

# Optimization of BLDC Motor Controller for Enhancing Battery Performance

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**Abstract**— Brushless DC (BLDC) motors are extensively used in electric two- and three-wheelers due to their superior electrical and mechanical performance, making them ideal for lightweight electric vehicles. The speed control of BLDC motors can be broadly classified into scalar and vector control techniques. Among scalar approaches, trapezoidal control is the simplest, where motor windings are sequentially energized. However, such methods tend to be less efficient and exhibit reduced performance at higher speeds. In contrast, Field Oriented Control (FOC), a vector-based technique, generates three-phase sinusoidal signals whose frequency and amplitude can be precisely controlled. This method offers improved torque and speed regulation, higher efficiency, faster dynamic response and a wider operational speed range. This paper focuses on optimizing BLDC motor speed control to enhance battery utilization. MATLAB simulations are conducted to evaluate the proposed optimization technique and the system's performance is assessed through the battery's State of Charge (SoC). Particle Swarm Optimization (PSO) is employed to fine-tune the controller gain parameters for improving the system efficiency.

**Index Terms**—first term, second term, third term, fourth term, fifth term and sixth term.

## I. INTRODUCTION

In electric bikes, BLDC motors are generally favoured over other motor types due to their superior efficiency and performance [1]. The speed regulation of these motors is managed by a BLDC motor controller. Over time, several control techniques have been developed for BLDC motor speed control, including voltage control, frequency control, pulse width modulation (PWM) control, and field-oriented control (FOC). Typically, Hall-effect sensors are used to detect the rotor's position, and this information is sent to the controller to generate appropriate PWM signals for speed regulation. More recently, sensorless control methods have also been introduced [2]. The BLDC motor control strategies are classified into trapezoidal and sinusoidal control methods. The design of a BLDC motor controller includes essential hardware components such as sensor data acquisition units, driver circuits, a three-phase inverter, and the main control logic. On the software side, key aspects include analog-to-digital conversion (ADC) sampling, PWM generation, current sensing, and battery protection response [3]. A smart motor controller for an e-bike incorporates all these features along with an efficient speed control strategy. The inclusion of regenerative braking further enhances the system's overall energy efficiency [4].

The important aspect of optimizing an EV controller is to implement efficient control algorithms that can balance the power demands of the vehicle's various systems, such as the motor, battery, and auxiliary systems. Another important consideration is to optimize the battery management system to ensure that the battery is operating within safe limits and that the battery life is maximized. Also, the EV controller can be optimized by implementing advanced regenerative braking strategies that can recover energy from the vehicle's kinetic energy during braking and store it back into the battery. This can significantly improve the driving range of the vehicle and reduce the overall energy consumption.

The performance of EV controllers always comes under scrutiny when it comes to optimization. The user's expectation of electric vehicles is simply, 'minimum cost maximum output'. To meet this expectation many researchers, designers and engineers have deployed various optimization techniques for battery management and speed control. This paper describes the optimization of electric bike controllers deploying FOC control to increase its traveling range per charging of battery.

## II. BLDC MOTOR SPEED CONTROL

The speed control techniques of BLDC motor are broadly categorized as scalar control and vector control techniques. The scalar techniques are conventional PWM control, trapezoidal control and sinusoidal control [5]. These techniques have drawbacks of low efficiency and unstable performance at higher speeds and higher torque ripples. A significant effort is also seen in identifying the sources of torque ripples and mitigation techniques for BLDC motors. An auto-tuning method of [6] is dedicated to reduce the vibrations and noise using repetitive control parameters. A comparison of trapezoidal back EMF control and FOC [8] has shown decrease in torque ripple with FOC. The dynamic response and current harmonics are found to be primary advantages of FOC control [9]. The speed control techniques of BLDC motor are broadly categorized as scalar control and vector control techniques. The scalar techniques are conventional PWM control, trapezoidal control and sinusoidal control [5]. These techniques have drawbacks of low efficiency and unstable performance at higher speeds and higher torque ripples. A significant effort is also seen in identifying the sources of torque ripples and mitigation techniques for BLDC motors. An auto-tuning method of [6] is dedicated to reduce the vibrations and noise using repetitive control parameters. A comparison of trapezoidal back EMF control and FOC [8] has shown decrease in torque ripple with FOC. The dynamic response and current harmonics are found to be primary advantages of FOC control [9].

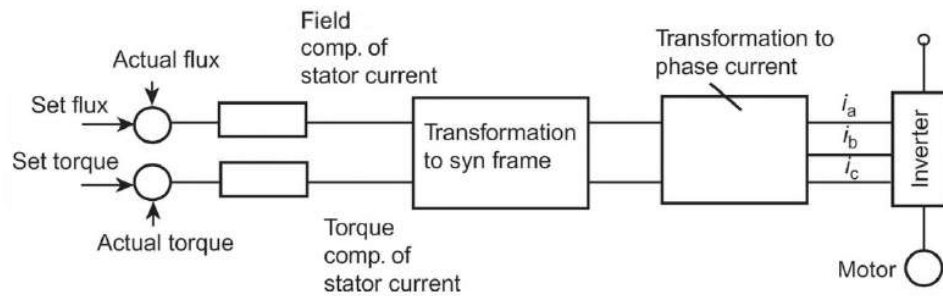


Figure 1 Implementation of field-oriented control

Figure 1 illustrates the fundamental concept of field orientation. In this method, the actual rotor flux value is compared with a reference flux, and the resulting error is used to regulate the direct-axis (d-axis) current component. Typically, this component is kept constant to ensure a steady rotor flux. The quadrature-axis (q-axis) current component is adjusted based on the error obtained by comparing the actual torque with the reference torque. Since these components exist in a synchronously rotating reference frame, achieving decoupling between the flux-producing and torque-producing components of the armature current requires establishing a reference coordinate system. The electrical quantities are then transformed into this rotating reference frame and subsequently back to the stator frame [10–13].

The mathematical equations for armature winding voltages of a BLDC Motor are expressed as

$$V_a = Ri_a + L \frac{di_a}{dt} + e_a$$

$$V_b = Ri_b + L \frac{di_b}{dt} + e_b$$

$$V_c = Ri_c + L \frac{di_c}{dt} + e_c$$

Where,  $i_a, i_b$  and  $i_c$  = motor current

$V_a, V_b, V_c$  = Terminal phase voltages

$R = R_a = R_b = R_c$  = Armature resistance

$L = L_a = L_b = L_c = L_s - L_m$  = Armature inductance

$L_s$  = Self-inductance of armature

$L_m$  = Mutual-inductance of armature

$e_a, e_b, e_c$  = motor back EMF

In matrix form,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R + \Delta L & 0 & 0 \\ 0 & R + \Delta L & 0 \\ 0 & 0 & R + \Delta L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Where,

$$\Delta = \frac{d}{dt}$$

The back EMF of BLDC motor has trapezoidal nature of waveform due to permanent magnets. Thus the back EMF equations can be written as,

$$e_a = k_E \phi(\theta) \omega(t)$$

$$e_b = k_E \phi(\theta - 2\pi/3) \omega(t)$$

$$e_c = k_E \phi(\theta + 2\pi/3) \omega(t)$$

Where,  $k_E$  is back EMF constant and  $\omega$  is the actual rotor speed.  $\theta$  is the rotor position angle.

When a PI controller is treated as a proportional controller, the integral component helps eliminate steady-state or offset errors, while the derivative component minimizes time delays and improves system response. The general expression representing the controller's operation in a parallel configuration is given as:

$$PI \text{ output} = k_p \cdot error + k_i \cdot error$$

The fitness function for the Particle Swarm Optimization (PSO) algorithm is determined based on the reduction of the error between the desired and actual speeds of the BLDC motor. It is expressed as the difference between the reference speed ( $\omega_{ref}$ ) and the actual motor speed ( $\omega_{actual}$ ).

$$e(t) = \omega_{ref} - \omega_{real}$$

The cost function for PSO with integral time square error as the objective for fast convergence is written as,

$$ITSE = \int_0^{\infty} t |e(t)|^2$$

$$cost \text{ function} = minimize(ITSE)$$

### III. OPTIMIZATION OF BLDC MOTOR CONTROLLER

Field-Oriented Control (FOC) is a highly efficient method for controlling electric motors. It's particularly popular for applications requiring precise torque and speed control, such as electric vehicles, robotics, and industrial automation. FOC can already achieve high efficiency, but optimization can further reduce energy consumption by minimizing losses in the motor and inverter. Optimized FOC [17] can improve the accuracy of torque and speed control, which is critical for applications requiring precise positioning or motion control. It can make the motor control system more adaptable to changes in load, temperature, or other environmental factors.

Particle Swarm Optimization (PSO) is a metaheuristic optimization technique inspired by the behaviour of bird flocks and fish schools. It can be effectively applied to optimize the control parameters of a BLDC motor for

speed control [18]. PSO can find near-optimal solutions even for complex and non-linear problems. The goal is to minimize the error between the desired speed and the actual speed of the motor. The flowchart of PSO algorithm is shown in figure 2.

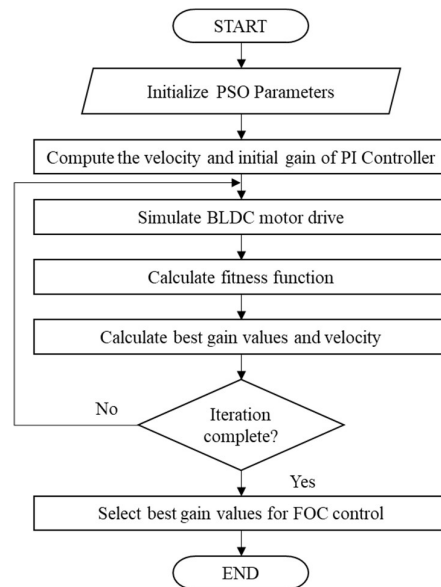


Figure 2: flowchart of PSO algorithm

#### IV. SIMULATION AND RESULTS

The proposed system is simulated by using MATLAB Simulink. To simulate the incline and decline of the road conditions, the load on the motor is changed and its effect on the motor speed is observed. Also. The state of charge of the battery is monitored for knowing the effective energy usage for running the motor. The figure 3 shows the MATLAB model of BLDC motor controller with optimized FOC using PSO.

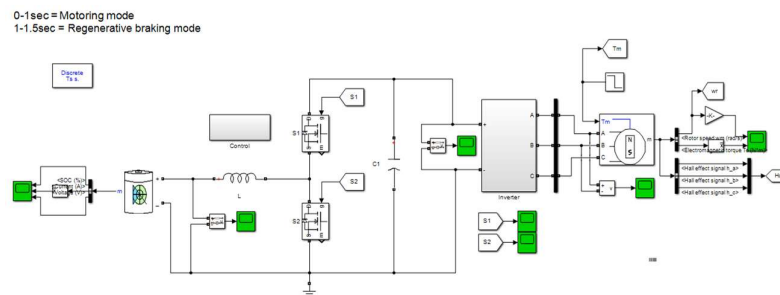


Figure 3: BLDC Motor Controller

The simulation is executed for a total duration of 1.5 seconds. Within this period, the system operates in motoring mode from 0 to 1 second, followed by regenerative mode from 1 to 1.5 seconds. The results show that variations in the reference torque are accurately tracked, ensuring effective speed regulation. The reversal of torque signifies that the motor transitions into generator mode, indicating that active power is being fed back from the motor. The results of motor speed control are shown in figure 4. The graph shown that the speed of the vehicle is controllable to the set point. During the time interval, the speed of vehicle was set at 5 KMPH. At  $t = 0.5$  second, the reference speed was changed from 5 to 10 KMPH. The achieved speed clearly shows the effectiveness of the control scheme.

In figure 5, the graph of actual motor speed in RPM and motor torque is shown. The speed changes and the torque values are indicated at the step change points of second and 1 second. At  $t = 1$  second, the torque value of reversed and made negative. The negative value of the torque indicates that the motor has entered into the

regenerative braking mode. In this mode the electrical power is generated by the BLDC motor and is converted into DC through the rectifier diodes of the inverter bridge.. The battery voltage, current and state of charge are shown in figure 6. At the end of the simulation cycle the battery SOC is noted to be 79.88% and with optimization the SOC is recorded to be 79.94% as seen in figure 7.

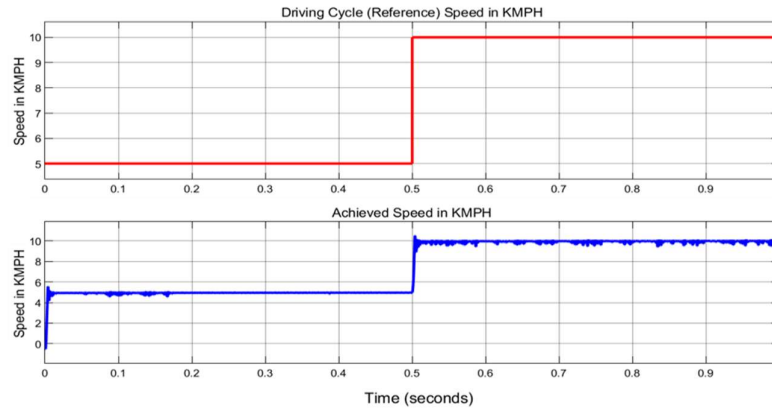


Figure 4: reference speed and actual speed of BLDC motor in motoring model

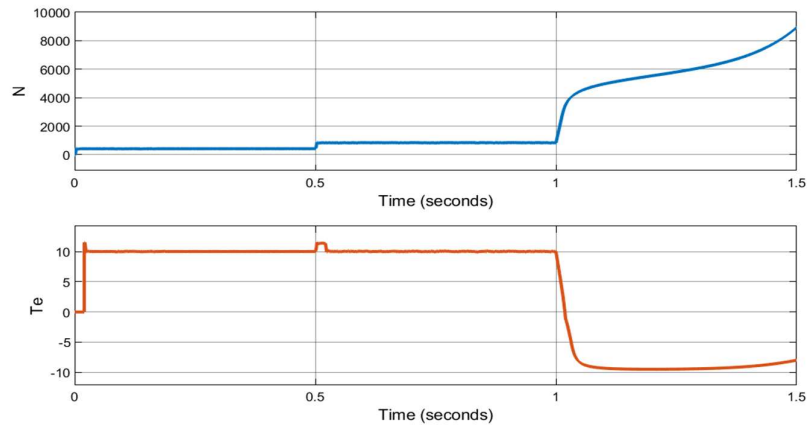


Figure 5: speed and torque of BLDC motor in motoring mode and regenerative braking mode

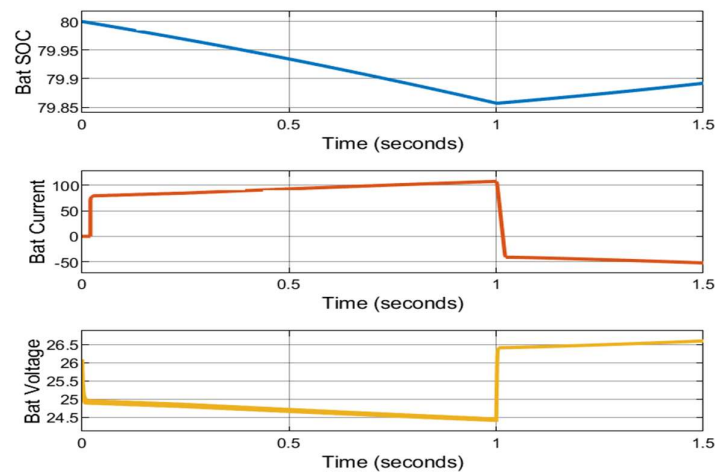


Figure 6: battery SOC, current and voltage without optimization

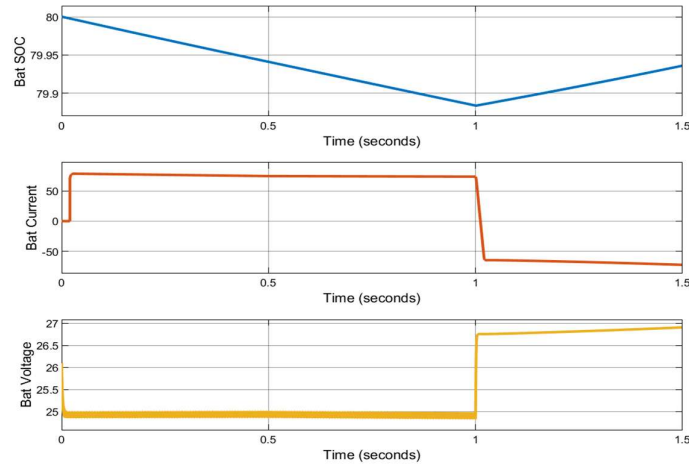


Figure 7: battery SOC, current and voltage with optimization

## V. CONCLUSION

This paper discusses the optimization of EV controller for improving the travel range of electric vehicle. The optimization of speed control is achieved through hill climbing algorithm. The regenerative braking is integrated with EV controller through a bidirectional DC – AC converter which is controlled in closed loop manner to control the BLDC motor speed in motoring mode and boost the voltage obtained through regenerative braking and bringing it to a level of the battery charging voltage. Upon comparing the performance of the optimized system with regular system, it is seen that the state of charge of the battery at the end of simulation cycle is more than that of the non-optimized system.

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