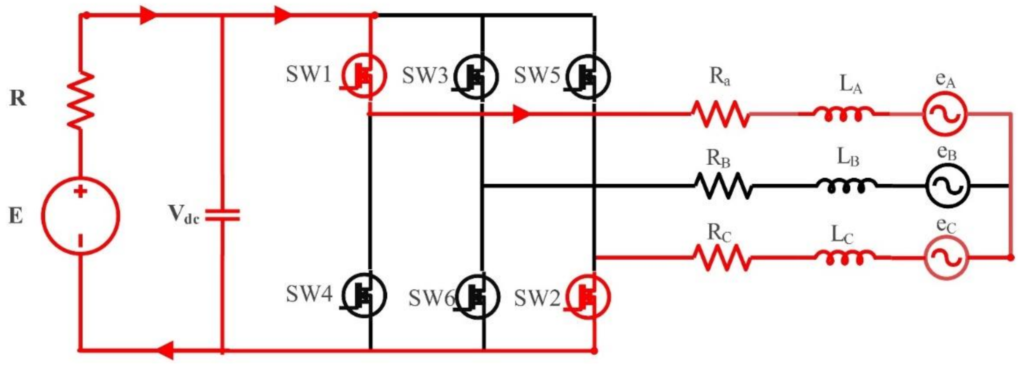

Figure 2 BLDC Motor Circuit When Phase A and C are Conducting [8]

$$e_{as} = -e_{cs} = K\omega_m$$
$$v_s = (R_s + sL_s)I_{as} + 2K\omega_m$$
$$v_s = (R_s + sL_s)I_{as} + 2K_b\omega_m \tag{2}$$

The electromagnetic torque (T_e) developed by the two-phase BLDC motor is given by.

$$T_e = 2KI_{as}$$

And also,

$$T_e = \omega_m(sJ + B)$$

So

$$K_b I_{as} = \omega_m(sJ + B)$$

$$\omega_m = \frac{K_b I_{as}}{(sJ+B)} \tag{3}$$

Plant transfer would be = $\frac{\omega_s}{v_s}$ .we can break it as

$$\frac{\omega_s}{v_s} = \frac{\omega_s}{I_{as}} \times \frac{I_{as}}{v_s}$$

From equation (2) and (3),

$$v_s = (R_s + sL_s)I_{as} + K_b\left(\frac{K_b I_{as}}{(sJ + B)}\right)$$

$$\frac{I_{as}}{v_s} = \frac{(sJ + B)}{(R_s + sL_s)(sJ + B) + {K_b}^2}$$

$$\frac{I_{as}}{v_s} = \frac{(sJ+B)}{s^2 L_s J + s(JR_s + BL_s) + ({K_b}^2 + R_s B)} \tag{4}$$

From equation (2)-

$$\frac{\omega_s}{I_{as}} = \frac{K_b}{(sJ+B)} \tag{5}$$

Plant transfer function from equation (5) and (4)

$$P_s = \frac{\omega_s}{I_{as}}$$

$$P_s = \frac{K_b}{(sJ+B)} \times \frac{(sJ+B)}{s^2 L_s J + s(JR_s + BL_s) + (K_b{}^2 + R_s B)} \quad (6)$$

"To analyse and design the control system effectively, it's essential to consider the transfer function of the speed controller. This function mathematically describes the relationship between the controller's input (typically the reference speed) and its output (usually the control signal sent to the inverter). We will denote the speed controller transfer function as"[8]

$$G_s = K_p + \frac{K_i}{s}$$

$$G_s = \frac{K_p(s + K_i)}{s}"$$

Now for K_p and K_i $values$,

$$P_s G_s = \frac{K_b}{(sJ+B)} \times \frac{K_p(s + \frac{K_i}{K_p})}{s}$$

"After solving: Kp = 4 and K_i = 9.84

To achieve precise control of the motor's stator current, a closed-loop current regulation strategy is employed. This involves comparing the reference current generated by the outer speed controller to the actual stator current measured from the motor. The difference between these two currents termed the current error, is subsequently fed into the hysteresis current controller. The hysteresis controller then utilizes a pre-defined tolerance band (as described in [7]) to generate the switching signals that control the inverter's MOSFETs. By adjusting the gate voltages of these MOSFETs based on the current error and the tolerance band, the hysteresis controller regulates the stator current, ultimately ensuring the motor operates at the desired speed dictated by the outer speed control loop"[8]

III. SIMULATION

"In the MATLAB/Simulink environment, the BLDC motor load is connected to a three-phase two-level Voltage source inverter and controller in a closed-loop System. Based on the BLDC motor domain listed in Table I, two PI controllers are planned, one for speed regulation and the other for handling current"[8]. Figure 3 is the main MATLAB Model of the BLDC Motor with an incorporated Brake Pedal to make the transition from Motoring mode to Braking mode. Figure 4 is a sub-system model that illustrates the Simulink block diagram of Controller and Inverter control for a closed-loop BLDC motor. Figure 5 represents a Hall decoder(sensor) subsystem that decodes the BLDC motor Position Wave and generates the EMF Wave and after that, the generated EMF wave is fed into the EMF to Gate pulse Generator which is depicted by Figure 6. Figure 7 shows the Brake pedal Subsystem when the brake is applied it signals 1 which in turn switches the motor mode to regenerative mode. Through simulation, the operation of the BLDC motor shifts from motor mode to regenerative mode using the brake pedal at t=3 sec, remaining in regenerative mode until t=5 sec, and subsequently returning to motoring mode after t=5 sec.. During the motoring operation, the brake pedal becomes inactive, and the electric motor retains its rated speed of 1455 rpm. Upon depression of the brake pedal, the system transitions from motoring mode to regenerative braking mode. Releasing the brake pedal at any vehicle speed triggers a return to motoring mode, with the motor aiming to achieve the reference speed of 1455 rpm.

Table I
Key Specification for BLDC Motor[8]

S no.	Domain	Magnitude
1	La	50e-6 H
2	Ra	0.25 Ohm
3	Torque Constant	15279 N-m
4	B	0.000492 Nms
5	J	0.0002 J Kg m2
6	Power Rating	2 Kw

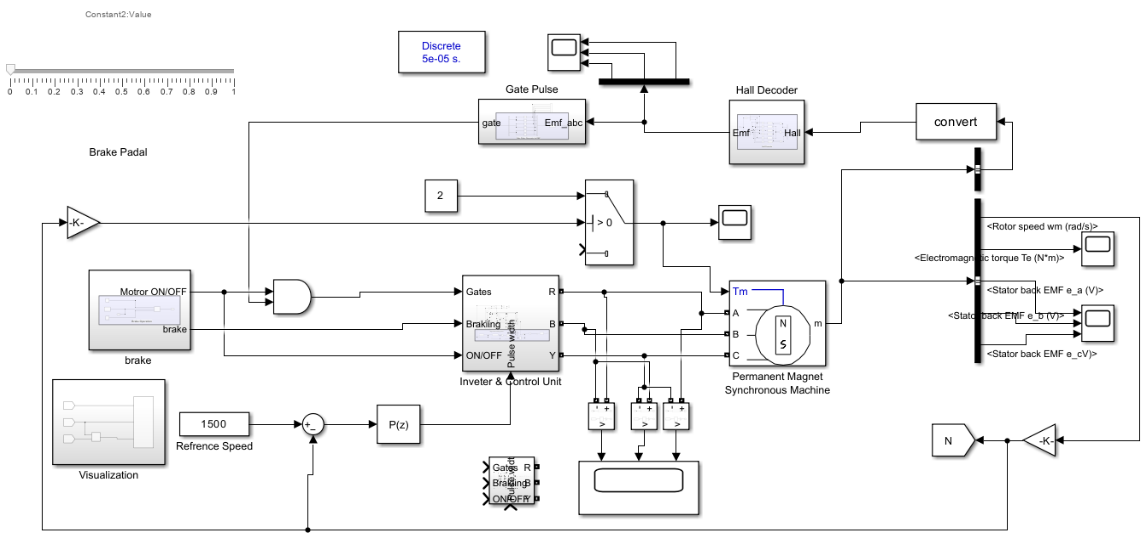

Figure 3 MATLAB model of BLDC Motor with Brake Pedal

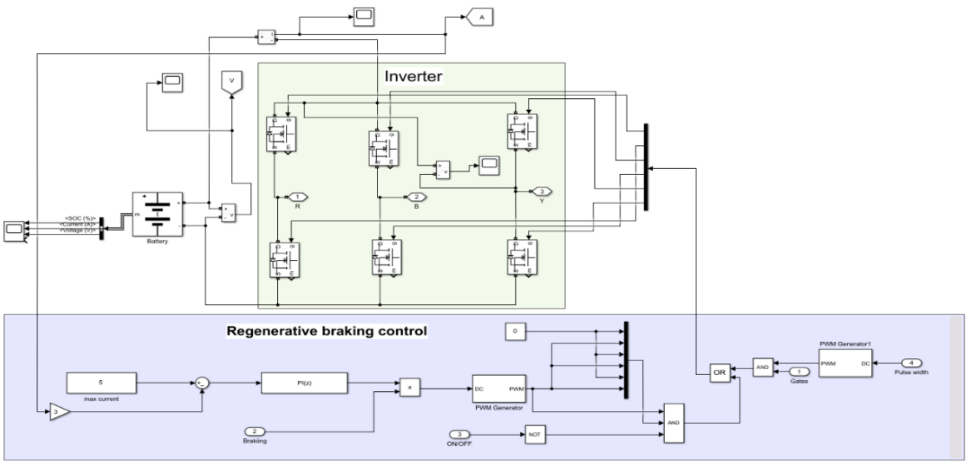

Figure 4 Controller and Inverter Sub-System in Matlab

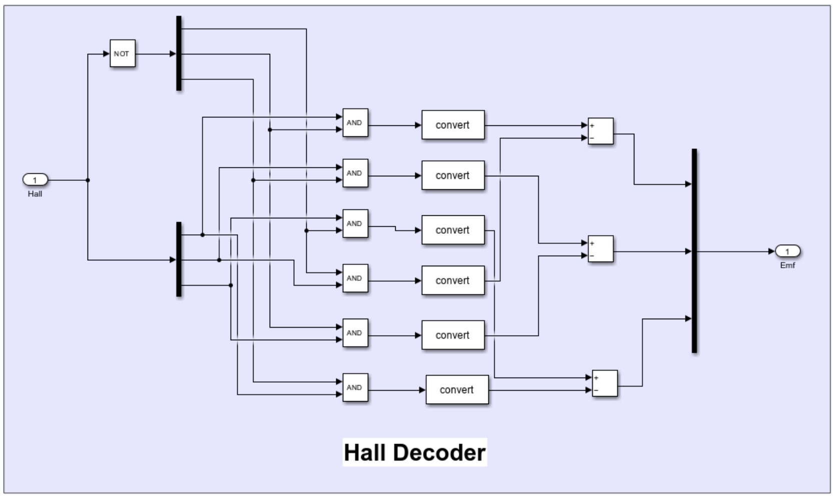

Figure 5 Hall Sensor Sub-system

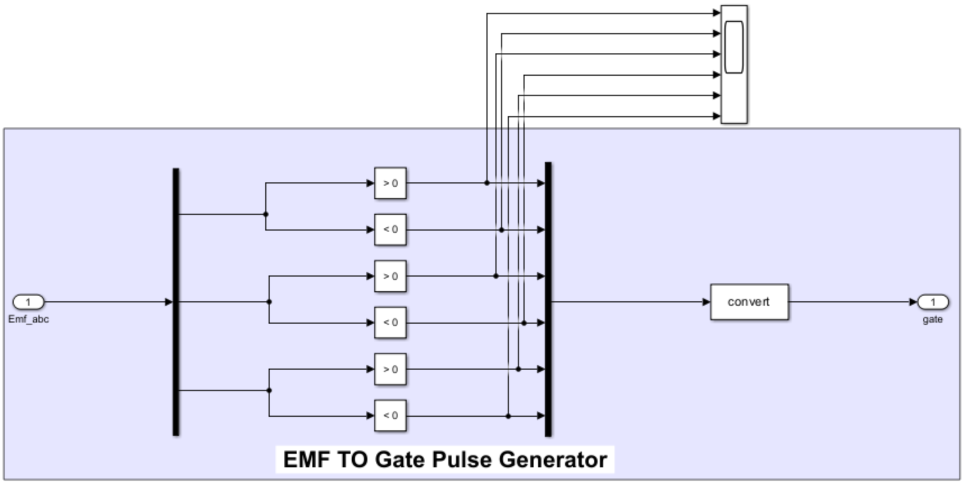

Figure 6 EMF to Gate Pulse Generator Subsystem

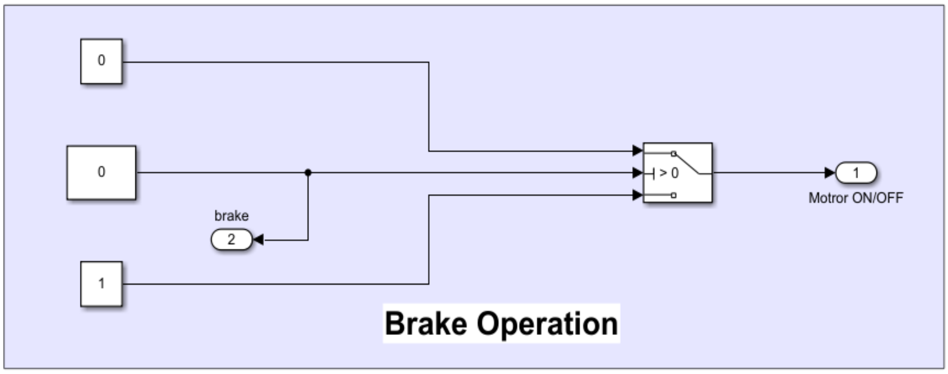

Figure 7 Brake Pedal Sub-System

IV. RESULT

In Figure 9, the waveforms display the electromagnetic torque, demonstrating the BLDC motor's shift between motoring and regenerative modes .When in motoring mode the motor gives a rated torque of 2 nm and when brakes are applied it produces a reverse torque of 7.6 nm. The simulation runs for 8 seconds. Brakes are applied at the 3-second mark and released at the 5-second mark.

A. Motoring to Braking mode (at 3 seconds)

- Speed: The motor’s speed gradually decreases to zero at 3 seconds when the brake pedal is pressed, indicating a transition from motoring to braking mode (Fig. 8).
- Electromagnetic Torque: During this period, the electromagnetic torque becomes negative. This signifies that the motor acts as a generator, converting kinetic energy from the vehicle’s motion into electrical energy.
- Battery Power: The negative battery power during braking confirms that the generated electrical energy is fed back to the battery for charging (regeneration).

B. Braking to Motoring (at 5 seconds and beyond)

- Speed: Following brake release at 5 seconds, the motor’s speed progressively increases, signifying a return to motoring mode.
- Electromagnetic Torque returns to its motoring mode characteristics with positive torque propelling the vehicle forward.
- Battery Power: This waveform will also return to its motoring mode characteristics, positive battery power indicating energy consumption from the battery.

Since back EMF is directly proportional to speed in BLDC motors, a decrease in speed leads to a corresponding decrease in back EMF. This relationship is evident in Figure 8, where the back EMF waveforms for all three phases (A, B, and C) decline as the motor slows down during braking.

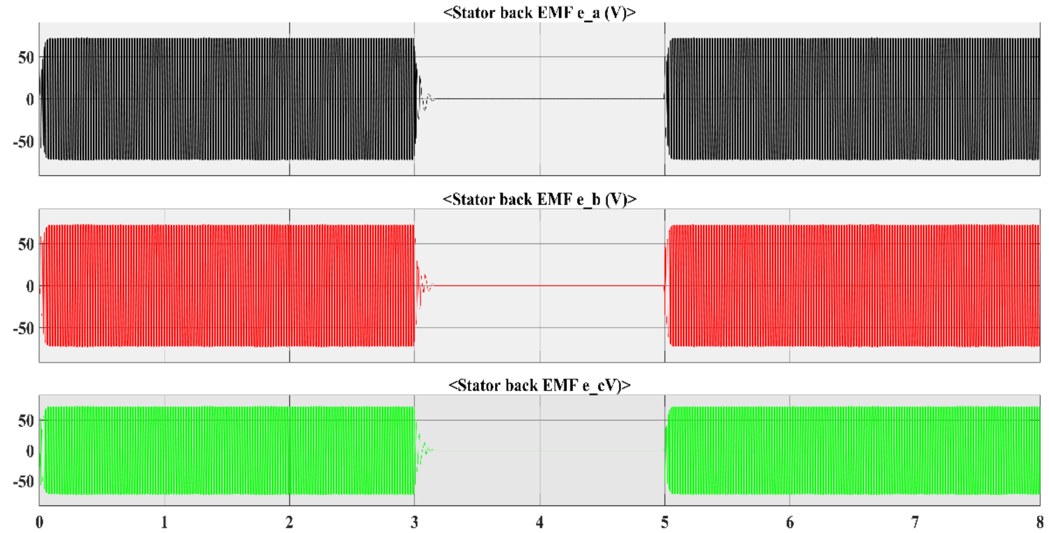

Figure 8 Waveforms depicting the Back-EMF of Phases A, B, and C .

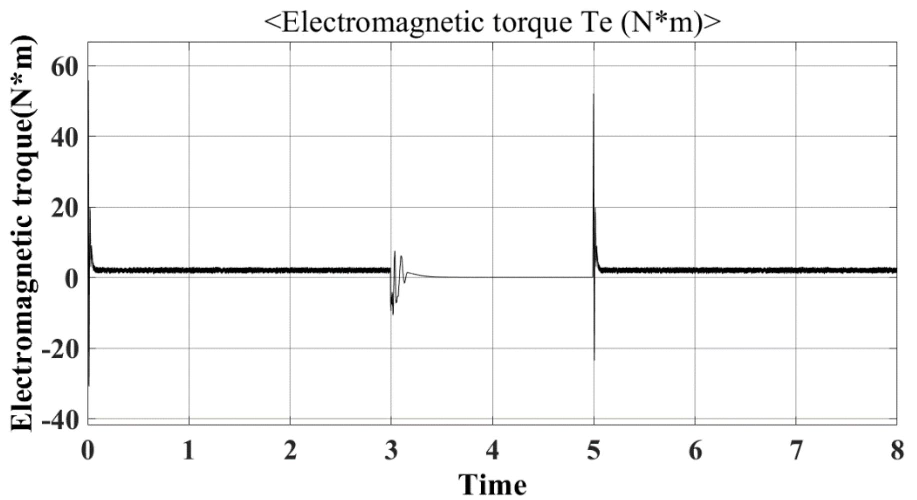

Figure 9 Waveform of Electromagnetic Torque (break applied at 3 sec and removed at 5sec)

When brakes are applied at time =3 sec the speed of the motor gradually declines to 0 from its normal speed of 1455 rpm and current also becomes -4 amp and a negative power of 252 W is generated (figure 10).

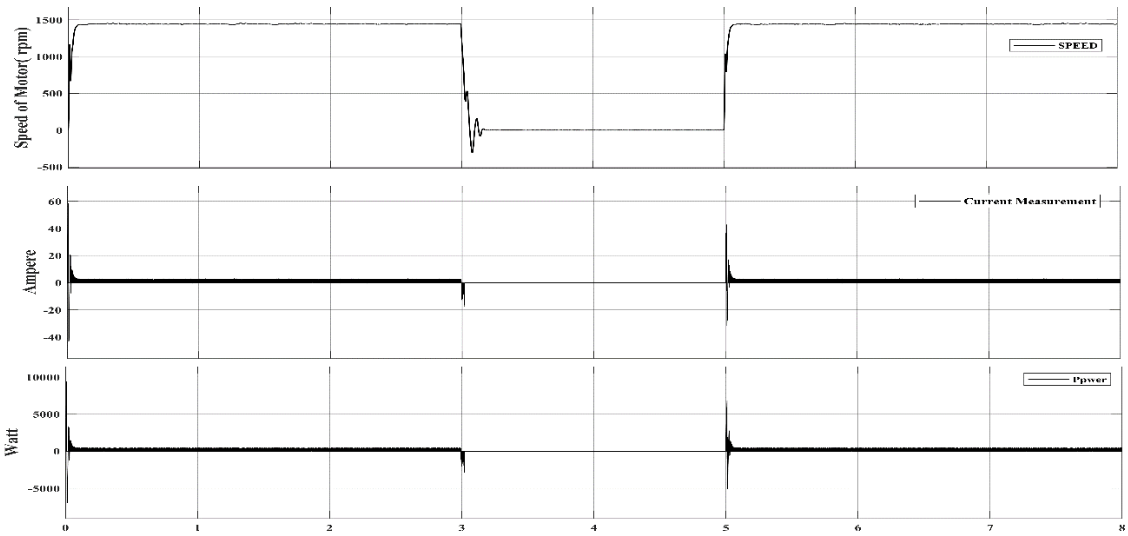

Figure 10 Waveform of Speed , Battery Current and Battery power

V. CONCLUSIONS

This study explores the utilization of regenerative braking with BLDC motors in electric vehicles . The analysis focuses on BLDC motor operation in regeneration mode with trapezoidal commutation and presents a numerical motor design to facilitate controller development. The paper concludes by showcasing simulation results of power, current and electromagnetic torque an d that of back emf of phase A,B,C which are directly proportional to speed of motor that illustrates the closed-loop behaviour of the BLDC motor in both motor and regeneration braking behaviour.

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