A Stable Sliding Mode Control Device for Controlling the Speed and Terminal Current of Permanent Magnet Synchronous Motor Drive

Dr. CH. Naga Sai Kalyan [1], D. Vasu Ankineedu[2], CH. Vaishnavi[3], D. Govind Kali Prasad[4], G. Karthik[5]

[1] Faculty, Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Andhra Pradesh, India
[2] Student, Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Andhra Pradesh, India
[3] Student, Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Andhra Pradesh, India
[4] Student, Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Andhra Pradesh, India
[5] Student, Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Andhra Pradesh, India

ABSTRACT

In this paper, we investigate a terminal sliding mode control approach based on nonlinear disturbance observer to implement the speed and current tracking control for PMSM drive system. Instead of using the conventional cascade control in the vector control of PMSM, the suggested method utilizes a speed-current single-loop control structure. Initially, using feedback linearization technology, a single-loop terminal sliding mode controller is created for the PMSM drive system while taking into account the nonlinear and coupling characteristics. This technique can achieve a quick transient response by allowing the motor speed and current to reach the reference value for an unlimited amount of time. The sliding mode control may provide a strong switching gain, which could result in the undesirable chattering, although being less sensitive to parameter uncertainties and outside disturbances. In the meantime, the presence of mismatched uncertainty prevents the sliding mode control from maintaining the property of invariance. The lump disturbance is then estimated using a nonlinear disturbance observer and employed in the feed-forward compensation control. As a result, the PMSM drive system is given a composite control scheme. The outcomes demonstrate that the motor control system based on the suggested method has great robustness, good speed and current tracking performance, and both.

Keyword : *- PMSM drive, terminal sliding mode control, feedback linearization, and nonlinear disturbance observer.*

1. Introduction

The permanent magnet synchronous drive has built-in advantages like high power density, highly effective, excellent speed and torque control and high dynamic performance has edge over dc motors and induction motors. Because of subsequent benefits of permanent magnet synchronous drives there are vast applications in our day to day life and industries like electric vehicles, industrial drives, robots, aerospace and wind turbines etc. The usage of permanent magnet synchronous motors is increased because of controllability of speed and torque of PMSM. Three phase permanent magnet synchronous drive are more suitable for power systems and industrial machines due to its high capability. Permanent magnet synchronous motor is a good choice for generating high power over a conventional synchronous generator. The permanent magnet synchronous motor has difficulty like non-linearity to overcome this disadvantage a clear research has been done in this paper.

Furthermore, it is challenging to determine the precise motor model and parameters in the real-world system due to parameter fluctuations and external disturbances that are unavoidable in PMSM drive systems.

The conventional PI control method has the ability to suppress the disturbance, although it typically operates at a slow rate.

Although the sliding mode control is less prone to parameter uncertainties and external disturbance, it can be difficult to estimate the upper bound of the disturbance. As a result, its robustness is frequently attained by a large switching gain, which will lead to the unfavourable chattering phenomenon. Combining the SMC with other methods that estimate the disturbance is a tempting idea to address the aforementioned disadvantages. This issue could have a viable remedy in the disturbance observer technology. It has the ability to predict the lump disruption.

2. PMSM modelling

A mathematical model of a Permanent Magnet Synchronous Motor (PMSM) can be expressed using a set of equations that describe the relationship between the motor's electrical and mechanical properties. The model can be divided into two parts, namely the electrical model and the mechanical model.

2.1 Electrical Model

The electrical model of a PMSM is based on Kirchhoff's laws and Faraday's law of electromagnetic induction. It can be represented by the following equations:

2.1.1 The voltage equation of the stator winding

$$V_s = R_s i_s + L_s(di_s/dt) + e_s$$

where (di_s/dt) is the derivative of the stator current with respect to time, i_s is the current flowing through the stator winding, R_s is the resistance of the stator winding, L_s is the inductance of the stator winding, and e_s is the back-EMF produced in the stator winding.

2.1.2 The voltage equation of the rotor winding

$$e_r = R_r i_r + L_r(di_r/dt)$$

where i_r is the current flowing through the rotor winding, L_r is the inductance of the rotor winding, e_r is the back-EMF created in the rotor winding, and R_r is the resistance of the rotor winding.

2.1.3 The electromagnetic torque equation

$$T_e = (3/2)P(L_d - L_q)i_s i_r$$

where P is the number of pole pairs, L_d and L_q are the d- and q-axis inductances, and i_s and i_r are the stator and rotor currents. T_e is the electromagnetic torque produced by the motor.

2.2 Mechanical Model

The mechanical model of a PMSM is based on the principles of Newton's laws of motion. It can be represented by the following equations:

2.2.1 The mechanical equation of motion

$$J*(d^2\theta/dt^2) + B*(d\theta/dt) = T_e - T_l$$

where P is the number of pole pairs, L_d and L_q are the d- and q-axis inductances, and i_s and i_r are the stator and rotor currents. T_e is the electromagnetic torque produced by the motor.

2.2.2 The position equation

$\theta_e = \theta + \theta_o$

where θ_e is the electrical angle, θ_o is the initial rotor position.

The above equations can be used to simulate the performance of a PMSM and design control systems to regulate the motor's speed or position.

2.2.3 PMSM control system block diagram

The control system for a PMSM typically involves a feedback control loop that regulates the motor's speed or position. The block diagram of a typical PMSM control system is as follows

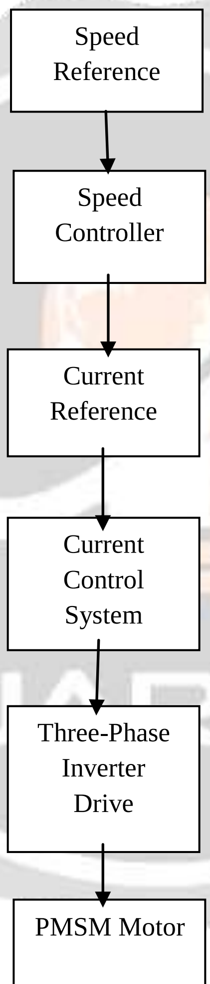

Fig-1: Block Diagram of PMSM Control System.

The control system starts with a speed reference signal, which is set by the operator or by an automated control system. The speed controller compares the speed reference signal with the actual speed of the motor and generates a current reference signal. The current reference signal is then fed into the current control system, which generates the required current signals for the motor.

The current control system typically uses a proportional-integral (PI) controller to regulate the stator current of the motor. The PI controller compares the current reference signal with the actual stator current and generates a control signal that is fed into the three-phase inverter drive. The inverter drive converts the DC voltage supply into a three-phase AC voltage, which is applied to the PMSM motor.

The PMSM motor generates a back-EMF that is proportional to its speed and position. This back-EMF is sensed by the controller and used to estimate the speed and position of the motor. The estimated speed and position are fed back to the speed controller to complete the feedback control loop.

The PMSM control system can be designed to achieve high-speed operation, high torque density, and high efficiency, depending on the application requirements. The control system can also be designed to provide protection against overcurrent, overvoltage, and overtemperature conditions.

3. Sliding mode controller for PMSM

This section explains the main phases of the recommended approach for PMSM drive. In this study, as opposed to sliding mode control techniques with the cascade control structure, where the sliding mode controllers are constructed in the speed or current loop, the speed and current controllers are merged via terminal sliding mode control based on linearization technology.

The elements of output speed and current are the factors that need to be managed. Finding the input action to implement speed and current tracking control is the controller's goal.

3.1 PMSM MODEL LINEARIZATION

The approximation approach is used to quadratic linearize the PMSM model. Tuning guidelines for the linearizing transformations to take higher-order terms into account are achieved via back propagation of error between the outputs of a quadratic linearized system with a normal form output.

A permanent magnet synchronous motor (PMSM) can be modeled by a set of differential equations that describe the relationship between the motor's electrical and mechanical properties. The mathematical model of a PMSM is usually nonlinear due to the nonlinear relationship between the stator current and the electromagnetic torque.

To simplify the PMSM model, a linearization technique can be used to approximate the nonlinear equations with linear equations. The linearization technique involves linearizing the nonlinear equations around a specific operating point.

One common way to linearize the PMSM model is to use small-signal analysis. In small-signal analysis, the nonlinear equations are linearized by taking the first-order Taylor series expansion around the operating point. The linearized equations can then be expressed in matrix form as follows:

$dx/dt = Ax + Bu$

where x is the state vector, u is the input vector, A is the state matrix, and B is the input matrix. The state vector consists of the electrical and mechanical variables of the motor, while the input vector consists of the electrical input to the motor. The state matrix and input matrix are determined by the linearized equations.

The linearized PMSM model can be used to design control systems for the motor, such as a feedback control system that regulates the motor's speed or position. The linearized model can also be used to analyze the stability and performance of the motor under different operating conditions.

3.2 Design of the PMSM's terminal sliding mode controller

Terminal sliding mode control is a robust control technique that can be used to regulate the speed or position of a PMSM with high accuracy and fast response. The following steps are involved in the design of a terminal sliding mode controller:

1. State-Space Model: The first stage is to derive the state-space model of the PMSM, which comprises the equations that characterize the electrical and mechanical behaviour of the motor.

2. Sliding Mode Control Law: The goal of the sliding mode control law is to compel the system's state to converge in a finite amount of time to a sliding manifold. The sliding mode control law for a PMSM may be written as:

$u = -k1sign(s) - k2s$

where u is the control input, s is the sliding variable, k1 and k2 are the control gains.

3. Terminal Sliding Mode Control: By including a switching function in the sliding mode control law, terminal sliding mode control is accomplished. The sliding variable will converge to zero in a finite amount of time thanks to the switching function. One way to represent the terminal sliding mode control law is as follows:

$$u = -k1sign(s) - k2s - k3sgn(s)|s|^n$$

where k3 is the terminal sliding mode control gain, n is an even integer greater than or equal to 2.

4. Control Implementation: The terminal sliding mode controller can be implemented using a digital signal processor or a microcontroller. The controller should be designed to operate at a sufficiently high sampling rate to ensure accurate control of the PMSM.

5. Performance Evaluation: The system may be simulated under a variety of operating situations, including as load disturbances, parameter fluctuations, and sensor noise, in order to assess the effectiveness of the terminal sliding mode controller. The controller should be able to provide fast and accurate regulation of the speed or position of the PMSM, while maintaining robustness to external disturbances and uncertainties.

Overall, the design of a terminal sliding mode controller for a PMSM entails the selection of appropriate control gains and the implementation of the control law on a digital platform. The performance of the controller should be evaluated under various operating conditions to ensure that it meets the requirements of the application.

3.3 Design of the PMSM nonlinear disturbance observer

To estimate and account for unknown disturbances and parameter variations in a PMSM control system, a nonlinear disturbance observer (NDO) can be used. The design of an NDO for a PMSM requires the following steps:

1. System Model: The first step is to derive a mathematical model of the PMSM that includes the effects of unknown disturbances and parameter variations. The model should be expressed in state-space form, which can be written as:

$$x_{dot} = f(x,u) + g(x,u)w$$

$$y = h(x)$$

where f(x,u) and g(x,u) are nonlinear functions that describe the system dynamics and h(x) is a nonlinear function that connects the state to the output. x is the state vector, u is the control input, w is the disturbance input, and y is the output.

2. Observer Design: The NDO is designed to estimate the unknown disturbances and parameter variations by observing the system output and comparing it with the model output. The observer can be expressed as:

$$z_{dot} = f(z,u) + l(y - h(z))$$

where z is the observer state vector, l is the observer gain.

3. Nonlinear Compensator: The estimated disturbances and parameter variations are used to design a nonlinear compensator that is added to the control law to cancel out the effects of the disturbances. The compensator can be expressed as:

$$u = u_c + u_d$$

$$u_c = -k*h(z)$$

$$u_d = -k*d_{hat}$$

where k is the control gain, d_hat is the estimated disturbance vector.

4. Control Implementation: The NDO and compensator can be implemented on a digital platform, such as a microcontroller or a digital signal processor. The controller should be designed to operate at a sufficiently high sampling rate to ensure accurate control of the PMSM.

5. Performance Evaluation: The performance of the NDO can be evaluated by simulating the system under various operating conditions, including load disturbances, parameter variations, and sensor noise. The controller should be able to provide accurate disturbance estimation and compensation, while maintaining robustness to external disturbances and uncertainties.

Overall, the design of an NDO for a PMSM involves the selection of appropriate observer and compensator gains, as well as the implementation of the control law on a digital platform. The performance of the NDO should be evaluated under various operating conditions to ensure that it meets the requirements of the application.

4. Results and Simulation

4.1 Sliding mode control

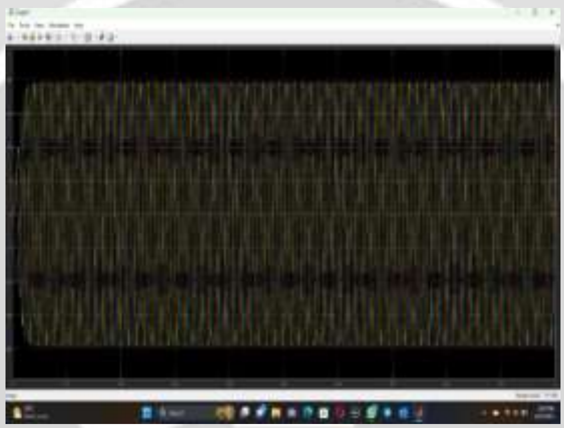

Fig: Current(I_{abc})

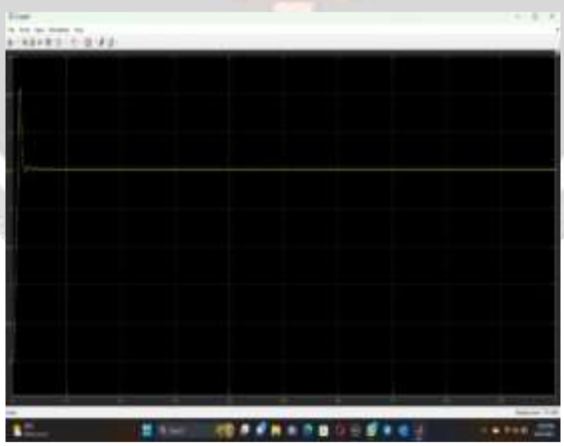

Fig: Torque(T_e)

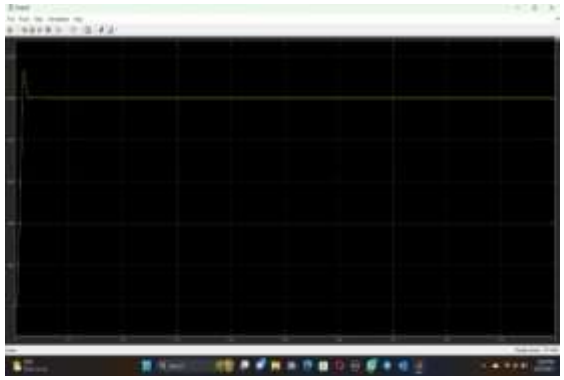

Fig: Speed (ω_m)

4.2 Future Scope

The development of more advanced sliding mode control strategies with improved robustness and performance can be a future scope of this research area. For example, integrating the sliding mode control with other advanced control techniques such as adaptive control, model predictive control, and fuzzy logic control can lead to more efficient and robust control systems.

It is possible to investigate the use of optimization methods such genetic algorithms, particle swarm optimization, and artificial neural networks to enhance the performance of the motor drive overall and optimize the control parameters of the sliding mode controller.

The sliding mode controller may be used with fault diagnostic and fault-tolerant control techniques to create reliable control systems that are capable of identifying and mitigating problems in the PMSM drive.

4.3 Conclusion

This thesis looks at permanent magnet synchronous motor speed tracking control. The quadrature-direct (qd) variables model of the PMSM is formed from the abc machine variables model by applying Park's transformation on the first model. The tracking controller is based on a sliding-mode control strategy and is derived from the q-d variable model. The SMC is derived using the Lyapunov Direct Method. Moreover, the SMC's derivation has been used to explore the PMSM's stability features. The maximum load torque was used to determine a fixed gain. By switching out the constant gain for a functional gain that is dependent on the speed error signal, the chattering phenomenon of the SMC has been minimized. It was discovered that the reaching time was influenced by the switching function increase value. An observer was created to compensate for torque under load.
For the control of permanent magnet synchronous motor (PMSM) drives, sliding mode control (SMC) is a potent control approach that has been applied extensively. SMC is a well-liked option for high-performance motor drives because it provides exceptional resilience and performance in the presence of disturbances and uncertainty.

5. Reference

[1] R. Tao, J. Ma and H. Zhao, “Torque ripple minimization in PMSM based on an indirect adaptive robust controller,” Mathematical Problems
in Engineering, vol. 2017, no. 2, pp. 1–10, Oct. 2017.
[2] J. Yu, P. Shi and L. Zhao, “Finite-time command filtered backstepping control for a class of nonlinear systems,” Automatica, vol. 2018, no. 92, pp. 173–180, Jun. 2018.
[3] T. Li and Y. V. Rogovchenko, “Oscillation criteria for second-order superlinear Emden–Fowler neutral differential equations,” Monatsheftef˝l´zrMathematik, vol. 184, no. 3, pp. 489–500, Apr. 2018.
[4] A. Darba, F. D. Belie and P. D. Haese, “Improved dynamic behavior in BLDC drives using model predictive speed and current control,” IEEE Trans. On Industrial Electronics, vol. 63, no. 2, pp. 728–740, Sep. 2016.
[5] X. Lang, M. Yang and J. Long, “A novel direct predictive speed and current controller for PMSM drive,” Proceedings of 8th International
Power Electronics and Motion Control Conference, Hefei, China, pp. 2551–2556, May. 2016.

[6] S. Katsuji, M. Yoshitaka and I. Toshiyuki, “Singularity-free adaptive speed tracking control for uncertain permanent magnet synchronous motor,” IEEE Trans. On Power Electronics, vol. 31, no. 2, pp. 1692–1701, Apr. 2015.

[7] J. Yu, Y. Ma, H. Yu and C. Lin, “Reduced-order observer-based adaptive fuzzy tracking control for chaotic permanent magnet synchronous motors,” Neurocomputing, vol. 214, pp. 201–209, Nov. 2016.

[8] V. Petrovic, R. Ortega and A. Stankovic, “Interconnection and damping assignment approach to control of PM synchronous motors,” IEEE Trans. On Control Systems Technology, vol. 9, no. 6, pp. 811–820, Nov. 2001.

[9] Z. Mynar, L. Vesely and P. Vaclavek, “PMSM model predictive control with field-weakening implementation,” IEEE Trans. On Industrial Electronics, vol. 63, no. 8, pp. 5156–5166, Apr. 2016.

[10] X. Zhang, Y. Jiang and K. Zhao, “Sliding-mode variable-structure control of high-speed PMSM based on precision linearization control,” Electric Power Automation Equipment, vol. 33, no. 6, pp. 58–63, Jun. 2013.

[11] J. Yu, B. Chen, H. Yu and C. Lin, “Neural networks-based command filtering control of nonlinear systems with uncertain disturbance,” Information Sciences, vol. 426, pp. 50–60, Feb. 2018.