Comparative Study Between PI Speed Control and Sliding Mode Control of BLDC Motor

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Abstract. The brushless DC motors (BLDC) are used in several applications such as electrical cars, medical and industrial equipment, where speed control with high efficiency is required to satisfy specifications regarding load and tracking references variations. In this paper we propose a comparative study between the classical PI controller and a Sliding Mode Controller (SMC) for closed loop speed control of a trapezoidal back-EMF BLDC using a DC/DC buck converter under various load conditions. Simulation results of speed response, torque and current behaviors of the studied BLDC are also presented to support the noted improvements.

Keywords: BLDC · PI control · Speed control · Sliding mode

1 Introduction

The brushless DC motors are becoming more popular due to their high efficiency, their high torque-weight ratio, noiseless operation and low maintenance cost. The BLDC motor has a permanent magnet rotor and the stator windings are wounded in different ways with one or multiple phases. The very common BLDC motor used is the three phases BLDC motor with a trapezoidal back-EMF or a sinusoidal back-EMF [1].

In order to make motion control more reliable, more efficient and less noisy, the recent trend has been to use brushless DC motors, they are also lighter compared to brushed motors with the same rated power, the brushes in conventional DC motors wear out over time and may cause sparking, that's why we use the BLDC motor in operations that demand long life and reliability, The BLDC motor is used in enormous applications that demand very high speed with low torque such the hard drivers or with big torque with high dynamic speed range such electrical cars.

In the industry the conventional PI controller still widely used due to his simple control structure, however, there are other more complex control strategies like Neural Network Control or the Fuzzy Logic Control [4] which need continuous learning, optimization and adjustment. In other hand, there are less complex control strategies like the Sliding Mode control [7, 8, 10]. Usually, on those control strategies, a dual loop of the speed and current is used [5, 6, 9]. In order to simplify the complexity of the

control algorithms we use two control loops; the inner loop controls the voltage of the buck converter and the outer loop controls the speed of the motor.

The organization of this paper is as follows. It initially begins by the description of the studied system structure, then the adopted control strategy for the speed control, and finally discuss and analysis the simulated results (Table 1).

Table 1. List of symbols and abbreviations.

Nomenclature			
K_e	Back EMF constant	v_k	Phase voltage applied from inverter
F (θ_e)	Back EMF force reference as function of rotor position	i_k	Phase current
θ_e	Electrical angle of the rotor	J	Rotor inertia
ω_r	Angular speed of the rotor	T_l	Load torque
L_s	Inductance of each phase	β	Damping constant
M	Mutual inductance	p	Number of poles
R	Resistance of each phase	θ_m	Mechanical angle of the rotor
SMC	Sliding Mode Control	$D_\%$	Percentage overshoot
Ω_{mes}	Measured angular speed	$Tr_{5\%}$	Response time
		Ω_{req}	Required angular speed

2   System Modeling and Description

The studied system shown in Fig. 1 is based on a three phases trapezoidal back-EMF BLDC motor equipped with Hall, armature current and speed sensors, a three phases power inverter, a DC/DC buck converter and a torque source for load variation.
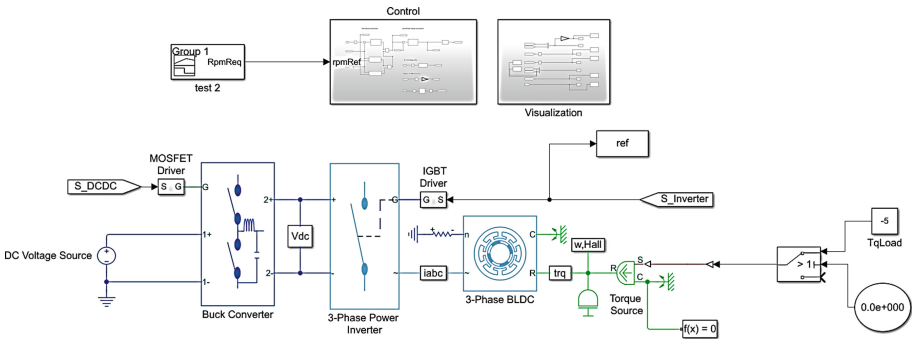
Fig. 1. System model under Matlab/Simulink software

The armature winding of the BLDC motor can be expressed as follows [2, 3]:

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + L_{ab} \frac{di_b}{dt} + L_{ca} \frac{di_c}{dt} + e_a$$
$$v_b = R_b i_b + L_b \frac{di_b}{dt} + L_{ba} \frac{di_a}{dt} + L_{bc} \frac{di_c}{dt} + e_b \quad (1)$$
$$v_c = R_a i_c + L_a \frac{di_a}{dt} + L_{ab} \frac{di_b}{dt} + L_{ca} \frac{di_c}{dt} + e_a$$

Which can be written in the matrix form as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ab} & L_{ca} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_a \end{bmatrix} \quad (2)$$

Assuming that the windings are symmetric and the system is balanced, we have:

$$i_a + i_b + i_c = 0 \quad (3)$$

$$L_a = L_b = L_c = L_s \quad (4)$$

$$R_a = R_b = R_c = R \quad (5)$$

$$L_{ab} = L_{ac} = L_{bc} = L_{ba} = L_{ca} = L_{ab} = M \quad (6)$$

So, the matrix become:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (7)$$

We put: $L = L_s - M$, then we have:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (8)$$

The trapezoidal back - EMF is given by : $\begin{cases} e_a = K_e.\omega_r.F(\theta_e) \\ e_b = K_e.\omega_r.F\left(\theta_e - \frac{2\pi}{3}\right) \\ e_c = K_e.\omega_r.F\left(\theta_e + \frac{2\pi}{3}\right) \end{cases}$ (9)

The torque equations can be deduced as:

$$T_e = K_\omega.\omega_r.F(\theta_e).i_a + K_\omega.\omega_r.F\left(\theta_e - \frac{2\pi}{3}\right).i_b + K_\omega.\omega_r.F\left(\theta_e + \frac{2\pi}{3}\right).i_c \quad (10)$$

$$T_e = J\frac{d\omega_r}{dt} + \beta\omega_r + T_l \tag{11}$$

Where the function F is defined as below:

$$F(\theta_e) = \begin{cases} = 1 \ if \ 0 \le \theta_e < \frac{2\pi}{3} \\ = 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) if \ \frac{2\pi}{3} \le \theta_e < \pi \\ = -1 \ if \ \pi \le \theta_e < \frac{5\pi}{3} \\ = -1 + \frac{6}{\pi}\left(\theta_e - \frac{5\pi}{3}\right) if \ \frac{5\pi}{3} \le \theta_e < 2\pi \end{cases} \tag{12}$$

In the other hand, the DC/DC buck converter can be modeled using the following equation:

$$V_{dc} = \alpha V_{source} \tag{13}$$

With α is the duty cycle to be controlled.

3   Control Strategy

Our study will be focused on the dynamic of BLDC speed according to the load variation. As shown in Fig. 2, two control loops are used, the inner loop controls the voltage of the buck converter and the outer loop controls the speed of the motor.
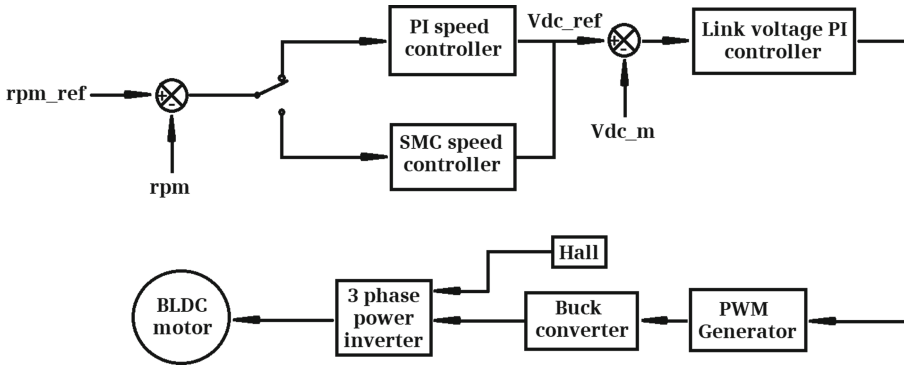

Fig. 2. Control strategy block diagram.

The BLDC motor parameters tested in simulation are defined in the following Table 2:

Table 2. The parameters of the BLDC motor

J	Rotor inertia	0.01 kg/m^2
L_s	Inductance of each phase	0.1 mH
M	Mutual inductance	0.01 mH
R	Resistance of each phase	0.2 Ω
p	Number of poles	4
pm	Maximum permanent magnet flux linkage	0.0175 Wb
P_N	Rated power	3 KW

3.1 PI Controller

The speed regulation is based on controlling the output voltage of the DC/DC buck converter using a PI controller. The proportional coefficient *Kpw* and the integral coefficient *Kiw* have been calculated using Tune function in Matlab and chosen value are respectively 0.1 and 15.

The results of the PI controller in Fig. 3 show the overshoots of the speed when the speed reference changes, also we notice that the speed drops significantly when we add a load of 5 N.m at T = 1 s.
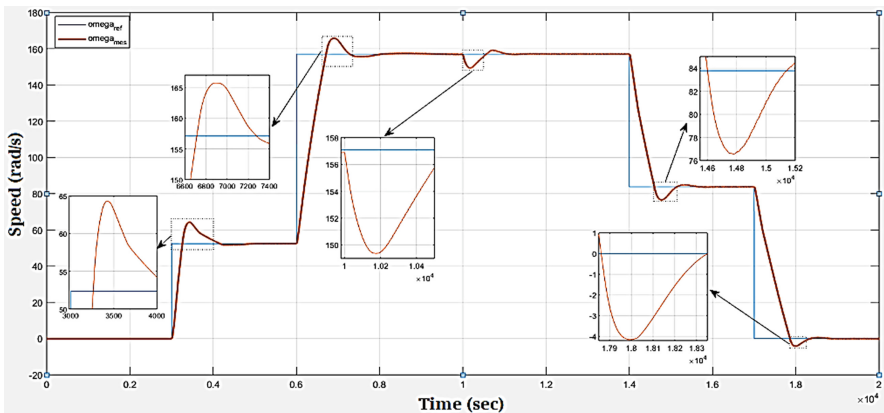
Fig. 3. The speed variation using a PI control

The PI controller track the speed reference but the response of the BLDC motor isn't as fast as desired.

3.2 Sliding Mode Control

In order to improve the speed response of the BLDC motor we propose a sliding mode control, which will be replacing the PI controller of the outer loop.

The sliding surface can be defined as:

$$S_\Omega = \Omega_{mes} - \Omega_{req} \tag{14}$$

The sliding surface derivative is then given by:

$$\frac{dS_\Omega}{dt} = \frac{d\Omega_{mes}}{dt} - \frac{d\Omega_{req}}{dt} = -K_\Omega.sign(S_\Omega) \tag{15}$$

From (8), (10), (11), (13) and (15), the referred V_{dc} voltage is given by:

$$V_{dc\_req} = K_1\Omega_{mes} + K_2 sign(S_\Omega) \tag{16}$$

With K_1 and K_2 constants to be chosen in order to insure system stability.

As shown in the Fig. 4, using SMC the speed reference tracking has been improved compared to the PI controller.
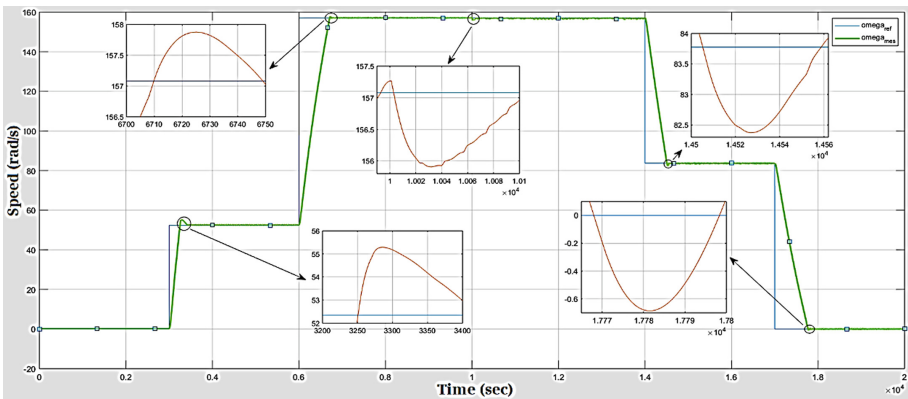

Fig. 4. BLDC speed response using Sliding Mode Controller

4   Comparative Analysis of Simulation Results

In this section, we compare the performance of the proposed SMC controller under the same conditions as the traditional PI controller. From Fig. 5 the response of the sliding mode control is much better than the PI control, and the drop of the speed when we add a load to the system is significant in the PI control and it's negligible in the SMC.
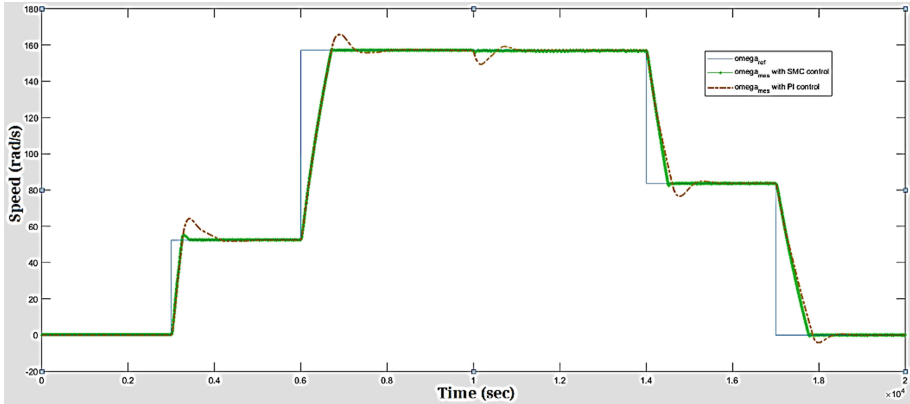
**Fig. 5.** Comparison between the PI and the sliding mode control

Table 3 shows the performances of the SMC controller in comparison with the conventional PI controller.

Table 3. Comparison between the response of the PI and the sliding mode control to the variation of the speed and load.

	500 rpm	1500 rpm	Adding load of −5 N.m	Decreasing to 800 rpm
Conventional PI controller	$D_\% = 22.8\%$ $Tr_{5\%} = 93$ ms	$D_\% = 5.5\%$ $Tr_{5\%} = 98.7$ ms	The speed drop by 4.9%	$D_\% = 8.6\%$ $Tr_{5\%} = 95$ ms
Sliding mode controller	$D_\% = 5.6\%$ $Tr_{5\%} = 31$ ms	$D_\% = 0.5\%$ $Tr_{5\%} = 64$ ms	The speed drop by 0.75%	$D_\% = 1.7\%$ $Tr_{5\%} = 47.5$ ms

In this study, the current is not controlled, there are two loops, the inner loop is dedicated to regulate the voltage and the outer loop is dedicated to regulate the speed, the current reach a maximum of 100 A in both controllers, and the average of the current is under 50 A, despite of the non-control of the current, the value of the current in the phases of the motor still tolerable (Fig. 6).

In both cases, as can be seen from Fig. 7, the motor generates the same amount of torque, which makes the SMC controller a very good option to have a good result acting only on the buck converter.
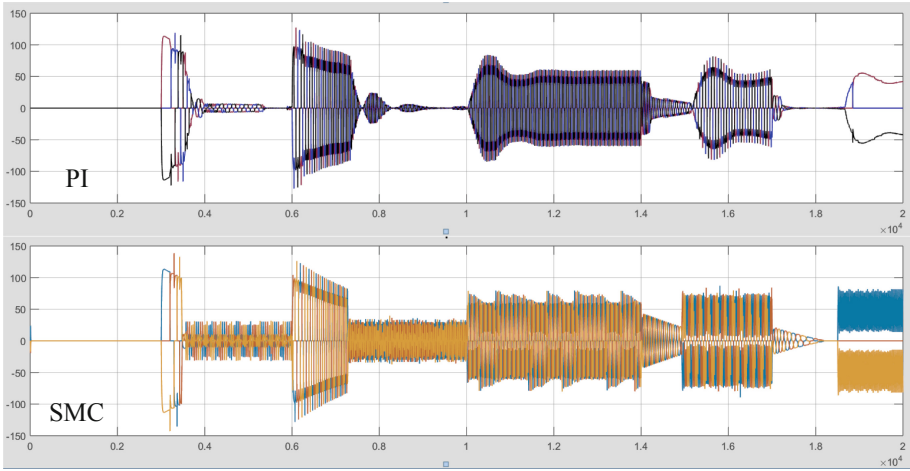
Fig. 6. The current in the three phases i_a, i_b and i_c using SMC vs PI controller
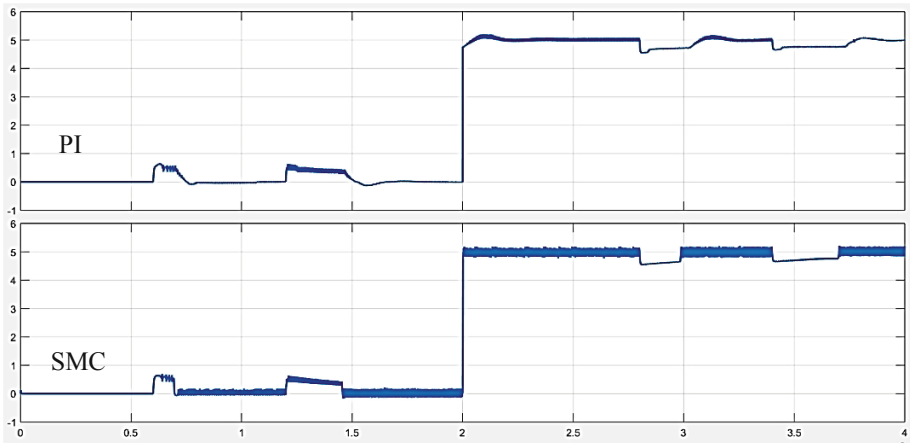
Fig. 7. The torque variations when SMC controller vs the conventional PI

5   Conclusion

In this paper, a particular attention was paid to speed variations of a BLDC motor. A closed loop speed control is carried out using PI and sliding mode controllers. A model of the studied system has been also developed under MATLAB/SIMULINK environment and simulation results with comparative analysis have been presented.

References

1. Rao, A.P.C., Obulesh, Y.P., Babu, Ch.S.: Mathematical modeling of BLDC motor with closed loop speed control using PID controller under various loading conditions. ARPN J. Eng. Appl. Sci. **7**(10), 1321–1328 (2012)
2. Tashakori, A., Ektesabi, M., Hosseinzadeh, N.: Modeling of BLDC motor with ideal back-EMF for automotive applications. In: Proceedings of the World Congress on Engineering, vol. 2 (2011)
3. Tibor, B., Fedak, V., Durovský, F.: Modeling and simulation of the BLDC motor in MATLAB GUI. In: 2011 IEEE International Symposium on Industrial Electronics. IEEE (2011)
4. Xu, W., Jiang, Y., Mu, C.: Novel composite sliding mode control for PMSM drive system based on disturbance observer. IEEE Trans. Appl. Supercond. **26**(7), 1–5 (2016)
5. Guo, D., et al.: Sliding mode high speed control of PMSM for electric vehicle based on flux-weakening control strategy. In: 2017 36th Chinese Control Conference (CCC). IEEE (2017)
6. Deenadayalan, A., Saravana Ilango, G.: Modified sliding mode observer for position and speed estimations in brushless DC motor. In: 2011 Annual IEEE India Conference. IEEE (2011)
7. Rath, J.J., Saha, S., Ikkurti, H.P.: 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). IEEE (2012)
8. Xiaojuan, Y., Jinglin, L.: A novel sliding mode control for BLDC motor network control system. In: 2010 3rd International Conference on Advanced Computer Theory and Engineering (ICACTE), vol. 2. IEEE (2010)
9. Hao, L., Toliyat, H.A.: BLDC motor full-speed operation using hybrid sliding mode observer. In: 2003 Eighteenth Annual IEEE Applied Power Electronics Conference and Exposition. APEC 2003, vol. 1. IEEE (2003)
10. Shao, Y., et al.: Sliding mode speed control for brushless DC motor based on sliding mode torque observer. In: 2015 IEEE International Conference on Information and Automation. IEEE (2015)