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Comparative Analysis of PWM and Sliding Mode Control for Speed Regulation in BLDC Motors

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***Abstract*— Brushless Direct Current (BLDC) motors are widely employed in industrial and automotive applications due to their high efficiency, compact size and superior dynamic performance over conventional DC and PMDC motors. Precise speed regulation of BLDC motors is essential for ensuring optimal performance under varying load and operating conditions. This paper presents a comparative analysis of Pulse Width Modulation (PWM) control and Sliding Mode Control (SMC) techniques for speed control of BLDC motors. A detailed mathematical model of the BLDC motor is developed, and both control strategies are implemented and tested under identical simulation conditions. The performance analysis is conducted for evaluation of rise time, steady state error, overshot in speed response during transient and steady state. The speed response analysis is also conducted for load change and change in reference speed during acceleration and deceleration of motor. The MATLAB simulation results are presented which indicates superior performance of SMC technique over PWM control with PI controller. The PWM-based control approach has ease of implementation whereas SMC shows ability to handle system uncertainties, parameter variations and external disturbances.**

***Keywords*— BLDC Motor, Pulse Width Modulation, Sliding Mode Control, Speed Control, dynamic response, steady state analysis.**

I. INTRODUCTION

BLDC motors have become integral to contemporary industrial systems ranging for electric vehicles, aerospace technologies and advanced medical devices. Their widespread adoption is largely attributed to advantages such as high power density, an excellent torque-to-weight ratio, and minimal maintenance needs when compared to conventional brushed motors [1]. Despite these benefits, achieving accurate control of speed and torque remains challenging because of the motor’s nonlinear characteristics and the requirement for precise electronic commutation. Conventionally, Pulse Width Modulation (PWM) has been employed as a primary control strategy, owing to its straightforward design and compatibility with digital control platforms for regulating the effective voltage supplied to the motor windings [2].
The PWM remains the most widely adopted technique in industrial and consumer electronics due to its cost-effectiveness and architectural simplicity.

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The fundamental principle is to vary the duty cycle of the voltage pulses applied to the stator windings to regulate the average DC bus voltage and thereby controlling the motor speed and torque [3]. In a typical six-step commutation sequence, PWM signals are applied to the power electronic switches (MOSFETs) to maintain the desired rotor velocity. The performance of PWM control is heavily dependent on the switching frequency; higher frequencies reduce current ripples but increase switching losses, necessitating a careful trade-off in inverter design [4].

Modern advancements in PWM control have moved beyond basic voltage scaling to more sophisticated schemes like Space Vector Pulse Width Modulation (SVPWM) and Current-Controlled PWM. SVPWM, in particular, has gained traction for its ability to provide better bus voltage utilization and reduced total harmonic distortion (THD) compared to traditional sinusoidal PWM [5]. The integration of PWM with Proportional-Integral-Derivative (PID) controllers allows for closed-loop speed regulation. However, researchers have noted that traditional PWM-PID frameworks often struggle with the non-linearities of BLDC motors, such as back-EMF fluctuations and torque ripples during commutation, which has led to the exploration of hybrid PWM techniques and fuzzy-logic enhancements to improve transient response [6]. Despite the emergence of advanced non-linear controllers, PWM control persists as the industry benchmark because of its ease of implementation on low-cost microcontrollers and digital signal processors. Its deterministic nature and predictable EMI (Electromagnetic Interference) profile make it ideal for mass-produced applications like home appliances and small-scale robotics [7].

While PWM-based proportional-integral (PI) control offers a straightforward approach, it often struggles with parameter variations and external disturbances, leading to performance degradation in dynamic environments. To address these limitations, researchers have increasingly turned toward robust control strategies, such as Sliding Mode Control (SMC). SMC is a non-linear control technique known for its exceptional insensitivity to modelling uncertainties and load fluctuations [8]. By forcing the system state onto a predefined sliding surface, SMC ensures stability and rapid response, making it an attractive alternative for high-performance BLDC motor drives where reliability is paramount [9].

Unlike traditional linear controllers, SMC is characterized by its high durability and resistance to external load variations, system disturbances, and internal parameter fluctuations [10]. By enforcing the system state onto a predefined sliding manifold, the controller ensures that the motor's speed and torque responses follow command trajectories with a low dependency on the exact mathematical motor model [11].

Despite its robustness, the primary challenge cited in the literature for conventional SMC is the chattering phenomenon in the control output caused by the discontinuous nature of the signum function [12]. To mitigate this, recent studies have explored advanced variants such as Fractional-Order Sliding Mode Control (FOSMC) and Higher-Order SMC. For instance, FOSMC optimized via genetic algorithms has been shown to significantly reduce integral time absolute error in speed tracking compared to conventional designs [13]. The application of second-order sliding mode observers allows for accurate back-EMF estimation, which is critical for sensor less BLDC operations where reliability and cost-reduction are required [14]. More complex architectures, including nested non-singular terminal sliding mode controllers and PID-nested surfaces, have been proposed to achieve finite-time convergence while remaining virtually chattering-free [15]. These innovations ensure that SMC remains a superior choice for mission-critical applications like electric vehicles and aerospace systems, where transient stability and robustness against dynamic perturbations are essential [16].

This paper evaluates the performance of PWM and SMC control strategies through MATLAB simulation. By analyzing metrics such as settling time, overshoot, steady-state error, current and torque ripples under varying load conditions, this paper aims to provide a comprehensive framework for selecting the most effective control methodology for advanced BLDC motor systems.

A. Control Techniques

PWM Control

For speed control of the BLDC motor speed control the basic technique is the adjustment of the voltage or current supplied to the stator windings, typically via PWM. The core equations involve electrical, electromechanical, and control domains.

In case of a DC motor, the back-EMF (E) induced in a winding is proportional to rotor speed (ω):

$$E_b = K_e \omega \quad \dots (1)$$

Where, K_e = back-EMF constant (V·s/rad).

For BLDC motor, the voltage equation for one phase is:

$$V = E_b + IR + L\frac{di}{dt} \quad \dots (2)$$

Where, V = applied voltage, R = phase resistance, L = phase inductance.
In the steady state, the equation (2) becomes,

$$V = E_b + IR \quad \dots (3)$$

The electromagnetic torque is given as

$$\tau_e = k_t I \quad \dots (4)$$

Where, K_t = torque constant and for BLDC motor, for BLDC motor, $k_t = k_e$
The motor accelerates against load torque (T_L) and friction:

$$\tau_e = J\frac{d\omega}{dt} + B\omega + \tau_L \quad \dots (5)$$

where: J = rotor inertia, B = viscous friction coefficient.
At steady state,

$$\tau_e = B\omega + \tau_L \quad \dots (6)$$

The equation of PWM output voltage (Vavg) in the form of duty cycle D and input voltage V_{DC} is,

$$V_{avg} = D.V_{DC} \quad \dots (7)$$

Therefore, equation (3) can be written as,

$$V_{avg} = K_e\omega + \frac{\tau_e}{k_t}R \quad \dots (8)$$

From (6) and (7)

$$D.V_{DC} = K_e\omega + \frac{B\omega + \tau_L}{k_t}R \quad \dots (9)$$

Solving equation (9) for speed,

$$\omega = \frac{D.V_{DC} - \frac{\tau_L}{k_t}R}{K_e + \frac{BR}{k_t}} \quad \dots (10)$$

The values of B and τ_L are small and if neglected, equation (10) becomes,

$$\omega = \frac{D.V_{DC}}{K_e} \quad \dots (11)$$

In equation (11), the values of VDC and Ke are constant. Hence, the speed of BLDC motor can be controlled by controlling the duty cycle of PWM waveform.
A PI controller is often tuned to adjust the duty cycle based on speed error (ω_e)

$$\omega_e = \omega_{reference} - \omega_{actual} \quad \dots (12)$$

The PI controller output i.e. duty cycle is hence computed as,

$$D = k_p\omega_e + k_i\int \omega_e dt \quad \dots (13)$$

Where, Kp and Ki are PI controller gains.

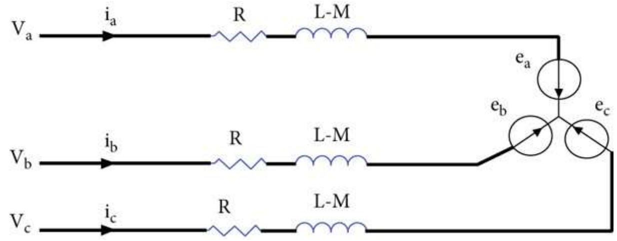

Figure 1. Equivalent circuit of BLDC motor

SMC Control of BLDC Motor

SMC is a robust control technique that drives the system state toward a predefined sliding surface and maintains it there despite uncertainties/disturbances.

For BLDC motor speed control, SMC ensures the rotor speed (ω) tracks a reference speed (ωref) under load torque variations and parameter uncertainties.

The BLDC motor acceleration is defined in equation (5) as, $\tau_e = J\frac{d\omega}{dt} + B\omega + \tau_L$

Rewriting for dynamics, $J\frac{d\omega}{dt} + B\omega = \tau_e - \tau_L$ … (14)

The torque τ_e is controlled via the *q*-axis current: $\tau_e = k_t i_q$ … (15)

The torque constant kt is defined as

$$k_t = \frac{3}{2}P\lambda_m \quad \ldots (16)$$

Where, P = no. of pole pairs λ_m = flux linkage

For sliding mode control, the speed error e is $e = \omega_{reference} - \omega_{actual}$ … (17)

The sliding surface s combines error and it's integral for zero steady-state error:

$$s = e + k_i\int_0^t e\,dt \quad \ldots (18)$$

Where, k_i is the tuning gain

The time derivative of sliding surface is,

$$\dot{s} = \dot{e} + k_i e \quad \ldots (19)$$

At zero reference,

$$\dot{e} = -\omega_{actual} \quad \ldots (20)$$

$$\therefore \dot{s} = -\omega_{actual} + k_i e \quad \ldots (21)$$

From the motor model of equation (14),

$$\dot{\omega} = \frac{k_t i_q - \tau_L - B\omega}{J} \quad \ldots (22)$$

$$\therefore \dot{s} = -\left[\frac{k_t i_q - \tau_L - B\omega}{J}\right] + k_i e \quad \ldots (23)$$

The control law of SMC has two components as equivalent control ($i_{q\ eq}$) which maintains time derivative of sliding surface zero under steady state conditions and switching control ($i_{q\ sw}$) which rejects disturbances and uncertainties

Equating equation (23) to zero and solving for equivalent control

$$0 = -\left[\frac{k_t i_{q\ eq} - \tau_L - B\omega}{J}\right] + k_i e \quad \ldots (24)$$

$$i_{q\ eq} = \frac{J}{k_t}\left[k_i e + \frac{B\omega}{J}\right] = \frac{Jk_i}{k_t}e + \frac{B}{k_t}\omega \quad \ldots (25)$$

The switching control is defined as

$$i_{q\ sw} = \frac{K}{k_t}.sgn(s) \quad \ldots (26)$$

Where, K = gain and sgn (s) is signum function

The quadrature axis reference current equation hence becomes,

$$i_q^* = i_{q\ eq} + i_{q\ sw} = \frac{Jk_i}{k_t}e + \frac{B}{k_t}\omega + \frac{K}{k_t}.sgn(s) \quad \ldots (27)$$

The stability analysis of this control law can be done with Lyapunov function as,

$$V = \frac{1}{2}s^2 \quad \ldots (28)$$

Differentiating with respect to time

$$\dot{V} = s\dot{s} = s\left[-\left[\frac{k_t i_q - \tau_L - B\omega}{J}\right] + k_i e\right] \quad \ldots (29)$$

Substitute $i_q = i_q^*$,

$$\dot{V} = s\left[-\frac{k_t}{J}\left(\frac{J k_i}{k_t}e + \frac{B}{k_t}\omega + \frac{K}{k_t}.sgn(s)\right) + \frac{B\omega}{J} + \frac{\tau_L}{J} + k_i e\right] \quad \ldots (30)$$

$$\dot{V} = s\left[-\frac{\tau_L}{J} - \frac{K}{J}.sgn(s)\right] \quad \ldots (31)$$

$$\dot{V} = -\frac{K}{J}|s| - \frac{\tau_L}{J}|s| \quad \ldots (32)$$

For sliding condition of $\dot{V} < 0$,

$$K > |\tau_L| + \eta \quad \ldots (33)$$

This ensures guaranteeing convergence to s = 0 when $\dot{V} < -\frac{\eta}{J}|s|$

B. Simulation and Results

The MATLAB Simulink model is built for speed control of BLDC motor with PWM Control and SMC control. The simulation results are analysed for speed tracking, response to reference speed change, torque ripples and dynamic speed characteristics. The system specifications are mentioned in table 1. The same specifications are used for both speed control techniques.

TABLE I: SYSTEM SPECIFICATIONS

Parameter	Details
DC Source	Battery – 48V, 20Ah
BLDC Motor Characteristics	Inductance = 8.5mH, Resistance = 0.05Ω, Poles = 4, Rated Torque = 2 NM
Inverter	Three phase full bridge
Feedback	Hall sensor
Switching frequency	10kHz
Filter	Inductor – 2.6 mH

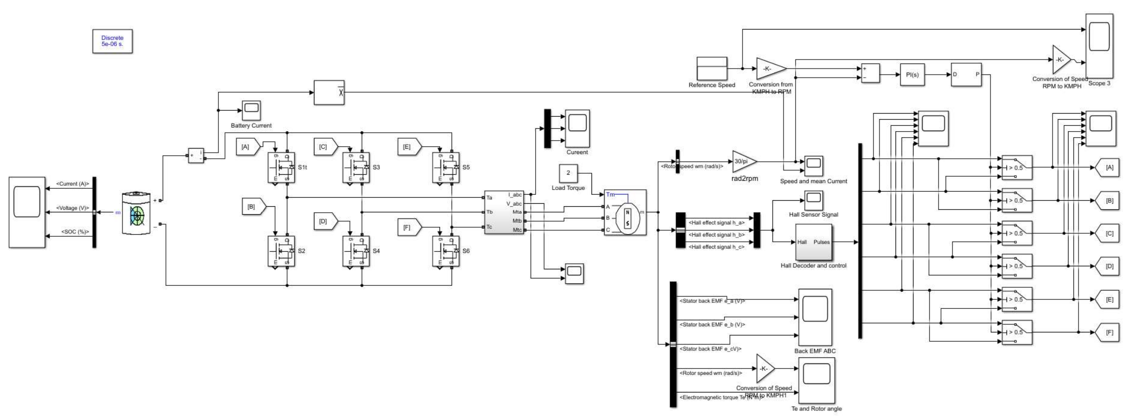

Figure 2: MATLAB Simulink Model of PWM Control of BLDC Motor

Figure 2 illustrates a PWM-based speed control scheme for a BLDC motor. The error between the reference speed and the measured speed is applied to a PI controller, which produces a corrective control signal. This signal is then supplied to a PWM generator that creates switching pulses with an adjustable duty cycle. Using feedback from Hall sensors, the switching matrix identifies the rotor position and performs electronic commutation by directing the PWM signals to the appropriate inverter switches. The inverter converts the DC input into a three-phase AC output with controllable voltage and frequency to drive the motor. Meanwhile, the Hall sensors continuously update rotor position information, enabling proper commutation and providing the actual speed for feedback to the PI controller. Through this closed-loop operation, the system maintains the motor speed at the desired setpoint and compensates for load variations or external disturbances.

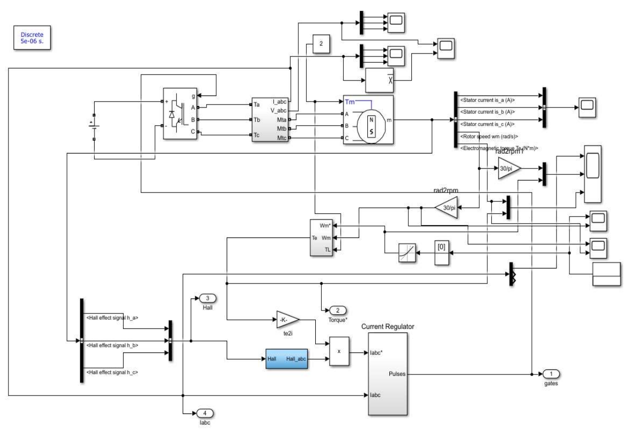

Figure 3: MATLAB Simulink Model of SMC Control of BLDC Motor

Figure 3 presents the MATLAB/Simulink implementation of a sliding mode control (SMC) strategy for a BLDC motor. The control process begins with the reference speed, which defines the target operating condition. The deviation between this reference and the measured speed is computed as the speed error and supplied to the SMC speed controller, where sliding mode control laws are applied. Based on this, the controller produces a reference current that is compared with the actual phase currents of the motor. The resulting current errors are processed by the SMC current controller to generate fast and precise control actions, ultimately producing the gating signals for the voltage source inverter. The inverter then delivers appropriately regulated voltage and current to drive the motor in accordance with the desired speed trajectory. Feedback from Hall sensors provides continuous information on rotor position and speed, enabling the control system to respond rapidly to disturbances and operating variations. This dual-loop SMC framework, incorporating both speed and current regulation, ensures improved dynamic performance, rapid current tracking, and strong robustness against parameter uncertainties, making it well-suited for high-performance BLDC motor applications.

The simulation results for both control techniques are recorded for speed response, torque response, voltage and current waveforms and current and torque ripples. The simulation models are executed for a period of 3 seconds. At initial state the reference speed is kept at 200RPM and reference speed change is introduced at 1 second. The mechanical load (torque) on the motor is initially set 1NM and at time instance of 2 second, the load torque is doubled to 2NM. The voltage and current waveforms of PWM control technique are shown in figure 4 and those for SMC Control in figure 5.

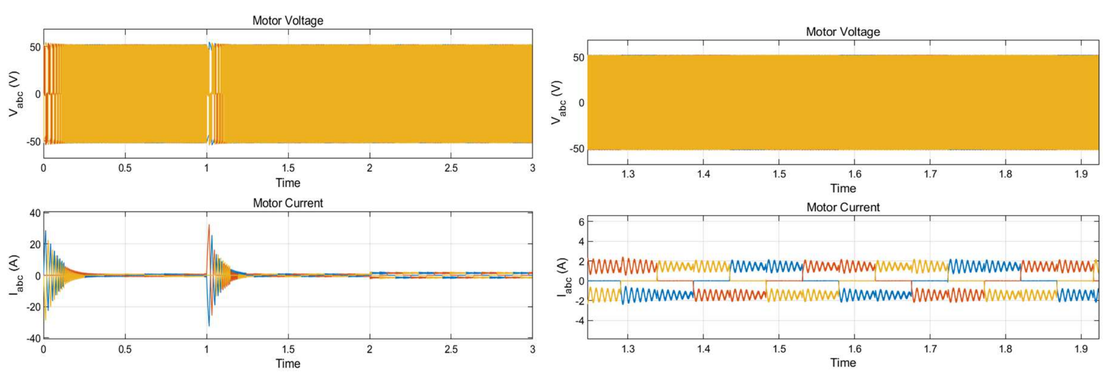

Figure 4: Voltage and current waveforms of PWM control technique (and zoomed view)

From the graph of voltage and current waveforms, is can be seen that, in the transient state where the motor start from the rest, the system forces a large current into the motor and large overshoots in the current waveforms are observed. The increase in amplitude of current waveform after 2 second is due to increase in load. In the steady state, the current waveforms settles and current ripples are observed in the waveforms. The current ripple can be calculated from equation (34). The current ripples in this case is calculated to be 45%.

$$I_{ripple} = \frac{I_{ripple\ pp}}{I_{peak}} \times 100 \qquad \dots (34)$$

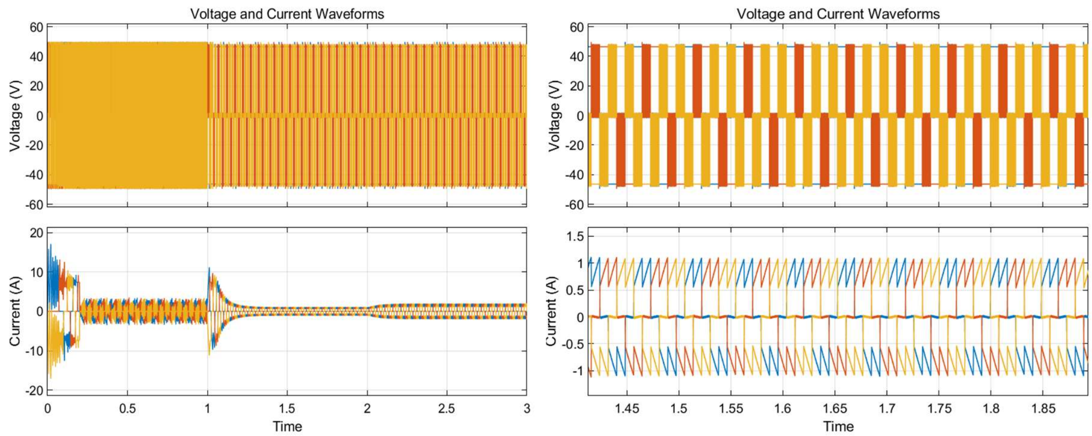

Figure 5: Voltage and current waveforms of SMC control technique (zoomed view)

From the current waveforms of SMC control, the current ripples are calculated from equation (34) and is noted to be 40%.

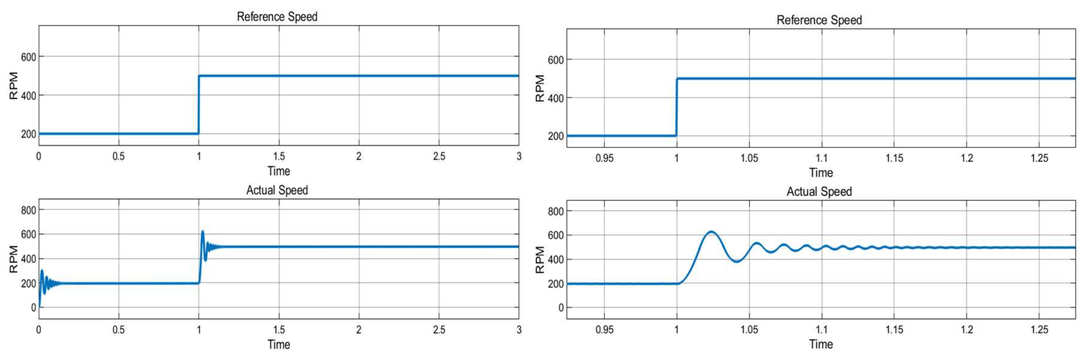

Figure 6: reference speed and actual speed with PWM control

The speed response of PWM control technique is plotted in figure 6. Significant oscillations are seen in the graph of speed response as motor starts from the rest or when speed change is introduced. The zoomed view of speed response clearly shows the overshoots and oscillations before settling to the new speed. For reference speed change from 200RPM to 500RPM the motor takes 0.15 seconds to settle to the new speed. In steady state the actual speed follows the reference speed with 0.3% error.

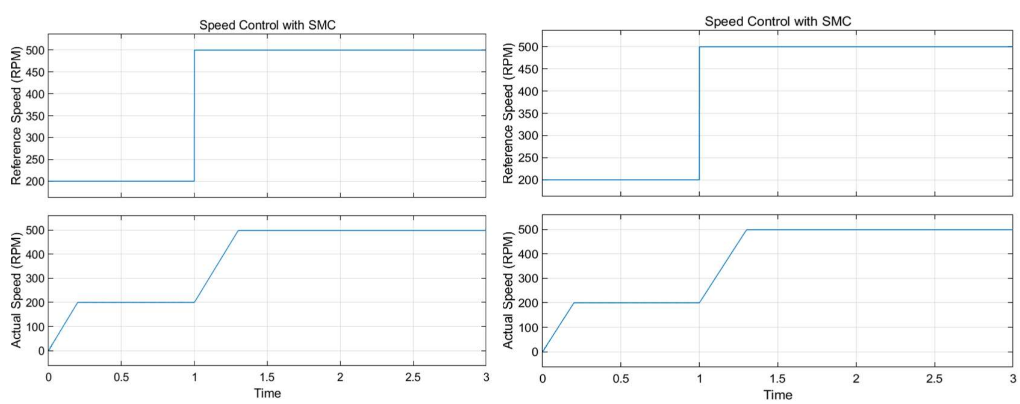

Figure 7: reference speed and actual speed with SMC control

The speed response of SMC control technique is seen in figure 7. It is seen that the motor smoothly accelerates from initial state to the reference speed linearly. No overshoots or oscillations are observed during the transient or steady state. The zoomed view of speed response clearly shows the overshoots and oscillations before settling to the new speed. For reference speed change from 200RPM to 500RPM the motor takes 0.30 seconds to settle to the new speed. In steady state the actual speed follows the reference speed with 0.5% error.

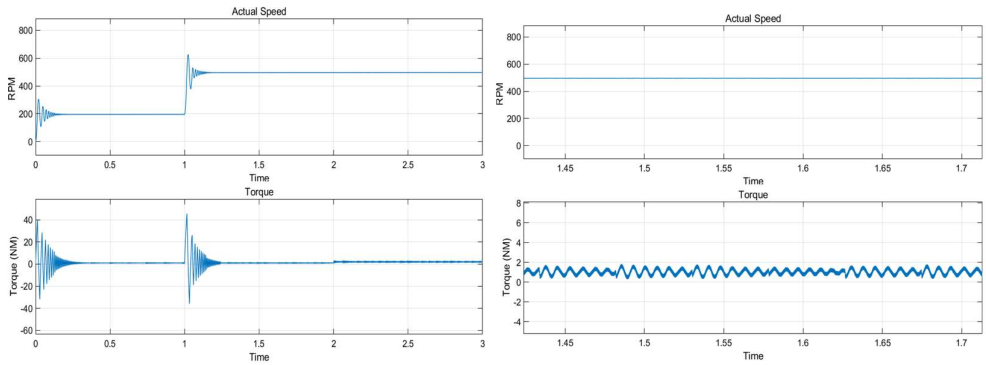

Figure 8: Speed and torque response with PWM control (Zoomed view)

The speed and torque response of PWM control are seen in figure 8. Large torque ripples are seen when motor starts from rest and at the instance of speed change. In steady state the torque ripple value is calculated from equation (35), and is noted to be 66%

$$\tau_{ripple} = \frac{\tau_{ripple\ pp}}{\tau_{peak}} \times 100 \qquad \dots (35)$$

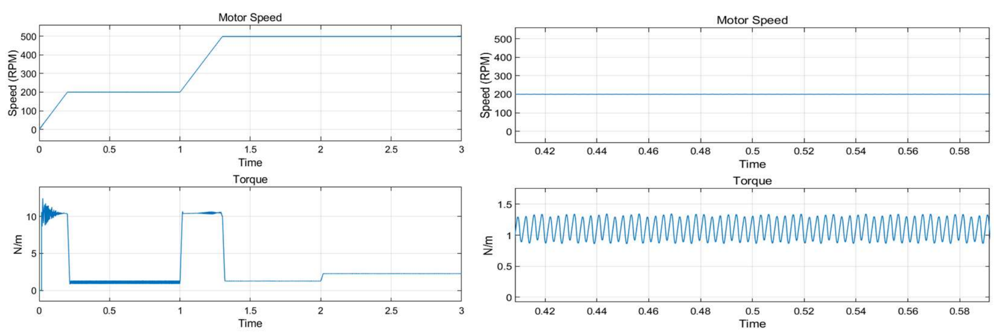

Figure 9: Speed and torque response with SMC control

The speed and torque response of PWM control are seen in figure 8. Large torque ripples are seen when motor starts from rest. In later part of the waveforms, the torque settles. In steady state the torque ripple value is calculated from equation (35), and is noted to be 20%

TABLE II: COMPARATIVE OF PWM AND SMC TECHNIQUE

Technique	Steady State Error (%)	Settling Time (S/ 100RPM)	Current Ripple (%)	Torque Ripple (%)
PWM Control	0.3	0.05	45%	66%
SMC Control	0.5	0.10	40%	20%

The comparison of speed control techniques at steady state and transient state is illustrated in table 2. Steady-State Error measures how accurately the motor maintains its target speed once stable. Settling Time indicates how quickly the motor reaches and stabilizes at a new target speed after a command is given to change the reference speed (lower seconds per 100 RPM is better). The steady state error with PWM technique is less than that of SMC. From figure 7, the SMC control shows no overshoots or undershoots while attaining the target speed. Whereas, significant overshoots and undershoots are seen with PWM control (figure 6). Torque Ripple quantifies unwanted torque fluctuations causing vibration (lower % is better), where the SMC (20%) offers better performance and PWM Control (66%) shows highest torque ripples.

II. CONCLUSION

This paper presents comparative analysis of PWM and SMC control techniques for speed control of BLDC motor. While simple and cost-effective, conventional PWM methods inherently produce significant commutation torque ripple and current ripples due to trapezoidal back-EMF and phase current discontinuities. Its performance is generally inadequate for demanding EV drive comfort and efficiency requirements. SMC demonstrates strong robustness against parameter variations and load disturbances. It effectively reduces torque ripple compared to basic PWM with hardly any overshoot or undershoot. Its steady-state error falls within 1% and torque ripple of just 20% leads to smoother operation of the BLDC motor.

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