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Research Paper

Comparative Design and Performance Analysis of Sliding Mode Control Techniques for BLDC Motor Speed Regulation in EV Applications

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Abstract: Brushless DC (BLDC) motors offer significant advantages over conventional DC motors, including high efficiency, low noise, enhanced reliability, longer lifespan, and a high torque-to-weight ratio, making them well suited for electric vehicle (EV) applications. However, precise speed regulation is essential to ensure optimal performance under varying load conditions. This paper presents a comparative analysis of three Sliding Mode Control (SMC) techniques—first-order SMC, second-order SMC, and Integral SMC—for BLDC motor speed control. The study considers a BLDC motor rated at 1 kW, 3000 rpm, operating under a load torque of 3 N·m. The performance of each control strategy is evaluated in terms of steady-state error, stability, and dynamic response. Simulation results obtained using MATLAB/Simulink demonstrate that the Integral SMC approach outperforms the other methods, achieving the lowest steady-state error of 2.4 rpm, compared to 4.9 rpm for first-order SMC and 9.5 rpm for second-order SMC. The findings indicate that Integral SMC provides superior accuracy and robustness for speed regulation. Overall, the proposed analysis confirms the suitability of BLDC motors and advanced SMC techniques for efficient and reliable operation in electric mobility applications such as e-bikes and tricycles.

Key Words: Brushless DC Motor (BLDC), Speed Control, Electric Vehicles (EV), Sliding Mode Control (SMC), First-Order SMC, Second-Order SMC, Control Systems.

1. INTRODUCTION

Brushless DC (BLDC) motors are widely used in modern electric vehicle (EV) propulsion systems due to their high efficiency, excellent torque-to-weight ratio, and low maintenance requirements. The elimination of brushes reduces friction, sparking, and mechanical losses, making BLDC motors more reliable and suitable for high-performance applications such as EVs. With the rapid expansion of the electric vehicle industry, there is an increasing need for precise and efficient motor control strategies to ensure smooth speed regulation and improved dynamic performance under varying operating conditions.

Speed control of BLDC motors is essential in EV applications as vehicle performance depends on accurate torque and speed regulation under different load conditions. However, BLDC motors exhibit nonlinear behavior, parameter variations, and external disturbances, which reduce the effectiveness of conventional control methods like PI controllers. To address these challenges, nonlinear and robust control techniques are preferred, with Sliding Mode Control (SMC) being one of the most effective approaches due to its strong disturbance rejection capability and robustness against uncertainties.

Sliding Mode Control ensures system stability by driving the system states toward a predefined sliding surface and maintaining them there despite disturbances. Although conventional SMC offers strong robustness, it suffers from the chattering problem, which can affect system performance and increase wear in practical implementations. To overcome this limitation, improved techniques such as higher-order SMC, integral SMC, and adaptive SMC have been developed. These approaches reduce chattering while maintaining robustness, making them highly suitable for BLDC motor speed control in electric vehicle applications.

2. LITERATURE REVIEW

[1] A. Kumar, R. Singh, and P. Sharma proposed an adaptive sliding mode control strategy for BLDC motor speed regulation in electric vehicle applications. The method improves robustness against parameter uncertainties and external disturbances. Their approach enhances tracking accuracy and reduces steady-state error compared to conventional SMC. The controller is validated under varying load conditions, showing stable and efficient motor performance.

[2] M. Elhassan, Y. Zhang, and H. Chen developed a robust higher-order sliding mode control technique for BLDC motor drives used in EV propulsion systems. The proposed method effectively reduces chattering while maintaining strong disturbance rejection capability. It ensures fast dynamic response and improved speed tracking performance. Simulation results confirm enhanced stability and suitability for real-time electric vehicle applications.

3. PROPOSED SYSTEM

The proposed system focuses on designing and implementing three different Sliding Mode Control (SMC) techniques for the speed regulation of a Brushless DC (BLDC) motor used in electric vehicle applications. The BLDC motor is mathematically modeled based on its electrical and mechanical dynamics to accurately represent real operating conditions. The entire system is developed and simulated in MATLAB/Simulink to analyze controller performance under rated speed, load variations, and disturbance conditions. The main objective is to compare the effectiveness of different SMC approaches in terms of speed tracking accuracy, robustness, and dynamic response.

3.1 Mathematical Modeling of BLDC Motor

To design and implement the control strategy, the Brushless DC (BLDC) motor is mathematically modeled based on its electrical and dynamic characteristics

Electrical Equation

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_a$$

3.1 Theoretical Analysis of BLDC Motor

The theoretical analysis of the proposed system begins with the mathematical modeling of the BLDC motor. The motor operates as a three-phase system where each phase has resistance and inductance. The voltage equations are derived using Kirchhoff's laws, considering self-inductance and mutual inductance between phases. The sum of the three-phase currents is always zero, which simplifies the model. The electromagnetic torque is generated based on the interaction between phase currents and back electromotive force (EMF), and it is directly proportional to motor speed.

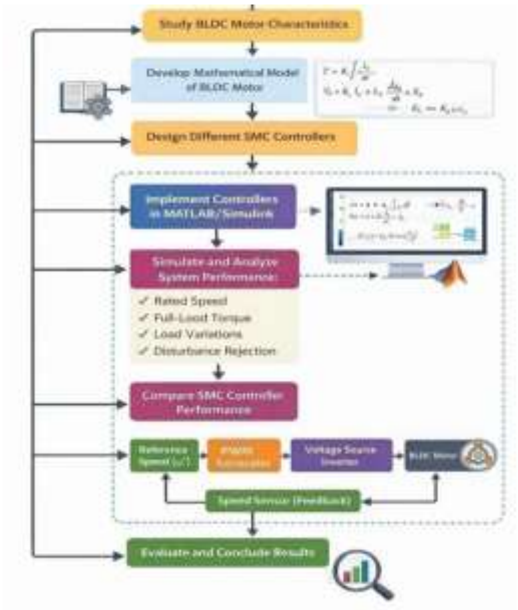

Fig 1: closed loop system

3.1.1 BLDC Motor Voltage Equations

The BLDC motor is modeled using three-phase voltage equations. Each phase voltage depends on resistance, inductance, and back EMF:

$$E_a = K_e \, \omega$$

Where:

- K_e= Back EMF constant
- ω= Angular speed (rad/s)

3.2 0verview of proposed system

3.2.1 Main Objective of the BLDC motor

The main objective of the proposed system is to achieve precise and stable speed control of a Brushless DC (BLDC) motor used in electric vehicle applications. The system aims to maintain the desired speed even when there are changes in load or operating conditions. It focuses on reducing speed error, improving response time, and ensuring smooth motor performance.

3.2.2 Control strategy of BLDC motor

The system uses Sliding Mode Control (SMC) as the main control technique, which is known for its robustness and fast response. Three types of SMC methods are used in this project: first-order SMC, second-order SMC, and integral SMC. These controllers help in minimizing speed error and improving system stability under different conditions.

3.2.3 Performance Improvement

The system is tested using MATLAB/Simulink simulation under different operating conditions. The results show that among the three controllers, the integral SMC provides the best performance. It achieves the fastest response time and the lowest steady-state error compared to first-order and second-order SMC methods.

4. SIMULATION MODEL AND RESULTS

The BLDC motor speed was effectively controlled using various Sliding Mode Control (SMC) techniques, showing high robustness against load and parameter variations.Among the methods, advanced SMC (like adaptive or fuzzy-based SMC) provided faster response and reduced chattering compared to conventional SMC.

The system achieved stable speed tracking with minimal steady-state error under different driving conditions. Overall, SMC-based control proved highly suitable for EV applications due to its reliability, efficiency, and strong disturbance rejection capability.

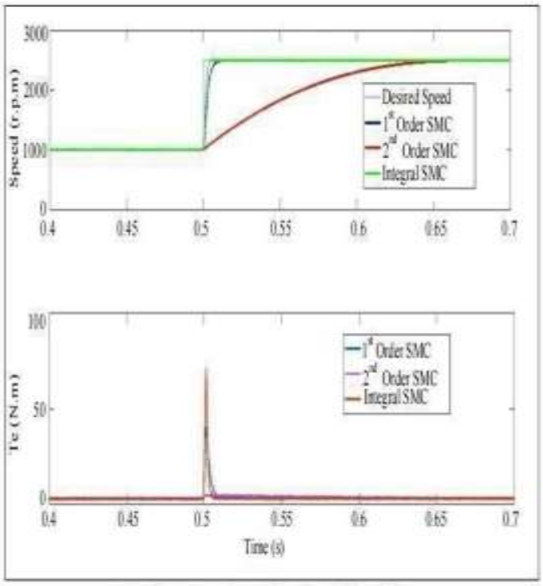

Fig2: Motor speed change Analysis Under Rated Load Conditions

The sudden speed change analysis studies how the BLDC motor reacts when the reference speed changes abruptly. In this paper, the speed is changed from 1000 rpm to 2500 rpm at rated load conditions.

This type of test is important because in real electric vehicles, speed changes suddenly when the driver accelerates.

4.1 Current Behaviour During Speed Change

1st Order SMC: Current dips to –25 Aand rises to 7.25 A. 2nd Order SMC: Smooth current transition. Integral SMC: Current dips to –50 A and rises to 5.4 A.

Torque Response

Faster Speed response leads to higher torque spikes. Integral SMC Producers larger trancient torque 2nd order SMC produces smoother Load Torque Variation Analysis

4.1.1 The load torque is suddenly changed from:

0.5 N.m→ 3 N.m(Full Load)

torque variations.

Fig 3: Load change at rated Speed

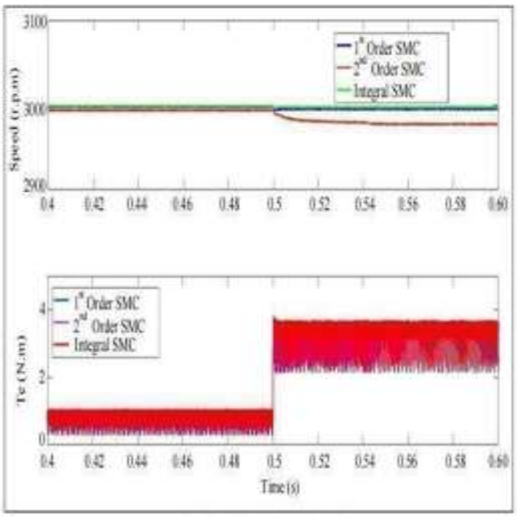

Fig 3: Load Change at Rated Speed

Load Change at Rated Speed Analysis

The load change analysis studies how the BLDC motor behaves when the load torque is suddenly varied while the motor is operating at rated speed. In this paper, the load is increased from 0.5 N·m to full load (3 N·m) while maintaining the motor speed at around 3000 rpm. This test is important because in real electric vehicles, load changes occur frequently due to road conditions, passenger weight, or acceleration.

Speed Response under Load Change

When the load is suddenly increased, the motor tends to slow down due to the additional torque demand. However, the controller quickly reacts and restores the speed to the rated value. Among the three controllers, the Integral Sliding Mode Control (ISMC) shows the best performance by maintaining the speed almost constant with very small deviation. The 1st order SMC also performs well but shows slightly more deviation than ISMC. The 2nd order SMC shows the largest deviation and takes more time to stabilize.

5. CONCLUSION

The analysed and compared 1st Order SMC, 2nd Order SMC, and Integral SMC for speed control of a 1 kW, 3000 rpm BLDC motor used in electric vehicle applications. Simulation results show that all three controllers ensure stable operation with effective speed regulation under various conditions such as startup, load disturbance, and sudden speed changes. Among them, Integral Sliding Mode Control (ISMC) provides superior performance with faster settling time, minimal steady-state error, and excellent disturbance rejection. Although it exhibits higher transient current and torque ripples, it delivers the best overall tracking accuracy and robustness, making it highly suitable for EV applications. The 1st Order SMC offers balanced performance, while the 2nd Order SMC provides smoother but comparatively slower response.

6. Future Scope:

The future work focuses on implementing the proposed ISMC on real-time hardware such as DSP or FPGA for practical validation. It can be extended to high-power BLDC motors and enhanced using advanced controllers like Adaptive SMC, Super-Twisting SMC, and AI-based hybrid methods. Further improvements include sensor less control, thermal analysis, regenerative braking optimization, and integration with BMS for complete electric vehicle applications.

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