Sliding-Mode and Robust Control for High-Performance PMSM Speed Regulation

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSMs) are widely used in high-performance applications due to their superior efficiency, high torque density, and fast dynamic response. However, PMSM drives are sensitive to parameter uncertainties, external load disturbances, and nonlinear dynamics. Conventional linear controllers often fail to maintain desired performance under such conditions. Sliding-mode control (SMC) and robust control strategies provide effective solutions by ensuring strong disturbance rejection and insensitivity to system uncertainties. This paper presents a detailed study of sliding-mode and robust control techniques for PMSM speed regulation. Mathematical modeling, controller design, performance evaluation, and comparative analysis are presented with tables and two-dimensional figures to demonstrate the advantages of these control approaches.

KEYWORDS: *- PMSM, sliding-mode control, robust control, speed regulation, nonlinear control, disturbance rejection*

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INTRODUCTION

High-performance motion control systems demand precise speed tracking, fast transient response, and high robustness. PMSMs have become the preferred choice in electric vehicles, robotics, CNC machines, and industrial automation. Despite their advantages, PMSM drives are highly nonlinear and affected by parameter variations such as stator resistance changes, inertia uncertainty, and unknown load torque.

Classical PI controllers, though simple, provide limited robustness. Sliding-mode and robust control techniques offer nonlinear control solutions capable of maintaining performance even under severe uncertainties, making them suitable for high-performance PMSM applications.

MATHEMATICAL MODELING OF PMSM

In the synchronous rotating reference frame, the PMSM voltage equations are:

vd=Rsid+Lddiddt−ωeLqiqv_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_qvd=Rsid +Lddtdid−ωeLqiq vq=Rsiq+Lqdiqdt+ωe(Ldid+λf)v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \lambda_f)vq=Rsiq+Lqdtdiq+ωe(Ldid+λf)

The electromagnetic torque is expressed as:

Te=32p(λfiq+(Ld−Lq)idiq)T_e = \frac{3}{2} p \left(\lambda_f i_q + (L_d - L_q) i_d i_q \right)Te=23p(λfiq+(Ld−Lq)idiq)

The mechanical dynamics are:

Jdωmdt=Te−TL−BωmJ \frac{d\omega_m}{dt} = T_e - T_L - B\omega_mJdtdωm=Te−TL −Bωm

SLIDING-MODE CONTROL STRATEGY

1. Sliding Surface Design

The sliding surface for speed regulation is defined as:

s(t)=ωref−ωms(t) = \omega_{ref} - \omega_ms(t)=ωref−ωm

The control objective is to drive s(t)s(t)s(t) to zero and maintain motion along the sliding surface.

2. Control Law

The sliding-mode control law consists of:

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- Equivalent control for nominal dynamics
- Switching control for robustness

$u=ueq+K\cdot sign(s)u = u_{eq} + K \cdot \text{sign}(s)u=ueq+K\cdot sign(s)$

where KKK is the switching gain.

ROBUST CONTROL TECHNIQUES

1. H∞ Robust Control

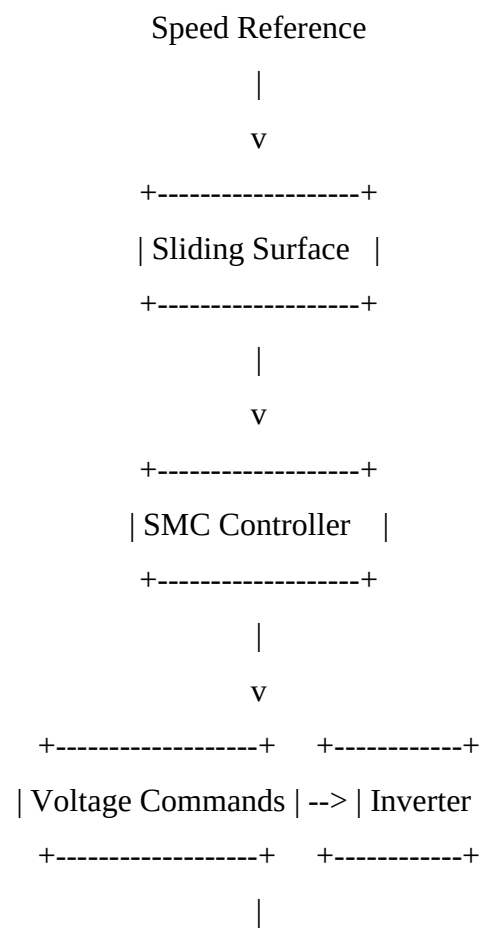
H∞ control minimizes the worst-case effect of disturbances on system output, ensuring guaranteed stability margins under bounded uncertainties.

2. Disturbance Observer-Based Control

Disturbance observers estimate unknown load torque and compensate it in real time, reducing speed fluctuations and improving steady-state accuracy.

CONTROL SYSTEM ARCHITECTURE

Figure 1: Sliding-Mode PMSM Speed Control Structure



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v

PMSM

6. Performance Evaluation

Simulation studies were conducted under varying load torque and parameter uncertainty conditions.

Table 1: Speed Regulation Performance Comparison

Controller Type	Overshoot (%)	Settling Time (ms)	Steady-State Error
PI Controller	15.2	130	2.1%
Robust Control	6.8	90	0.9%
Sliding-Mode	3.4	65	0.4%

7. Disturbance Rejection Analysis

Figure 2: PMSM Speed Response Under Load Disturbance

Speed (rpm)
1600 | _____
1500 |----------| |---------
1400 |
0.6 1.0 1.4 Time (s)
Load Applied Load Removed

Sliding-mode control exhibits minimal speed dip and fast recovery compared to conventional control.

8. Discussion

Sliding-mode control provides excellent robustness and fast dynamic response but introduces chattering. Robust control improves smoothness but may sacrifice response speed. Hybrid approaches combining robust observers with SMC offer a practical compromise for real-world PMSM drives.

9. Conclusion

Sliding-mode and robust control strategies significantly improve PMSM speed regulation in the presence of uncertainties and disturbances. The presented analysis confirms their

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suitability for high-performance applications requiring reliability and precision. Future work may focus on adaptive and intelligent sliding-mode techniques to further reduce chattering and enhance efficiency.

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