Speed Regulation for PMSM using a Novel Sliding Mode Controller

Hongjie Lin[a], Kyunghyun Lee[a], Sangkyuem Kim[a], Hyungki Ahn[a], Kwanho You[a,b,]*
[a] Department of Electrical and Computer Engineering, Sungkyunkwan University, Korea
[b] Department of Smart Fab. Technology, Sungkyunkwan University, Korea
E-mail address: hongjie.lin@skku.edu, naman2001@skku.edu, interpost94@skku.edu, ahk5721@skku.edu.
*Corresponding Author: khyou@skku.edu

***Abstract*— This paper proposes a novel sliding mode controller (NSMC) and applies it to control the speed of a permanent magnet synchronous motor (PMSM) for the possession of a faster dynamic response, stronger anti-disturbance ability, and high stability of input. The proposed integral sliding surface is based on the traditional linear sliding surface, in which the nonlinear term includes the integral of the power of the state variable. Lyapunov function is used to verify the stability of the system. Finally, a simulation is used to prove the validity of the proposed sliding mode speed controller. The results show that the motor control system based on the proposed method has less overshoot and faster convergence speed than the TSMC controller.**

Keywords—PMSM; integral sliding surface; speed regulation; torque ripple suppression

I. INTRODUCTION

Recently, countries all over the world have put forward a timetable for electric vehicles to replace fossil-fuel based vehicles. Electric vehicles use electricity to generate power, which leads to reduced carbon dioxide emissions, energy conservation, and protection of the environment. Permanent magnet synchronous motor (PMSM) is widely used in electric vehicles because of its simple structure, small volume, light weight, high efficiency, lack of rotor heating problems, good overload performance and small moment of inertia and torque ripple. In order to realize high-performance control of PMSM, two-current controllers are adopted in a field-oriented control mechanism. Therefore, a PMSM can realize torque control performance similar to that of a separately excited DC motor, in which torque and flux can be controlled separately [1]. In recent decades, there have been several studies on the control of PMSMs. Generally, these control methods can be divided into vector control [2], direct torque control [3], and adaptive control [4]. In practical industrial applications, external interference is inevitable. Therefore, it is difficult to establish an accurate PMSM model and corresponding motor parameters in a servo system, and it is restricted to obtain accurate steady-state control and a fast dynamic response current loop.

The existing speed control methods can be divided into two categories. The first is the traditional linear control method, such as a proportional-integral-derivative (PID) [5]. PI regulator is simple and has high reliability. According to the reference value and the actual output value, control deviation is formed. The proportion and integral of the deviation form the control quantity through a linear combination to realize the controlled speed. However, the three-phase PMSM is a nonlinear, multivariable and strong coupling system. If the control system is affected by the external disturbance or the change of internal motor parameters, the traditional PI control method cannot eliminate the unmolded factors.

The other category is nonlinear control theories, for example: neural network control [6], auto disturbance rejection control [7], fuzzy control [8], predictive control [9], sliding-mode control (SMC) [10]. Among these control theories, SMC has become a research hotspot because of its low dependence on the model and strong robustness to various disturbances so that it has been successfully applied to PMSM speed control [11]. Under traditional SMC (TSMC), the speed controller has better dynamic performance; however, the overshoot is large, and the anti-interference ability needs to be strengthened. To be applied for the real system, it is necessary to propose a modified sliding mode control method to optimize the controller. New sliding mode control method was designed and applied to the PMSM system. Li [12] proposed terminal sliding mode surface controller and Liu [13] suggested a non-singular terminal sliding mode control method to improve the control performance. Its dynamic speed response is faster and the anti-interference ability is good.

In this paper, we propose a new integral sliding surface to further improve the dynamic performance of the PMSM speed regulation system. On the basis of the TSMC, the system state variable integral and exponential term are introduced in the novel sliding surface. This paper is organized as follows. Section II introduces a mathematical model of the PMSM. A speed controllers based on a reaching law are designed in Section III and Section IV simulates these control algorithms. Related conclusions are given in Section V.

II. PMSM MODEL

In this paper, the system model is for a three-phase PMSM, and the rotor has a permanent magnet structure. The mathematical model of a surface mounted PMSM motor in the d-q axes rotational reference frame is written as,

$$
\begin{aligned}
u_d &= Ri_d + L_s\frac{di_d}{dt} - p_n\omega L_s i_q, \\
u_q &= Ri_q + L_s\frac{di_q}{dt} + p_n\omega L_s i_d + p_n\omega\psi_f, \\
\frac{d\omega}{dt} &= \frac{3p_n\psi_f}{2J}i_q - \frac{T_L}{J},
\end{aligned}
\tag{1}
$$

where i_d, i_q represent the *d-q* axes stator current, and u_d, u_q are the voltages of the *d* and *q* axes, respectively. R is the resistance and ψ_f is the flux linkage of the permanent magnet; p_n is the number of pole pairs; J, T_L, and B are the moment of inertia, load torque and damping coefficient, respectively. The actual speed of the PMSM is expressed as ω . Equation (1) can be rewritten by setting d axis reference current as $i_d^* = 0$ to guarantee a constant flux operating condition. Then the model can be expressed as,

$$
\begin{aligned}
\frac{di_q}{dt} &= \frac{1}{L_s}\left(-Ri_q - p_n\omega\psi_f + u_q\right), \\
\frac{d\omega}{dt} &= \frac{1}{J}\left(-T_L + \frac{3}{2}p_n\psi_f i_q\right).
\end{aligned}
\tag{2}
$$

The state variables of the PMSM system are defined as follows,

$$
\begin{aligned}
x_1 &= \omega_{ref} - \omega, \\
x_2 &= \dot{x}_1 = -\dot{\omega},
\end{aligned}
\tag{3}
$$

where ω_{ref} denotes the reference speed. According to (2) and (3), the PMSM speed regulation model can be rewritten in the state equation,

$$
\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ -D\end{bmatrix}u, \tag{4}
$$

where u is a differential of the *q* axis referent current i_q^* and *D* is set as $3p_n\psi_f/2J$.

III. SPEED CONTROLLER DESIGN

Sliding mode controller can use a different reaching law and sliding surface to guarantee the reachability to the equilibrium point within a finite time. There are three kinds of common reaching laws. The exponential reaching law (RL 1) can be chosen as

$$
\dot{s}_1 = -\varepsilon\,\mathrm{sgn}(s) - qs, \tag{5}
$$

where ε and q are positive constants and exponential term $-qs$ can guarantee that the state of the system approaches to the sliding mode with the value of s and usually the convergence speed is faster than the traditional reaching law of $\dot{s} = -\varepsilon\,\mathrm{sgn}(s)$.

The power reaching law (RL 2) can be chosen as,

$$
\dot{s}_2 = -\varepsilon|s|^{\alpha}\,\mathrm{sgn}(s). \tag{6}
$$

Using small control gain can ensure to reduce the overshoot by adjusting the value of when the state is far away from the sliding mode. Combining (5) and (6), we can obtain the modified power reaching law (RL 3) as,

$$
\dot{s}_3 = -\varepsilon|s|^{\alpha}\,\mathrm{sgn}(s) - qs, \tag{7}
$$

which guarantees the faster convergence speed by the exponential term and reduces the overshoot. With the modified reaching law, a new integral sliding surface is proposed. The conventional sliding surface [14] can be written as,

$$
s = cx_1 + x_2. \tag{8}
$$

Due to the conventional sliding surface, the asymptotic stability of the sliding mode is guaranteed by choosing the proper value of c. However, the controller of the PMSM makes the conventional sliding surface to be susceptible to external interference or disturbance. In order to achieve more robustness and fast convergence, a new integral sliding surface is proposed as,

$$
s = c_1x_2 + c_2\int_0^t x_1^{\beta}d\tau, \tag{9}
$$

where c_1, c_2 and β are positive constants and the integral term can improve the robustness of controller. In order to design a new controller based on the integral sliding surface, by combining (5) and (9), we can obtain the PMSM speed controller of *q*-axis reference current described as,

$$
i_q = \frac{1}{D}\int_0^t\left(\frac{c_2}{c_1}x_1^{\beta} + \frac{\varepsilon}{c_1}\mathrm{sgn}(s) + \frac{q}{c_1}s\right)d\tau. \tag{10}
$$

By defining $k_1 = c_2/c_1$, $k_2 = \varepsilon/c_1$, $k_3 = q/c_1$, (10) can be rewritten as,

$$
i_q = \frac{1}{D}\int_0^t\left(\frac{c_2}{c_1}x_1^{\beta} + \frac{\varepsilon}{c_1}\mathrm{sgn}(s) + \frac{q}{c_1}s\right)d\tau. \tag{11}
$$

The Lyapunov function candidate can be used to prove control system stability, i.e., the system state of this sliding mode control can reach the sliding surface from any initial state in finite time, and it is defined as,

$$
V = \frac{1}{2}s^2. \tag{12}
$$

By combining (5) and (12) and taking the derivative of (12), we have

$$
\dot{V} = s\dot{s} = s\left[-\varepsilon\,\mathrm{sgn}(s) - qs\right] = -\varepsilon|s| - qs^2 \le 0. \tag{13}
$$

As ε and q are positive constants in (5), it means $\dot{V} \le 0$. Therefore, according to Lyapunov theory, the speed error for (3) can converge to zero in finite time by

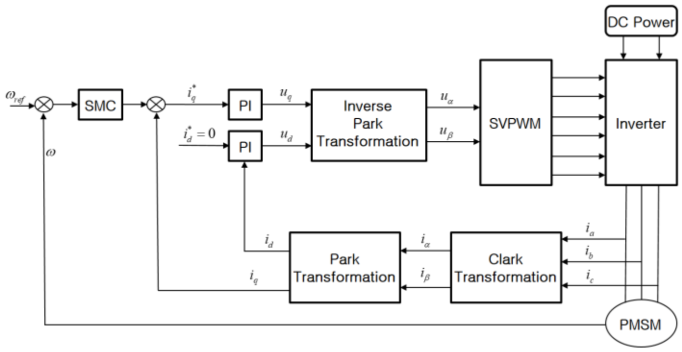

Fig 1. Three-phase PMSM simulation block diagram.

designing the sliding surface of (5) and sliding mode control law of (11).

If a different reaching law of a sliding surface is used, the performance of the controller is different. Next, the dynamic performance of the proposed controller is verified by comparing the controller composed of a traditional sliding mode surface with the proposed controller. Three reaching laws (RL 1 through RL 3) for the same control parameters are selected and applied to the proposed speed control law for PMSM, and the simulation has verified the influence of different reaching laws on the performance of the controller.

IV. SIMULATION

In this section, to demonstrate the effectiveness of the NSMC based on the novel sliding mode surface, simulations of TSMC and NSMC in one PMSM system were conducted. The block diagram of the PMSM speed-regulation system is shown in Fig. 1. Relative tolerance of the system was set to 0.0001 and the sampling cycle time was set to $T_s = 10\ \mu s$. The external load torque is applied during 0.075 and 0.125 seconds with the value of $10\ N \cdot m$. MATLAB/Simulink is used to build the simulation environment.

Fig. 2 and 3 show that the convergence speed of a system based on the exponential reaching law with a traditional sliding surface is slower than that with the proposed sliding surface. As shown in Fig. 3 (a) and (b), when the external disturbance is added at 0.075 sec. and removed at 0.125 sec., the speed and electrical magnetic torque fluctuations can happen.

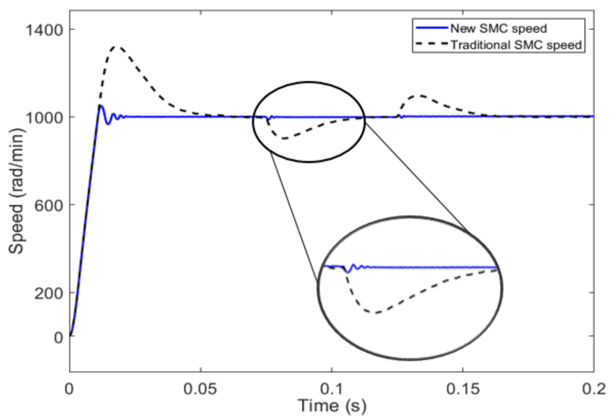

Fig 2. *Simulation results based on the exponential reaching law.*

TABLE I. PMSM PARAMETERS

Parameter	Value	Unit
R_s	2.875	$[\Omega]$
L_s	8.5	$[mH]$
φ_f	0.175	$[Wb]$
J	0.0003	$[kg \cdot m^2]$
B	0.0008	$[N \cdot m \cdot \sec / rad]$
n_p	4	
ω_{ref}	1000	$[rad / \min]$

The PMSM parameters used in the simulation are given in table 1, and the PI parameters of both current loops are the same as $k_{pc} = 17, k_{ic} = 5.75$. On the contrary, as shown in Fig. 3 (c) and (d), when the NSMC is applied, the system shows better dynamic performance. Table 2 is used for all simulation parameters of PMSM controller as follows

TABLE II. SIMULATION PARAMETERS OF THE PROPOSED CONTROLLER

Parameter	Value
Sliding surface gain, $c = c_2$	60
Sliding surface gain, c_1	40
Reaching law gain, ε	200
Reaching law gain, q	300
Gain of the controller, β	9/8
Power reaching law gain, α	0.5

Moreover, the anti-disturbance ability for the proposed sliding surface case shows better performance. The controller of the proposed sliding surface with exponential reaching law also has better dynamic performance. For the same reaching law, the proposed sliding surface controller obtains a faster convergence rate and stronger interference anti-disturbance robustness.

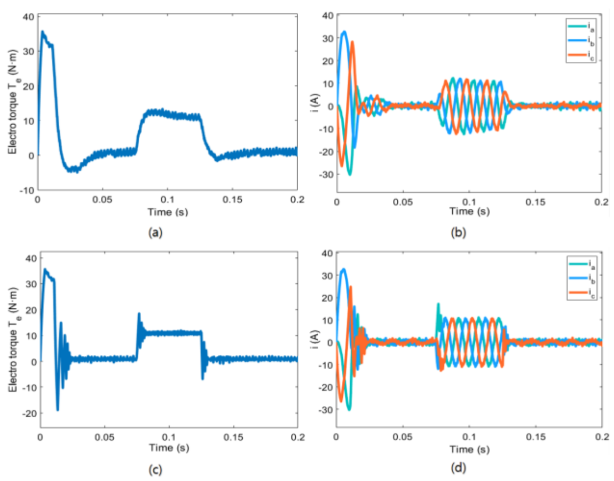

Fig 3. *Simulation results of dynamic response under the TSMC controller: (a) electro torque and (b)three-phase current. Under the NSMC controller: (c) electro torque. (d)three-phase current.*

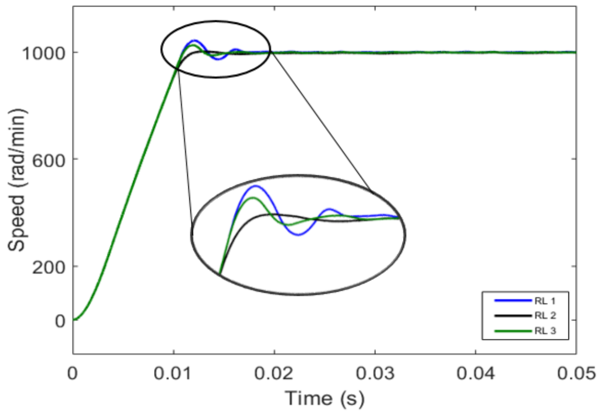

Fig 4. *Simulation results based on new integral sliding surface.*

Next, the proposed controller is simulated with a different reaching law with the same parameters values in table 2. Fig. 4 shows a comparison of different speed responses based on the new integral sliding surface incorporated into the reaching law. The PMSM controller of convergence speed in RL 1 and RL 3 are faster than RL 2 in same control parameters, but the responses exist overshoot and chattering. The speed response based in RL 2 shows no overshoot, but convergence time is prolonged.

V. CONCLUSTION

This paper proposed a speed controller based on a new integral sliding surface for PMSM in terms of improving speed tracking and reducing anti-disturbance properties compared with the TSMC. Through simulation, it was verified that the proposed novel sliding surface control not only achieves the high dynamic performance, but also ensures strong anti-disturbance robustness and suppresses unexpected torque. In this paper, different reaching law methods based on the new integral sliding surface were applied to compare the dynamic response, and an optimal reaching law was obtained. For the same sliding mode surface, it was also proved that different reaching laws affect controller performance.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2019R1A2C1002343, NRF-2020R1I1A1A01061632) and the BK21 FOUR Project.

REFERENCES

[1] Y. Wang, Y. Feng, X. Zhang, and J. Liang, “A new reaching law for anti-disturbance sliding-mode control of PMSM speed regulation system,” IEEE Trans. Power Electronics, vol. 35, pp. 4117–4126, 2020.

[2] M. Marufuzzaman, M. Reaz, L. Rahman, and T. Chang, “High- speed current d-q PI controller for vector controlled PMSM drive,” Scientific World J., vol. 2014, pp. 1-9, 2014

[3] Y. Zhang, and J. Zhu, “Direct torque control of permanent magnet synchronous motor with reduced torque ripple and commutation frequency,” IEEE Trans. Power Electron, vol. 26, pp. 235-248, 2011.

[4] Y. Deng, J. Wang, H. Li, J. Liu, and D. Tian, ‘‘Adaptive sliding mode current control with sliding mode disturbance observer for PMSM drives,’’ ISA Trans., vol. 88, pp. 113–126, 2019.

[5] B. Li, and Y. Feng, “Researching of speed regulation system for AC permanent magnet synchronous motor,” Appl. Mech. Mater., vols. 303-306, pp. 1204-1208, 2013.

[6] H. Jie, G. Zheng, J. Zou, X. Xin, and L. Guo , “Adaptive decoupling control using radial basis function neural network for permanent magnet synchronous motor considering uncertain and time-varying parameters,” IEEE Access, vol. 8, 2020.

[7] J. Li, H. Ren, and Y. Zhong, “Robust speed control of induction motor drives using first-order auto-disturbance rejection controllers,” IEEE Trans. Ind. Appl., vol. 51, pp. 712–720, 2015.

[8] A. Asri, A. Samat, and M. Fazli, “Regular paper speed control design of permanent magnet synchronous motor using Takagi-Sugeno fuzzy logic control,” J. Elect. Syst., vol. 13, pp. 689-695, 2017.

[9] Z. Ma, S. Saeidi, and R. Kennel, “FPGA implementation of model predictive control with constant switching frequency for PMSM drives,” IEEE Trans. Ind. Informat., vol. 10, pp. 2055–2063, 2014.

[10] Q. Song, and C. Jia, “Robust speed controller design for permanent magnet synchronous motor drives based on sliding mode control,” Energy Procedia., vol. 88, pp. 867-873, 2016.

[11] X. Zhang, L. Sun, K. Zhao, and L. Sun, “Nonlinear speed control for PMSM system using sliding-mode control and disturbance compensation techniques,” IEEE Trans. Power Electron., vol. 28, pp. 1358-1365, 2013.

[12] S. Li, M. Zhou, and X. Yu, “Design and implementation of terminal sliding mode control method for PMSM speed regulation system,” IEEE Trans. Ind. Inform., vol. 9, pp. 1879–1891, 2013.

[13] X. Liu, H. Yu, J. Yu, and L. Zhao, ‘‘Combined speed and current terminal sliding mode control with nonlinear disturbance observer for PMSM drive,’’ IEEE Access, vol. 6, pp. 29594–29601, 2018.

[14] P. Gao, G. Zhang, H. Ouyang, and L. Mei, “A sliding mode control with nonlinear fractional order PID sliding surface for the speed operation of surface-mounted PMSM drives based on an extended state observer,” Math. Problems Eng., vol. pp. 1-13, 2019.