# A Disturbance Observer Based Sliding Mode Controller for BLDC Motors

Zhang, Xing Guo; Li, Jie; Desai, Keval Prakash; Tripathi, Prabhat Ranjan

*Published in:*
Journal of Physics: Conference Series

*DOI (link to publication from Publisher):*
10.1088/1742-6596/3074/1/012037



*Publication date:*
2025

*Document Version*
Publisher's PDF, also known as Version of record

Journal of Physics:
Conference Series



**PAPER • OPEN ACCESS**

# A Disturbance Observer Based Sliding Mode Controller For BLDC Motors

To cite this article: Xing-guo Zhang *et al* 2025 *J. Phys.: Conf. Ser.* **3074** 012037

Journal of Physics: Conference Series **3074** (2025) 012037 doi:10.1088/1742-6596/3074/1/012037

# A Disturbance Observer Based Sliding Mode Controller For BLDC Motors

**Xing-guo Zhang[1], Jie Li[2*], Keval Prakash Desai[3] and Prabhat Ranjan Tripathi[4]**

[1] College of Mechanical and Electrical Engineering, Xi'an Technology and Business College, Shanxi, P.R.China
[2] Department of Electronics, Aalborg University, Aalborg, Denmark
[3] Department of Electrical Engineering, Polytechnic University of Catalonia, Catalonia, Spain
[4] FleetRF Pvt Ltd.,Greater Noida, India
*Corresponding author E-mail:jiel@es.aau.dk

**Abstract.** This paper proposes a sliding-mode variable structure controller (SMC) based on a disturbance observer for BLDC motors. The SMC exhibits strong insensitivity to turbulence, effectively suppressing disturbances in the BLDCM system. To further enhance performance, a novel variable exponent reaching law is designed, significantly reducing chattering. Additionally, a disturbance observer is integrated to eliminate steady-state errors, improving control precision. Simulation results demonstrate that the proposed SMC achieves superior control performance for BLDCM, along with excellent robustness against external disturbances.

## 1. Introduction

BLDCM combine the advantages of both DC and AC motors. They exhibit excellent speed regulation characteristics and high operating efficiency, similar to traditional DC motors. Additionally, BLDCMs inherit the high reliability, simple structure, and easy maintenance of AC motors. These superior characteristics have led to their increasingly widespread adoption in industrial applications [1–3].

A BLDCM control system typically employs PID controllers. However, PID controllers exhibit poor regulation capability when facing parameter variations and external disturbances, making them inadequate for servo system requirements. Alternative approaches such as neural networks and model reference adaptive control suffer from structural complexity and significant computational demands, resulting in high hardware requirements and implementation challenges [4, 5]. Similarly, fuzzy control methods are limited by interdependent fuzzy rules and heavy reliance on operator expertise, often yielding unsatisfactory performance [6–9].

Sliding mode variable structure control (SMVSC) demonstrates strong robustness against parameter variations and external disturbances, making it particularly suitable for brushless DC motor applications [10]. While its discontinuous switching mechanism provides excellent disturbance rejection, this characteristic simultaneously introduces undesirable chattering effects that limit practical implementation. Previous studies have employed various approaches to mitigate this issue: an exponential convergence law was shown to effectively reduce chattering, though it only guarantees convergence to a neighborhood of the origin rather than exact convergence [11]. Alternative methods combining intelligent control with variable structure

Journal of Physics: Conference Series **3074** (2025) 012037 doi:10.1088/1742-6596/3074/1/012037

control have demonstrated improved chattering suppression [12–16], yet these approaches fail to address load torque variations. To overcome these limitations, this paper proposes a novel SMVSC speed controller integrated with a disturbance observer. This combined approach not only maintains the system's robust performance but also compensates for torque variations, thereby enhancing the motor's speed regulation capability.

## 2. BLDC Mathematical Model

The BLDCM employs a star connection without a neutral line. During normal operation, it functions with two-phase conduction, resulting in six distinct operating states. The motor exhibits trapezoidal back-EMF waveforms characterized by a flat-top width of $2/3\pi$ electrical angle. For analytical purposes, we make the following assumptions: (1) the magnetic circuit operates in the unsaturated region, (2) hysteresis and eddy current losses are negligible, and (3) stator windings maintain perfect symmetry. Under these conditions, the three-phase winding voltage balance equation can be expressed as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + D \begin{bmatrix} n & m & m \\ m & n & m \\ m & m & n \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

Where:$p$ is the resistance of the stator phase winding;$u_a$,$u_b$,$u_c$ are the stator phase winding voltages; $e_a$,$e_b$,$e_c$ are the stator phase winding counter electromotive force; $i_a$,$i_b$,$i_c$ are the stator phase winding current; $n$ is the self-inductance of the phase winding; $m$ is the mutual inductance between the windings of each two phases; $D$ is a differential operator $D = d/dt$ .

It is obtained because the three-phase stator windings are connected using a star connection:

$$i_a + i_b + i_c = 0 \tag{2}$$

then

$$mi_b + mi_c = -mi_a \tag{3}$$

The joint equations (1),(2),(3) are obtained:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + D \begin{bmatrix} n-m & 0 & 0 \\ 0 & n-m & 0 \\ 0 & 0 & n-m \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

Simplification of equation (4) gives the motor voltage balance equation:

$$u = H_e\omega + p'i + n'\frac{di}{dt} \tag{5}$$

Where:$p'$is the motor phase resistance; $u, i$ are the motor terminal voltage and phase current, $\omega, H_e$ are the motor angular velocity and reverse electromotive force coefficient, $n'$ is the phase inductance.

The torque balance equation for a brushless DC motor is

$$T_e - T_i = B\omega + J\frac{d\omega}{dt} = C_T\phi i_a = Q_t i \tag{6}$$

Where:$Q_t, J$ are the torque coefficient and the moment of inertia,$T_i, T_e$ the load torque and electromagnetic torque, is the motor damping factor.
The differential equation model of the brushless DC motor is derived from the above equation:

$$\begin{cases} \frac{d\omega}{dt} = -\frac{B}{J}\omega + \frac{(Q_t)}{J}i - \frac{1}{J}T_l \\ \frac{di}{dt} = -\frac{Q_s}{n'}\omega - \frac{p'}{n'}i + \frac{1}{n'}u \end{cases} \tag{7}$$

Derivation of the first equation in Eq. (7) yields

$$J\frac{d^2\omega}{dt^2} = -B\frac{d\omega}{dt} + Q_t\frac{di}{dt} \tag{8}$$

From(6)

$$i = \frac{J}{Q_t}\frac{d\omega}{dt} + \frac{B}{Q_t}\omega + T_i \tag{9}$$

Substituting the second equation in (7), (9) into (8) yields

$$\frac{n'J}{Q_t}\frac{d^2\omega}{dt^2} = -(\frac{p'J}{Q_t} + \frac{Bn'}{Q_t})\frac{d\omega}{dt} - (\frac{Bp'}{Q_t} + H_e)\omega + u - \frac{p'}{Q_t}T_i \tag{10}$$

Order $x_1 = \omega, x_2 = \dot{\omega}$ ,Obtain the equation of state of the brushless DC motor power system.

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -\frac{(Bp' + Q_tQ_s)}{n'J}x_1 - \frac{(p'J + Bn')}{n'J}x_2 \\ \qquad + \frac{(Bp' + Q_tQ_s)}{n'J}\omega^* - \frac{Q_t}{n'J}u + \frac{p'}{n'J}T_l. \end{cases} \tag{11}$$

In brushless DC motor control systems, the regulation of motor speed is accomplished through precise modulation of the PWM inverter's output average voltage by the implemented controller.

## 3. Sliding mode variable structure controller design based on disturbance observer

### *3.1. Convergence law based sliding mode control*

Consider the following nonlinear affine system

$$\dot{x} = f(x) + b(x)u + d(t) \tag{12}$$

In the system formulation, the state and control vectors are respectively defined as $x \in R^n$ and $u \in R^n$ , where $f$,$b$,and $d(t)$ represent the smooth uncertain vector field and the bounded system perturbation. The sliding mode switching surface is subsequently defined according to the following expression:

$$s = gx \tag{13}$$

For the affine system under consideration, where $g$ denotes an n-dimensional row vector, the control input is determined according to the following formulation:

$$u_i(x) = \begin{cases} u_i^+(x) & s_i(x)>0 \\ u_i^-(x) & s_i(x)>0 \end{cases} \tag{14}$$

In the phase plane representation, the system state trajectory is compelled to asymptotically converge toward the predefined sliding manifold when operating outside this surface, and is subsequently constrained to maintain motion along the sliding manifold until ultimate convergence to the equilibrium point is achieved.

The exponential convergence law, originally proposed and developed by Professor Weibing Gao in the late 20th century, has been extensively adopted in domestic and international applications for characterizing state trajectory behavior during the reaching phase of sliding mode control systems. However, this methodology exhibits inherent limitations as its switching band constitutes a finite region wherein system trajectories asymptotically approach but cannot achieve complete convergence to the origin, instead demonstrating persistent chattering phenomena in proximity to the equilibrium point. To mitigate these oscillatory effects, an enhanced variable exponent convergence law is herein proposed.

$$\dot{s} = -ks - \alpha|s|sgn(s) \tag{15}$$

The exponential component is observed to exhibit rapid asymptotic decay to zero as the sliding manifold is approached, where the $-\alpha|s|sgn(s)$ term governs the variable-velocity phase dynamics, while the magnitude-dependent $|s|$ term results in progressive attenuation of the corresponding control action in the variable structure control formulation.Ultimately, asymptotic convergence to the origin is guaranteed, thereby completing the convergence law-based control design.

$$\dot{s} = g\dot{x} = slaw \tag{16}$$

where $slaw$ is the convergence law (15) Substituting equation of state (12) into (16) yields the control inputs

$$u = -[gb(x)]^{-1}[gf(x) + gd(t) + slaw] \tag{17}$$

*3.2. Sliding mode variable structure controller design based on disturbance observer*

This paper presents the design of a speed controller capable of maintaining precise velocity tracking performance under parametric variations and torque disturbances, with simultaneous disturbance observation implemented for effective disturbance rejection. The controller generates voltage output signals, through which motor speed regulation is accomplished, with the complete system architecture illustrated in Figure 1.

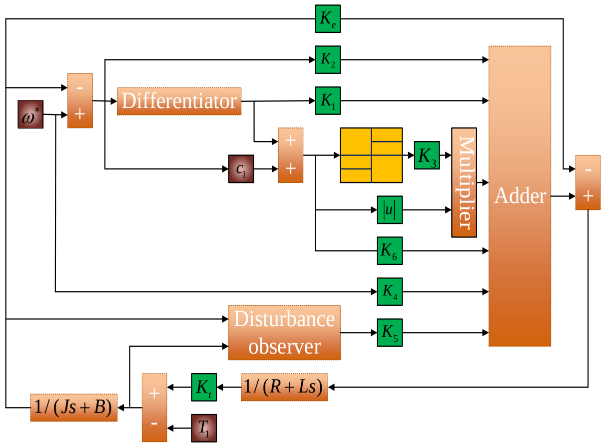


**Figure 1.** Structure control system architecture

For the object model (7), let the system instruction speed be , then the tracking error of the system is

$$e = \omega^* = \omega \tag{18}$$

Substituting equation (18) into equation (7) yields

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -\dfrac{(Bp' + Q_t Q_s)}{n'J} x_1 - \dfrac{(p'J + Bn')}{n'J} x_2 \\ \qquad + \dfrac{(Bp' + Q_t Q_s)}{n'J} \omega^* - \dfrac{Q_t}{n'J} u + \dfrac{p'}{n'J} T_l. \end{cases} \tag{19}$$

Where: $x_1 = e, x_2 = \dot{e}$. So

$$f(x) = \begin{bmatrix} 0 & x_2 \\ -\dfrac{(Bp' + Q_t Q_s)}{n'J} x_1 & -\dfrac{(p'J + Bn')}{n'J} x_2 \end{bmatrix}$$

$$b(x) = \begin{bmatrix} 0 & -\dfrac{Q_t}{n'J} \end{bmatrix}$$

$$d(t) = \begin{bmatrix} 0 & \dfrac{(Br' + Q_t Q_s)}{n'J} \omega^* - \dfrac{p'}{n'J} T_l \end{bmatrix}^T$$

order

$$g = \begin{bmatrix} g_1 & 1 \end{bmatrix}^T$$

Substituting the above equation into equation (17) gives the control inputs $u$. To achieve reduction of steady-state error, system perturbations must be observed and subsequently compensated through feed-forward control utilizing the observed values, thereby enabling elimination of residual steady-state error. In the present study, a disturbance torque observer is constructed through utilization of the system's torque current and rotational speed measurements. From the torque equation of a brushless DC motor, it can be written as

$$Q_t i - T_i = J \frac{d\omega}{dt} + B\omega \tag{20}$$

The design observer is

$$\hat{T}_i = \frac{-B\omega - Q_t i - J\dfrac{d\omega}{dt}}{Gs + 1} \tag{21}$$

Where $G$ represents a positive constant, a first-order filtering component is incorporated into the observer structure to attenuate high-frequency noise induced by velocity differentiation in the numerator. The observation error is guaranteed to converge to zero exponentially, with the convergence rate being governed by the time constant $1/G$.

## 4. Control System Simulation

The parameters of the prototype chosen for the actual simulation are as follows: The phase resistance of the stator is $2.3\Omega$ ,phase inductance $n = 6.8mH, H_e = 0.95, f = 0.001N \cdot S, B = 0.0001, Q_t = 0.93, J = 3 \times 10^{-3} Kg \cdot m^2$.

The controller is validated through MATLAB/SIMULINK.Where: $Q_1 = 0,00742, Q_2 = 0,95023, Q_3 = 0.4, Q_5 = 2,473, Q_6 = 10, 1/G = 0.019, c_1 = 500$.

To evaluate the performance of the proposed disturbance observer-based variable structure controller, a comparative analysis was conducted with a conventional PID controller. As demonstrated in Figure 2, the speed response characteristics of both controllers were examined under a sudden load variation from $20N \cdot S$ to $100N \cdot S$ within $0.1s$. The variable structure controller exhibited superior transient performance, characterized by faster settling time and reduced oscillation amplitude compared to the conventional PID controller, thereby validating its enhanced disturbance rejection capability and improved overshoot suppression. Furthermore, as illustrated in Figure 3, the controller maintained stable speed regulation despite a parameter variation from $2.3\Omega$ to $4.5\Omega$ in phase resistance, confirming its robustness against system parameter uncertainties.

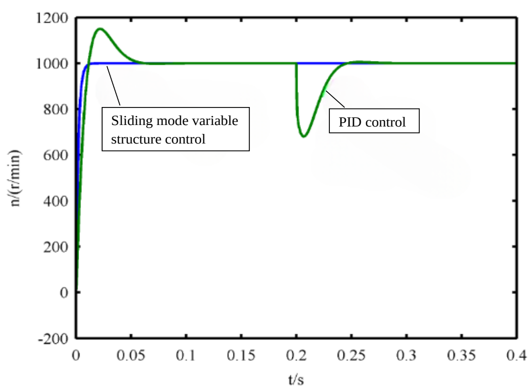


**Figure 2.** Speed response curve contrllled by SMC and PID

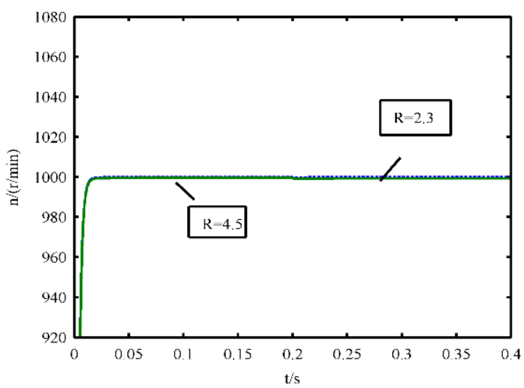


**Figure 3.** Speed response curve under different resistances

## 5. Conclusion

This paper presents the design of a disturbance observer-based variable structure controller for brushless DC motor systems, which demonstrates superior speed regulation performance and enhanced robustness. Through the implementation of a disturbance observer, system perturbations are effectively estimated and compensated, thereby achieving optimal control performance. The effectiveness of the proposed control scheme is rigorously verified through comprehensive simulation studies.

## Acknowledgments

This work was supported by Xi'an Technology and Business College President's Scientific Research Fund(23YZZ08) and China Scholarship Council under Grant (202109010020). I would like to extend my sincere gratitude to the Electrical Automation and Intelligent Control Teaching group of Xi'an Technology and Business College for their invaluable support of this project.

## References

[1] F. Zhang and Y. Zhang, "Analysis and implementation of brushless dc motor control system without position sensor," in *2019 IEEE 3rd Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, 2019, pp. 809–813.
[2] C. Xia, J. Liu, W. Yu, and Z. Li, "Variable structure control of bldcm based on extended state observer," in *IEEE International Conference Mechatronics and Automation, 2005*, vol. 2, 2005, pp. 568–571 Vol. 2.
[3] S. S. Bharatkar, R. Yanamshetti, D. Chatterjee, and A. K. Ganguli, "Reduction of commutation torque ripple in a brushless dc motor drive," in *2008 IEEE 2nd International Power and Energy Conference*, 2008, pp. 289–294.
[4] A. Rubaai, R. Kotaru, and M. Kankam, "A continually online-trained neural network controller for brushless dc motor drives," *IEEE Transactions on Industry Applications*, vol. 36, no. 2, pp. 475–483, 2000.
[5] H. Song, Y. Yu, M. Yang, and D. Xu, "A hybrid adaptive fuzzy variable structure speed controller for brushless dc motor," in *IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02*, vol. 3, 2002, pp. 2126–2130 vol.3.
[6] J. Choi, C.-W. Park, S. Rhyu, and H. Sung, "Development and control of bldc motor using fuzzy models," in *IEEE Conference on Robotics, Automation and Mechatronics, 2004.*, vol. 2, 2004, pp. 1180–1185 vol.2.
[7] N. Almutairi and M. Chow, "A modified pi control action with a robust adaptive fuzzycontroller applied to dc motor," vol. 1, 02 2001, pp. 503 – 508 vol.1.
[8] R.-J. Wai, "Total sliding-mode controller for pm synchronous servo motor drive using recurrent fuzzy neural network," *IEEE Transactions on Industrial Electronics*, vol. 48, no. 5, pp. 926–944, 2001.
[9] S. Fan and H. Zhu, "Simulation of the fuzzy pid control system for brushless dc motors based on matlab," in *International Conference on Automatic Control and Artificial Intelligence (ACAI 2012)*, 2012, pp. 1854–1857.
[10] J. Hung, W. Gao, and J. Hung, "Variable structure control: a survey," *IEEE Transactions on Industrial Electronics*, vol. 40, no. 1, pp. 2–22, 1993.
[11] P. Shuwen, S. Hongye, H. Xiehe, and C. Jian, "Variable structure control theory and application: a survey," in *Proceedings of the 3rd World Congress on Intelligent Control and Automation (Cat. No.00EX393)*, vol. 4, 2000, pp. 2977–2981 vol.4.
[12] A. Levant, "Universal single-input-single-output (siso) sliding-mode controllers with finite-time convergence," *IEEE Transactions on Automatic Control*, vol. 46, no. 9, pp. 1447–1451, 2001.
[13] H. Jia and Y. He, "Variable structure sliding mode control for pmsm dtc," vol. 21, pp. 1–6, 01 2006.
[14] 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)*, 2012, pp. 450–455.
[15] K.-W. Tong, X. Zhang, Y. Zhang, Z. Xie, and R.-X. Cao, "Sliding mode variable structure control of permanent magnet synchronous machine based on a novel reaching law," vol. 28, pp. 102–106, 07 2008.
[16] Y. Liu, B. Zhou, and S. Fang, "Sliding mode control of pmsm based on a novel disturbance observer," in *2009 4th IEEE Conference on Industrial Electronics and Applications*, 2009, pp. 1990–1994.