Integral Sliding Mode Control with Improved Reaching Law for Brushless DC Motor Speed Control

Ferhat BODUR
Department of Electrical Electronics Engineering
Gazi University
Ankara, Turkey
ferhatbodur@gazi.edu.tr

Orhan KAPLAN
Department of Electrical Electronics Engineering
Gazi University
Ankara, Turkey
okaplan@gazi.edu.tr

***Abstract*—The design of speed control under various operation such as constant load situations, variable load situations and variable regulated speed situations of brushless DC motors is an important requirement. In brushless DC motors applications, there are modeling errors and external disturbance due to environmental conditions between the actual model and the nominal one. Besides these, due to the non-linearity of the brushless DC motor driver's properties, traditional linear control methods fall short of their expectations in terms of efficiency. Therefore, a robust control method is necessary to overcome these issues. Sliding mode control is a robust nonlinear control technique against external disturbances and parameter uncertainties. This article proposes a sliding mode controller that uses integral sliding surface and has an improved reaching law in order to enhance the dynamic performance of management of the speed in brushless DC motors. The efficiency of the proposed controller under different test scenarios is evaluated and compared with other existing methods such as traditional SMC. The simulation results show that the proposed controller is superior to other methods and improves its dynamic performance.**

Keywords—BLDC, sliding mode control, speed regulation, chattering reduction

I. INTRODUCTION

Brushless Direct Current Motor (BLDC) are from the special electrical machine group. BLDC motors are a type of motor that delivers commutation electronically rather than mechanically. It is similar in structure to synchronous machines. These motors have many advantages such as long life, no brush maintenance, noiseless operation, strong stability, high torque, fast response, low inertia and, high efficiency [1]. Classical linear control methods such as PI, PID and their variants are widely used in BLDC speed control due to their simple parameter setting and easy implementation [2]. However, the performance of classical linear methods reduces in the presence of motor internal parameter uncertainties and external disturbances. Recently, many researchers are interested in the nonlinear control methods such as model predictive control [3], MPPT based control [4], fuzzy logic [5] and, sliding mode control (SMC) [6] for BLDC motors, one of the nonlinear systems.

SMC have been studied intensively by researchers due of its advantages in fast dynamic response, robustness against disturbance or internal parameters uncertainty, and simplicity [7]. However, there is an important dilemma between the chattering which is oscillation occurring in the state variables of the system, and increasing the rate of convergence of the system [8] . When the gains in the reaching law of the SMC are increased to improve the dynamic performance of the system, the chattering size also increases.

To overcome this issue, the researchers are suggested that efforts are being improved the sliding surface dynamics using reaching law methods. In [9], constant reaching law (CRL), constant proportional reaching law (CPRL) and, power reaching law (PRL) methods are presented to reduce chattering and improve dynamic responses. To increase system robustness while reducing chattering and quickly reaching the sliding surface, double power reaching law (DPRL) [10] is used. In [11] , a sliding mode controller based on the exponential reaching rule is constructed to regulate the speed of a BLDC motor. The Kalman Filter also increased the system's control effects, which enhanced performance in the presence of noise disturbances. Double-loop first order sliding controllers based on the exponential reaching law algorithm was proposed to control the both speed and current of the BLDC motor in [12]. In order to reduce chattering, the authors of [13] suggested an SMC control approach that uses the tangent function instead of signum function in the control rule. In [14], torque observer-based dual-loop current mode SMC using exponential reaching law BLDC motor was designed to meet high performance demands. A novel reaching laws has the ability to self-adaptively adjust in response to various system reaching stages for high-performance speed regulation requirement. Saturation function was used instead of signum to reduce the chattering in reaching law in [15]. Robust SMC with a hysteresis current controller has been proposed in [16] to fulfill the demand for robustness of BLDC motor against disturbance effects. Recently, it has been offered to improve performance in applications such as renewable energy based dc or ac microgrids [10], speed control of permanent magnet synchronous motors [17], power electronics converters [18], as well as BLDC motor. As a result, the performance of BLDC motor speed control can be enhanced through improving the reaching law approaches that effect the sliding surface dynamics.

In this paper, an improved reaching law is proposed to improve the speed regulation for BLDC motor speed control.

The following are the contributions in this paper:

- The output angular velocity (ω) is tracked the desired reference velocity (ω_{ref}). An improved reaching law rule is proposed using speed error as the state variable in SMC.
- It is presented to have a faster convergence rate compared to existing control reaching law rules. Then, saturation function (sat) is used to prevent the chattering in the proposed improved control rule.
- The simulation findings clearly show that the proposed method performs significantly better in terms of a decrease in steady state error, a quicker settling time, a lower overshoot in the speed response. It also has increased disturbance rejection abilities against load torque changes.

The rest of this paper is organized as follows. Section II describes the BLDC motor system model. The design procedure of the sliding mode controller with improved reaching law is presented in Section III. Section IV shows simulation results to validate the effectiveness of the proposed strategy. Finally, conclusions are given in Section V.

II. Dynamic Model of BLDC Motor

The mathematical model of the motor is developed based on the under following assumptions.

(I) The motor stator core is not saturated that the magnetic circuit is linear.

(II) Inductance's parameters are constant.

(III) The motor mechanical and iron losses are omitted.

The mathematical model under the dq coordinate system is as follows:

$$v = iR + L\frac{di}{dt} + k_e\omega \tag{1}$$

Where i, v, R, L, ω are phase current, phase voltage, resistance and inductance of winding, respectively. k_e is the back emf coefficient.

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{2}$$

Where $T_e = k_t i$ is the electromagnetic torque, $T_L$is the load torque, k_t is torque coefficient and Equation (2) are rearranged as [11]:

$$\frac{di}{dt} = \frac{1}{L}(v - iR - k_e\omega) \tag{3}$$

$$\frac{d\omega}{dt} = \frac{1}{J}(k_t i - B\omega - T_L) \tag{4}$$

Suppose that the speed error is as

$$x_1 = \omega_{ref-}\omega \tag{5}$$

where ω_{ref} is reference speed of BLDC motor, that is, $x_1$is the error and $x_2$is the error dynamic. From Eqs. (1, 2, 3, 4 and 5), we can define that:

$$\dot{x}_1 = \dot{\omega}_{ref-}\dot{\omega} = x_2 \tag{6}$$

$$\dot{x}_2 = \ddot{\omega}_{ref-}\ddot{\omega} \tag{7}$$

$$\dot{x}_2 = \ddot{\omega}_{ref-}\left(\frac{RB+k_tk_e}{JL}\right)x_1 - \left(\frac{R}{L}+\frac{R}{J}\right)x_2 + \left(\frac{R}{L}+\frac{R}{J}\right)\dot{\omega}_{ref} + \left(\frac{RB+k_tk_e}{JL}\right)\omega_{ref} - \frac{k_t}{JL}u + \frac{R}{JL}T_L + \frac{T_L}{J} \tag{8}$$

As a result, BLDC motor state dynamics can be rearranged as

$$\dot{x}_1 = x_2 \tag{9}$$

$$\dot{x}_2 = f(x) + g(x)u + d(x,t) \tag{10}$$

where, $f(x)$ and $g(x)$ are known smooth function, d is a bounded disturbance and $D \geq |d|$. D is the disturbance boundary.

III. Design of SMC with Improved Reaching Law

A. Problem Statement of SMC

The SMC design consists of two phases, the reaching phase and the sliding phase. In the reaching phase, the states of the system are driven from any initial condition on the phase plane toward a predefined sliding surface (s). Sliding variables are remained on the sliding surface in the sliding mode. In SMC design, the reaching law technique is characteristic of different reaching laws used to achieve convergence of the state variables onto the sliding surface. The reaching laws techniques directly describes the sliding surface dynamics during the reaching phase. The properties of some reaching law techniques used in the literature are given in Table-1. In addition, Table-1 shows that the convergence time of the system depends on the chosen sliding gain parameters ($s(0)$:initial condititon). These gains can be increased to decrease the reaching time. However, because this parameter selection generates the chattering from discontinuity functions in the reaching law, the magnitude of its value is limited.

TABLE I. The Different reaching Laws Charecteristics

Methods	*Dynamics of Sliding Surface*	*Reaching Time (t_r)*	*Positive/Negative*
Constant Rate RL	$\dot{s} = \eta_1 sign(s)$	$\frac{s(0)}{\eta_1}$	• The simplest SMC design • t_r is linear function
Constant Proportional RL	$\dot{s} = \gamma s - \eta_1 sign(s)$	$\frac{1}{\gamma}ln\left(1+\frac{\gamma\|s(0)\|}{\eta_1}\right)$	• Basic SMC design • t_r is the logarithmic function
Power RL	$\dot{s} = -\eta_1\|s\|^\alpha sign(s)$	$\frac{\|s(0)\|^{(1-\alpha)}}{\eta_1(1-\alpha)}$	• Simple design • t_r is the exponential function • Changeable reaching time
Double Power RL	$\dot{s} = -\eta_1\|s\|^\alpha sign(s) - -\eta_2\|s\|^\beta sign(s)$	$\frac{\|s(0)\|}{\eta_1(1-\alpha)} + \frac{1}{\eta_1(1-\beta)}$	• Complex SMC Design • Changeable and fast reaching time

B. Proposed Integral Sliding Mode Controller with Improved Reaching Law

In the SMC design, a surface that satisfies the stable condition is chosen. Then, an appropriate control rule is determined that drives the sliding states towards sliding surface in finite time. The sign(s) function, which is the main cause of the chattering, in traditional reaching laws is discontinuous. In proposed reaching law, the saturation function sat(s) is used to replace the sign(s). Let us define the proposed the improved reaching law is as

$$\dot{s} = -\eta_1(|s|^{\alpha} - 1)sat(s) \; - \eta_2|s|^{\beta}sat(s) \quad (11)$$

$$sat(s) = \begin{cases} sign(s), & |s| > \varepsilon \\ x, & |s| \le \varepsilon \end{cases} \quad (12)$$

where $\eta_1 > 0, \eta_2 > 0$, $\beta \geq 1$ *and*, $0 < \alpha < 1, \varepsilon$ is boundary layer thickness. The proposed integral sliding surface is as

$$s = \lambda x_1 + x_2 + \int x_1 dt \quad (13)$$

where $\lambda > 0$. From Equations (9, 10 and 13) the time derivative of sliding surface is attained as follows.

$$\dot{s} = \lambda \dot{x}_1 + \dot{x}_2 + x_1 \quad (14)$$

$$\dot{s} = \lambda x_2 + f(x) + g(x)u + d(x,t) + x_1 \quad (15)$$

From Equations (11 and 15), the control rule is obtained as follows.

$$u = \frac{1}{g(x)}\big[-\lambda x_2 - f(x) - D - x_1 - \eta_1(|s|^{\alpha} - 1)sat(s) \; - \eta_2|s|^{\beta}sat(s)\big] \quad (16)$$

To prove Stability analysis of improve reaching law, candidate Lyapunov function is chosen as: $V = \frac{1}{2}s$. For stability of the system, the following condition is ensured as

$$\lim_{s\to 0}\dot{V} = \lim_{s\to 0} s\dot{s} \le 0 \quad (17)$$

Substitute Equation (15) into Equation (17), we can obtain as

$$s\dot{s} = s[\lambda x_2 + f(x) + g(x)u + d(x,t) + x_1] \quad (18)$$

Substitute the control rule into Equation (18)

$$s\dot{s} = -(\eta_1(|s|^{\alpha} - 1) \; - \eta_2|s|^{\beta} + D)|s| + d(x,t).s \quad (19)$$

Where $(|s|^{\alpha} - 1) \geq 0$, $|s|^{\beta} \geq 0$, and, $D \geq |d|$, $sat(s)s \cong |s| > 0$, all gains are greater than zero as previously defined. So $\dot{V} < 0$, and if and only if s = 0, the equality holds. As a result, the sliding surface's stability condition could be proved.

IV. Simulation Results

In order to prove the superiority of the proposed method, the speed control model of the BLDC motor is established in Matlab/Simulink. First, the proposed reaching law was analyzed. Then, simulation tests are performed for the BLDC motor, the parameters of which are presented in Table 2.

TABLE II. BLDC Motor Parameters

Parameters	Values
DC voltage (v)	20 V-24 V
Reference speed (ω_{ref})	1000-1800 *rpm*
Inertia (J)	(0.8).10^3
Stator Phase Inductance (L)	1mH
Rotor flux linkage (C)	0.175
Stator Phase Resistance	3 Ω
Pole pairs	4

A. Performance Analysis the Proposed Improved Reaching Law

Combining the functions of the two terms, the proposed improved reaching law in Equation (11) can give the system a better dynamic performance during the reaching phase. The proposed method is compared fairly with the existing reaching law methods given in Table 1 using the same parameters. The selected parameters are as: $\eta_1 = 1.1, \eta_2 = 5.5, \alpha = 0.7, \beta = 1.5, \varepsilon = 0.2$ and, the initial conditions $x_o = (0.2,1)$. It is clear from the Figs. 1 and 2 that the proposed approach has a faster convergence rate and causes less the chattering in states variables. Figs. 3 and 4 are showed sliding variables of the proposed reaching law and CRL. It is showed that while chattering does not exist in the proposed method, it does occur in the CRL using sign(s).

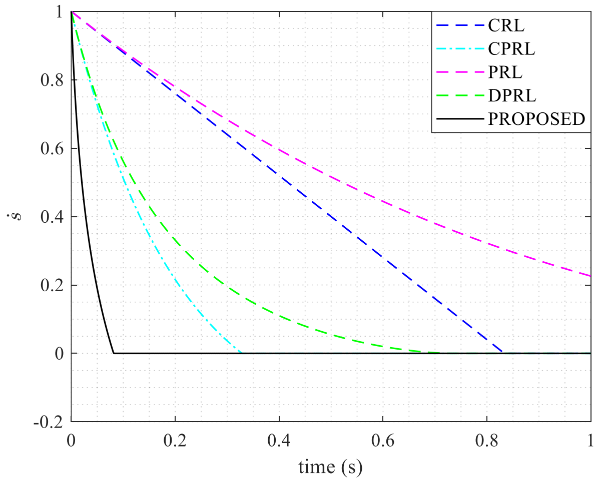

Fig. 1. Comparison of the convergence rate of different reaching laws.

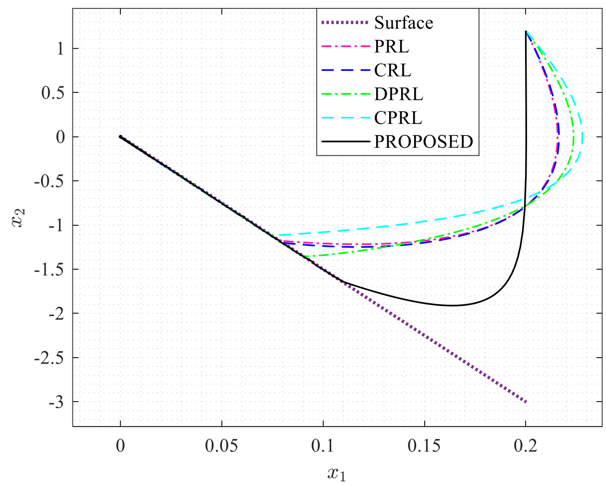

Fig. 2. The phase trajectories of the different reaching laws

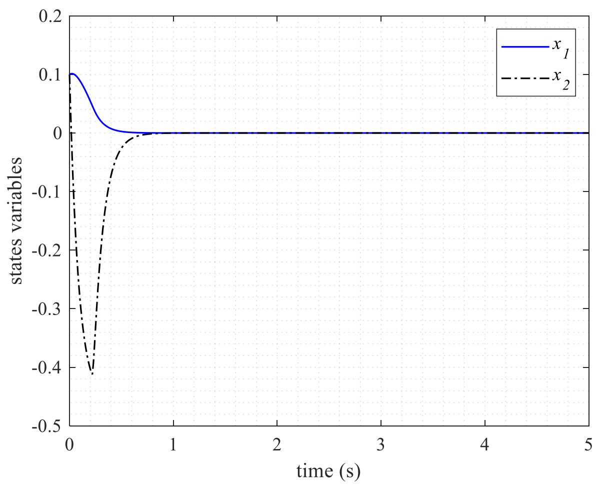

Fig. 3. Sliding variables of the proposed reaching law using *sat(s)*

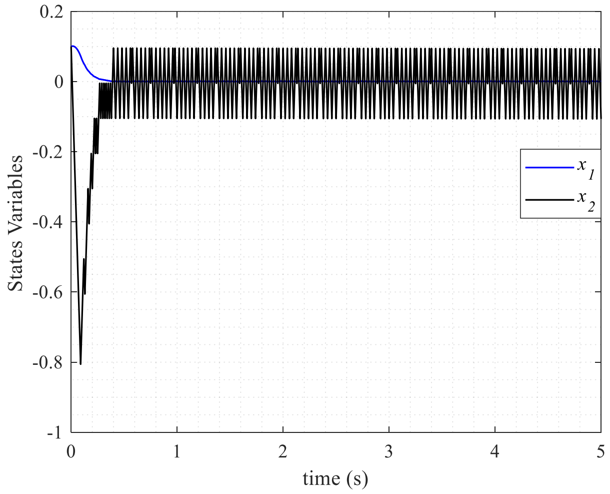

Fig. 4. The sliding variables of CRL using *sign(s)*

B. BLDC Motor Speed Control via Proposed Method

Fig. 5 shows the BLDC motor speed control scheme. The proposed controller receives special commutation signals from the hall effect sensor and controls the rotor speed. The simulations are offered for constant load condition, variable load condition and variable speed condition. The dynamic responses of the proposed method are compared traditional SMC method and its dynamic responses given in the following Tables 3 and 4.

Firstly, the speed tests are carried out for different reference speed changes given in case 1 and case 2. It is clear from Figs. 6 and 7 that the proposed method is tracked the reference speed in a faster time with less chattering.

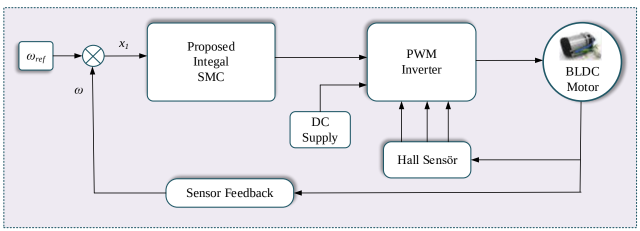

Fig. 5. The BLDC motor the speed control scheme

Case-1:

$$\omega_{ref} = \begin{cases} 1000\ rpm, 0 \leq t < 0.1s \\ 750\ rpm, 0.1s \leq t < 0.2s \end{cases}$$

Case-2:

$$\omega_{ref} = \begin{cases} 500\ rpm, 0 \leq t < 0.1s \\ 800\ rpm, 0.1s \leq t < 0.2s \end{cases}$$

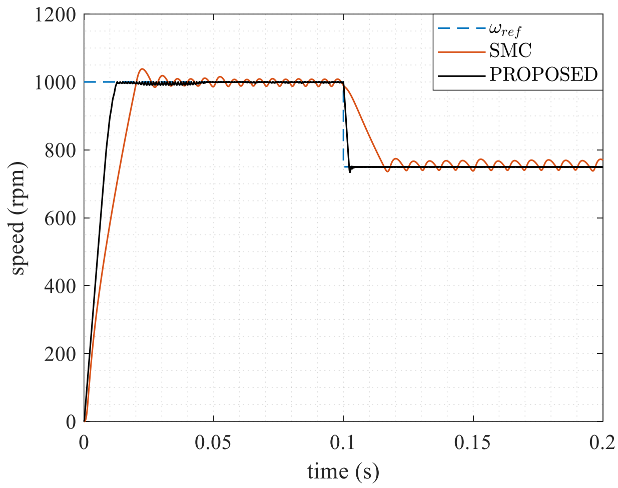

Fig. 6. The step response for speed change in *case-1*

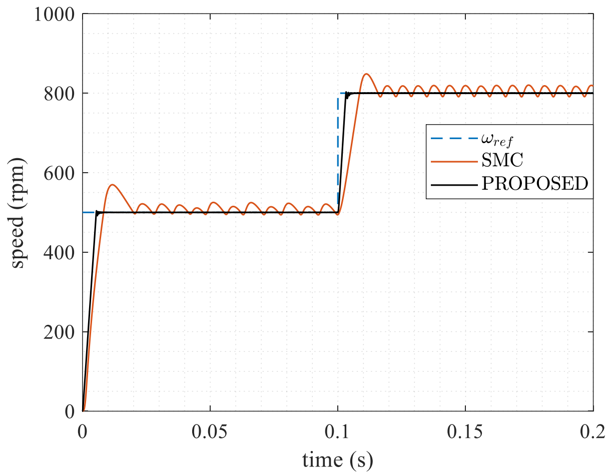

Fig. 7. The step response for speed change in *case-2*

Secondly, the proposed method is tested under different load conditions. Load tests are given in case 3 and case 4. The speed of the BLDC motor is chosen as $\omega = 500\ rpm$. Fig. 8 depicts the dynamic response to change under no load at start-up and then for the condition going from no load to full load.

Case-3:

$$torque_{ref} = \begin{cases} No\ load, 0 \leq t < 0.5s \\ 10\ Nm, 0.5s \leq t < 1s \end{cases}$$

Case-4:

$$torque_{ref} = \begin{cases} 10\ Nm, 0 \leq t < 0.5s \\ 5\ Nm, 0.5s \leq t < 1s \end{cases}$$

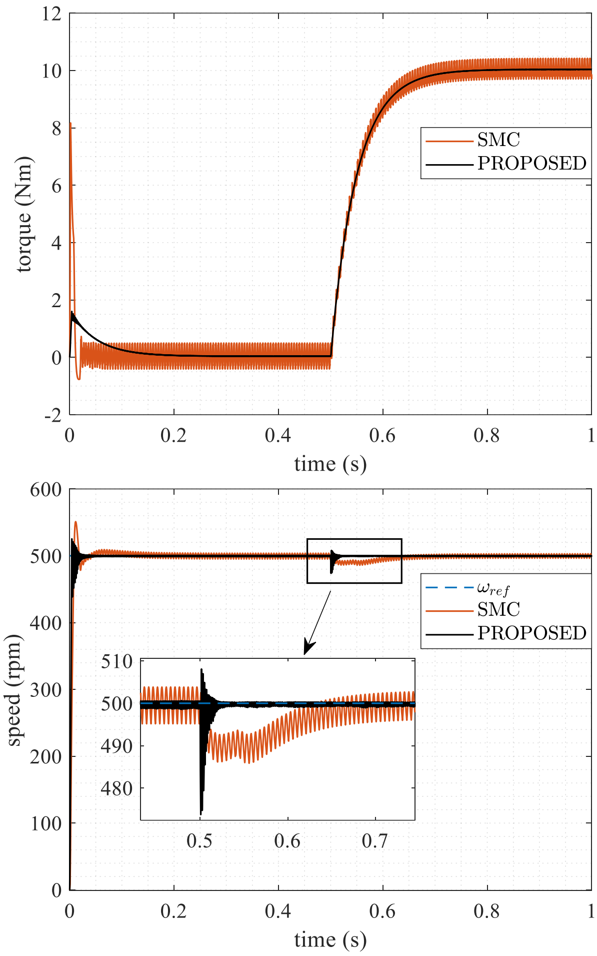

Fig. 8. The dynamic responses for no load in case-3

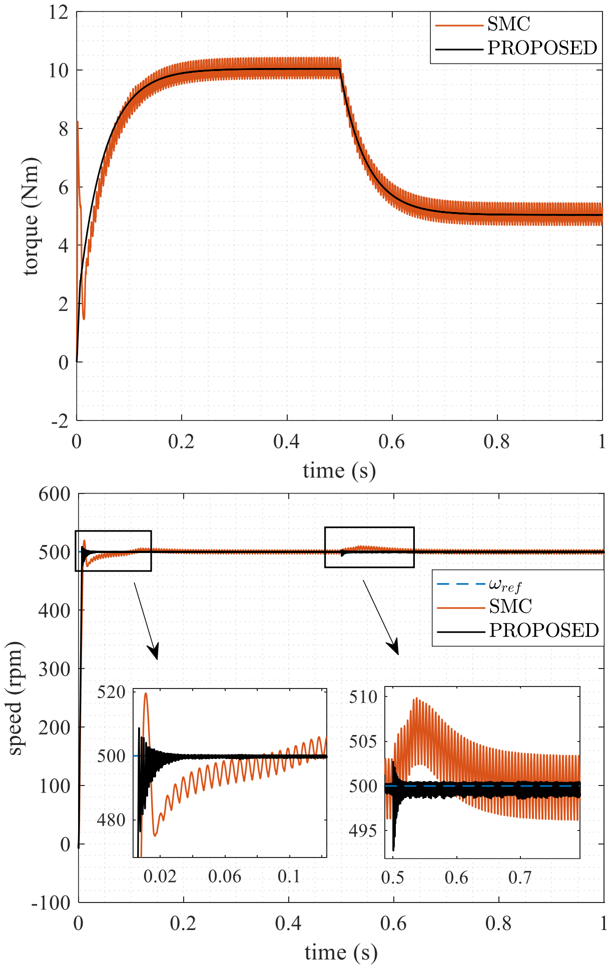

Fig. 9. The step response for load change in case-4

It can be seen in Fig. 8 that the proposed method follows the reference speed more effectively during load changes. The proposed method also has less chattering compared to SMC. Fig. 9 shows that when there is a decrease from full load to half load, according to the change given in case 4, the proposed method has less overshoot at the beginning. It also captures the reference speed value more quickly.

TABLE III. THE DYNAMIC RESPONSE ANALYSIS

Test case	Controllers	Performances			
		RT (s)	*ST (s)*	*SSE(rpm)*	*Mp (%)*
Case1	*SMC*	*0.0156*	*0.0449*	*6.4741*	*4.8229*
	PROPOSED	*0.0089*	*0.0120*	*0.6172*	*0.0513*
Case2	*SMC*	*0.0058*	*0.0297*	*17.62*	*13.932*
	PROPOSED	*0.0042*	*0.0053*	*0.1149*	*0.8131*
Case3	*SMC*	*0.0058*	*0.0650*	*5.0655*	*10.215*
	PROPOSED	*0.0028*	*0.0590*	*1.7834*	*0.1404*
Case4	*SMC*	*0.0062*	*0.0519*	*3.6356*	*3.9167*
	PROPOSED	*0.0049*	*0.0120*	*1.0408*	*1.744*

The dynamic results obtained from all cases are presented in Table 3. Table 4 offers a numerical comparison of the simulation results of SMC and proposed approach. According to the finding obtained from the Tables 3 and 4, the improved proposed method has a much better performance. The proposed method has lower steady state error (*SSE*), faster settling time (*ST*) and rise time (*RT*), smaller overshoot in speed (*Mp*), and much better anti-disturbance capabilities than SMC.

TABLE IV. THE PERFORMANCE ANALYSIS

Test case	Controllers	RMSE	MSE	MAE	ISE	IAE
Case1	*SMC*	*0.218*	*0.4757*	*0.8434*	*0.0547*	*0.0603*
	PROPOSED	*0.135*	*0.1840*	*0.3015*	*0.0233*	*0.0414*
Case2	*SMC*	*0.946*	*0.8967*	*0.3714*	*0.0570*	*0.0198*
	PROPOSED	*0.534*	*0.2853*	*0.0961*	*0.0429*	*0.0172*
Case3	*SMC*	*0.311*	*0.968*	*0.5711*	*0.0365*	*0.0204*
	PROPOSED	*0.191*	*0.366*	*0.1952*	*0.0345*	*0.01952*
Case4	*SMC*	*0.273*	*0.7490*	*0.4701*	*0.0683*	*0.1825*
	PROPOSED	*0.251*	*0.633*	*0.2376*	*0.0289*	*0.0237*

V. CONCLUSION

This paper proposes a sliding mode control method that uses an integral sliding surface and has an improved reaching law, for BLDC motor speed control. The integral sliding mode control with proposed reaching law is compared with existing other reaching law methods. It is seen in the simulation results that it has been shown to be faster and its have less chattering. The controllers' efficiency has been analyzed for various operating conditions of BLDC motors. The proposed controller is tracked the reference speed values faster and more robustly. Furthermore, the proposed controller provides robust dynamic responses in the presence of disturbances such as speed fluctuations and load uncertainties. The proposed method can also be implemented for the power electronics converters and different motors such as permanent magnet synchronous motor.

References

[1] E. Ş, B. Fincan, and M. Imeryuz, "A BLDC motor drive with four switch three phase inverter," in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, 20-23 Nov. 2016 2016, pp. 804-808, doi: 10.1109/ICRERA.2016.7884447.

[2] G. S. John and A. T. Vijayan, "Anti-windup PI controller for speed control of brushless DC motor," in *2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI)*, 21-22 Sept. 2017 2017, pp. 1068-1073, doi: 10.1109/ICPCSI.2017.8391874.

[3] K. Xia, Y. Ye, J. Ni, Y. Wang, and P. Xu, "Model Predictive Control Method of Torque Ripple Reduction for BLDC Motor," *IEEE Transactions on Magnetics*, vol. 56, no. 1, pp. 1-6, 2020, doi: 10.1109/TMAG.2019.2950953.

[4] H. Alrajoubi, S. Oncu, and S. Kivrak, "An MPPT Controlled BLDC Motor Driven Water Pumping System," in *2021 10th International Conference on Renewable Energy Research and Application (ICRERA)*, 26-29 Sept. 2021 2021, pp. 116-119, doi: 10.1109/ICRERA52334.2021.9598595.

[5] M. K. Al-Nussairi and R. Bayindir, "Stabilization of a DC-Link of Microgrids feeding a Inverter-BLDC motor drive using a PI-Fuzzy," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 14-17 Oct. 2018 2018, pp. 1514-1519, doi: 10.1109/ICRERA.2018.8566941.

[6] Z. Alqarni, "Higher Order Sliding Mode Control for Speed Control of BLDC Motor," in *2023 IEEE 13th Annual Computing and Communication Workshop and Conference (CCWC)*, 8-11 March 2023 2023, pp. 0212-0217, doi: 10.1109/CCWC57344.2023.10099280.

[7] B. F and K. O, "Second-Order Sliding Mode Control Algorithms in DC/DC Buck Converter," in *2022 10th International Conference on Smart Grid (icSmartGrid)*, 27-29 June 2022 2022, pp. 380-386, doi: 10.1109/icSmartGrid55722.2022.9848696.

[8] O. Kaplan and F. Bodur, "Super Twisting Algorithm Based Sliding Mode Controller for Buck Converter Feeding Constant Power Load," *International Journal of Renewable Energy Research*, vol. 12, no. 1, pp. 134-145, Mar 2022. [Online]. Available: <Go to ISI>://WOS:000787787500014.

[9] G. Weibing and J. C. Hung, "Variable structure control of nonlinear systems: a new approach," *IEEE Transactions on Industrial Electronics*, vol. 40, no. 1, pp. 45-55, 1993, doi: 10.1109/41.184820.

[10] T. K. Roy, M. A. H. Pramanik, and S. K. Ghosh, "Design of an integral terminal-based sliding mode controller for PV and BESS-based DC microgrids," *Energy Nexus*, vol. 7, p. 100130, 2022/09/01/ 2022, doi: https://doi.org/10.1016/j.nexus.2022.100130.

[11] S. Tingna, L. Na, Z. Qian, and X. Changliang, "Brushless DC motor sliding mode control with Kalman Filter," in *2008 IEEE International Conference on Industrial Technology*, 21-24 April 2008 2008, pp. 1-6, doi: 10.1109/ICIT.2008.4608509.

[12] J. J. Rath, S. Saha, and H. P. Ikkurti, "Sliding mode scheme for speed and current control of brushless DC (BLDC) motor," in *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM -2012)*, 30-31 March 2012 2012, pp. 450-455.

[13] J. R. B. A. Monteiro, C. M. R. Oliveira, and M. L. Aguiar, "Sliding mode control of brushless DC motor speed with chattering reduction," in *2015 IEEE 24th International Symposium on Industrial Electronics (ISIE)*, 3-5 June 2015 2015, pp. 542-547, doi: 10.1109/ISIE.2015.7281525.

[14] Y. Shao, R. Yang, J. Guo, and Y. Fu, "Sliding mode speed control for brushless DC motor based on sliding mode torque observer," in *2015 IEEE International Conference on Information and Automation*, 8-10 Aug. 2015 2015, pp. 2466-2470, doi: 10.1109/ICInfA.2015.7279700.

[15] S. Yang, D. Shan, and J. Zheng, "Sliding Mode Control for Brushless Direct Current Motor Drive Based on a New Reaching Law," in *2021 IEEE International Conference on Artificial Intelligence and Computer Applications (ICAICA)*, 28-30 June 2021 2021, pp. 906-910, doi: 10.1109/ICAICA52286.2021.9498127.

[16] J. Mehmood, M. Abid, M. S. Khan, and A. Q. Khan, "Design of Sliding Mode Control for a Brushless DC Motor," in *2020 IEEE 23rd International Multitopic Conference (INMIC)*, 5-7 Nov. 2020 2020, pp. 1-5, doi: 10.1109/INMIC50486.2020.9318215.

[17] Y. Wang, Y. Feng, X. Zhang, and J. Liang, "A New Reaching Law for Antidisturbance Sliding-Mode Control of PMSM Speed Regulation System," *IEEE Transactions on Power Electronics*, vol. 35, no. 4, pp. 4117-4126, 2020, doi: 10.1109/TPEL.2019.2933613.

[18] H. Komurcugil, S. Bayhan, N. Guler, and H. Abu-Rub, "A New Exponential Reaching Law Approach to the Sliding Mode Control: A Multilevel Multifunction Converter Application," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 8, pp. 7557-7568, 2023.