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Original Article

Speed Control for BLDC Motor for Electric Vehicles Applications by Different Kinds of Sliding Mode Control Techniques

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Abstract - *Brushless DC (BLDC) motors provide many benefits over normal DC motors. They have high efficiency, stability, low noise, longer lifetime than other motor kinds, high torque to weight ratio, and most importantly, no commentator sparks. With the other advantages, BLDC motors are widely used in electric vehicle applications. But in most cases, their rotational speed has to be regulated. This paper presents a comparative study of BLDC motor speed control by three types of Sliding Mode Control (SMC) techniques, which are 1st order, 2nd order, and Integral SMC. The motor ratings are 1 kW, 3000 r.p.m, at 3 N.m load torque. The aim is to use the BLDC for electric vehicle applications. This research found that the integral SMC is superior to the 1st-order and 2nd-order SMC techniques. Also, the lowest BLDC performance is obtained using the 2nd-order SMC technique. At rated speed and full load conditions, it was found that steady-state errors for each controller are (2.4, 9.5, and 4.9) r.p.m for each integral SMC, 2nd order SMC, and 1st order SMC, respectively. The entire system is simulated successfully by MATLAB SIMULINK. The motor ratings are suitable for e-bike and tricycle applications.*

Keywords - *1st order, 2nd order, BLDC, Driver, Integral, SMC.*

1. Introduction

Due to the high reliability, efficiency, and low noise rate in operation with extended operation duty and low maintenance cost, Brushless DC motors (BLDC) are widely used in many applications like electric vehicles, robots, drones, and etc. [1-3]. Compared to motors like DC or induction motors, BLDC motors, with their high efficacy, also gain rapid dynamic response and can be regulated in a broader range of rotational speeds [4, 5]. Many control schemes regulate the BLDC motor's speed [6].

The driver control for the BLDC motors is quite complex since it uses many electronic switches, and their operation should be precisely synchronized [7]. These motors can be operated either in open-loop or closed-loop control systems, but most speed regulation is made through a closed-loop system [8]. On the other hand, Slide Mode Controllers (SMC) are considered a robust control technique with rapid response, unlike conventional control techniques like PID controllers [9-11].

Various researchers have used many controlling techniques to regulate the speed of the BLDC motors. F. Davoudkhani and M. Akbari [12] compared the BLDC motor speed regulation methods among PID, Fuzzy type-1, and Interval Fuzzy Type 2 with PID controller (IT2FLPIDC). The results presented the superiority in response to the IT2FLPIDC over the other controlling techniques. A braking system via regenerative energy of BLDC motor had been made by A.J. Godfrey and V. Sankaranarayanan [13] for Electric Vehicles (EV). Their work is based on energy regeneration and stopping time. The performance is tested through braking torque, maximum conversion, and boost rations.

H. Hu et al. [14] employed a Genetic Algorithm (GA) as a tuner for the PI-Fuzzy logic technique to control the speed of the BLDC motor. The role of the tuner is to set the proper gains for the PI-Fuzzy logic technique. This method is tested via simulation at various operating conditions. A control algorithm can raise the BLDC motor output torque at high speeds by selecting the inverter Pulse Width Modulation (PWM) made by H. Kim et al. [15]. The relation among voltage utilization, dead time, and switching frequency are analyzed mathematically. They aimed to use this algorithm for EV applications. A Sensorless Control Strategy for position control of the BLDC motors was made by X. Lee et al. [16]. A 3-phase 4-switch inverter operates the BLDC motor. The scheme is used for flux-linkage, which varies with the maximum jump time. It can get 6 points of commutation that are required for the BLDC motor with no interpolation. H. Maghfiroh et al. [17] designed a simulation speed controller for the BLDC motor using the fuzzy-PID technique. Their research uses two Fuzzy PID methods: PID and PI with a "Fuzzy logic controller."

D. Bhavya and A. Raghuram [18] compared two types of DC/DC converters, CukSEPIC and SEPIC converters, to supply BLDC motors for EV applications. PV solar panels power the converters. The incremental Maximum Power Point Tracking (MPPT) is used as well. The regenerative braking is implemented through a logic control. In the Sliding Mode Control (SMC) field to regulate the speed of the BLDC motor, K. Cherif et al. [19] used Fuzzy logic SMC (FSMC) as speed control of the BLDC motor where its performance is compared with a PID controller.

Also, J.W. Chan has developed a new SMC method to control the speed of the BLDC motor with a tiny overshoot percentage [20]. Most of the previous studies presented in the literature focus on using a Fuzzy logic controller to tune PID or SMC parameters to regulate the motor speed. The BLDC motor speed must be regulated precisely at various speeds for EV applications. This can be achieved through employing robust control techniques such as SMC methods. The current paper presents a comparative study among three types of SMC techniques used to control the speed of a BLDC motor for EV applications. This paper is arranged as follows: An introduction, system description, speed regulation (SMC) techniques, results and discussion, and finally, the conclusions.

2. Description of the BLDC Motor System

The BLDC motors are also known as trapezoidal permanent magnet machines because of the non-uniform air gap between the stator and rotor sides [21-23]. Trapezoidal refers to the shape of the induced voltage at the motor stator side. In most cases, the rotor is built from permanent magnets, whereas the stator is made from identical windings separated by 1200. Usually, the BLDC motors are supplied by DC voltage through a three-phase inverter driver circuit, as shown in Figure 1.

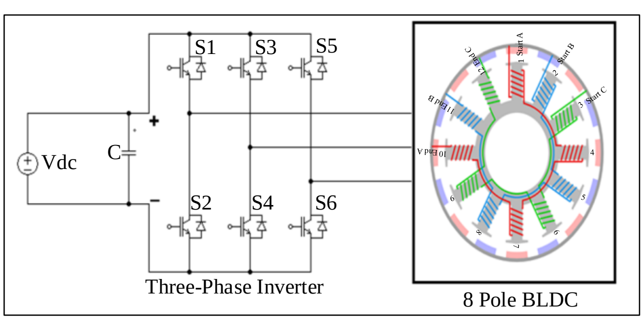

Fig. 1 8-pole BLDC motor with its driver circuit

The BLDC dynamic model is expressed by the following Equation [24]:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + S \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where M refers to the mutual inductance between phases, L refers to self-inductance, v represents the instantaneous of the supplied phase voltage, and S is the "Laplace operator." Then,

$$i_a + i_b + i_c = 0 \quad (2)$$

$$Mi_b + Mi_c = -Mi_c \quad (3)$$

By substituting Equation (3) in (1) yields:

$$L_s = L \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} - \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

Where L_s=L-M, which represents per phase equivalent self-inductance. The electromagnetic torque T_e is:

$$T_e = \left(\frac{P}{2}\right) \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (5)$$

Where ω_m is the rotational speed in (r.p.m). Usually, three hall-effect sensors are placed inside the motor to measure the motor position and generate the required pulses of the driver circuit. For the 8-pole BLDC motor, Table 1 lists the true table for the three-phase back e.m.f reference signals based on the measurement status of each hall-effect sensor [22]. Table 1 lists the three reference signals and the six pulses for each IGBT switch of the driver circuit.

Table 1. Module implements the following true table

H(a)	H(b)	H(c)	EMF (a)	EMF (b)	EMF (c)
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

3. Speed Regulation via Sliding Mode Control (SMC)

The functional block diagram for controlling the BLDC motor's speed is shown in Figure 2.

The speed control via Sliding Mode Control (SMC) technique is well-thought-out, discontinuous, nonlinear, and robust [25]. It is a suitable technique used to regulate or obtain the desired operation of systems that their structure may change during their typical operating conditions [25-27].

The SMC is used to slide the system State Variables (SV) on such a surface as a "sliding surface" [27]. Each SMC technique puts the SV close to the sliding surface [27]. In our system, let's presume that the error e and change of error signifies the $\dot{e}$.

To make these SVs in an "asymptotic convergence" e and $\dot{e}$ go towards zero value, i.e., $\lim_{t\to\infty} e\,,\dot{e}=0$, then:

$$e(t)=e(0)e^{-ct} \tag{6}$$

$$\dot{e}(t)=-ce(o)e^{-ct} \tag{7}$$

Where C>0, and there is a new variable called "σ" where:

$$\sigma=\sigma(e,\dot{e})=\dot{e}+ce \tag{8}$$

Essentially, to drive σ towards zero in a limited time by providing a regulatory variable called as "u" which is performed via applying "Lyapunov function techniques" to the σ dynamics where:

$$\dot{\sigma}=c\dot{e}+f(e,\dot{e},t)+u \tag{9}$$

Where $\sigma(0)=\sigma_0$.

In this paper, three types of SMC techniques are presented below:

3.1. 1st Order SMC

In this SMC technique, the σ is determined by the following formula [27]:

$$\sigma=\dot{e}+ce \tag{10}$$

It is desired to reach the sliding variable (σ) to zero, i.e., each state variable values $e,\dot{e}$ should go to zero. The controller output is represented by the controlling variable u(t) where:

$$u(t)=-\rho\,\text{sign}(\sigma) \tag{11}$$

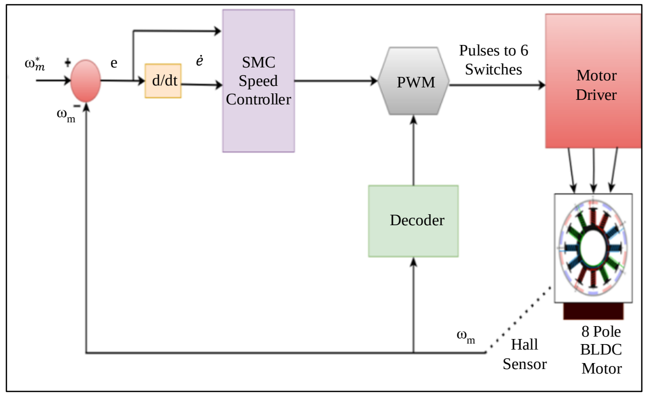

Fig. 2 Functional block diagram of speed control of the BLDC motor

3.2. 2nd Order SMC

In this technique, the sliding surface is nonlinear. The σ is determined by the following Equation [27]:

$$\sigma=\dot{e}+c|e|^{\frac{1}{2}}sign(e) \tag{12}$$

3.3. Integral SMC

This method uses the integral SMC technique to compensate for system disturbances without an attainment phase [27]. This technique lets the uncertainty equivalent control variable $u_2(t)$ be multiplied by -1. Figure 3 represents the flowchart of this technique to control the speed of the BLDC motor.

4. Results and Discussion

The proposed eight pole, 1 kW, and 3000 r.p.m BLDC motor is used in this research. The specifications of the motor are listed in Table 2. For each SMC technique, the proposed system is simulated by MATLAB SIMULINK.

At the startup operating condition, the motor is accelerated from a standstill to the rated speed at complete load condition. The speed measurements at each SMC technique are presented in Figure 4.

By examining this figure, the system performance employing the Integral SMC technique shows the fastest response, whereas the lowest response uses the 2nd order SMC technique.

The system performance with the 1st order SMC technique is also faster than the 2nd order but slightly slower than the Integral SMC. Table 3 lists the main response features of each SMC technique at startup. In this table, the system performance while utilizing Integral SMC is superior to the other used SMC techniques. Figure 5 shows the phase-A current and back EMF voltage of the BLDC motor.

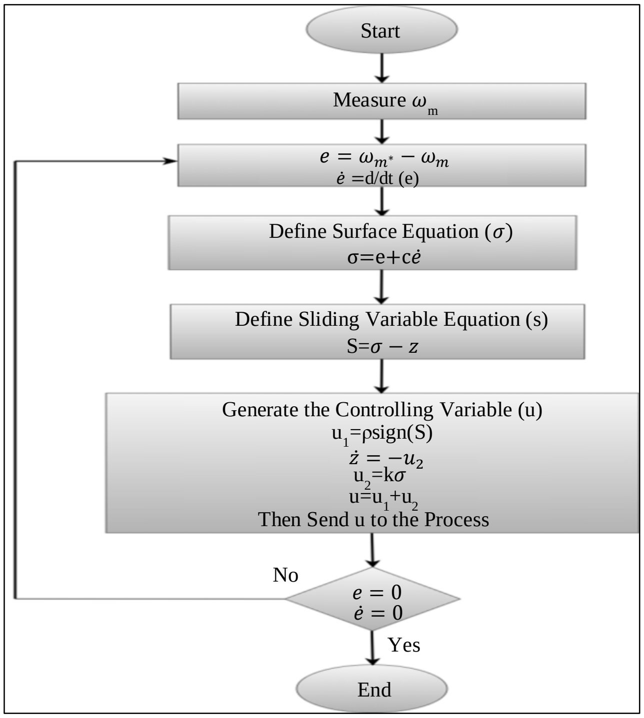

Fig. 3 Flow chart of the integral SMC technique

Table 2. Specifications of the BLDC motor

Parameter	Value
Nominal Power	1 kW
No. of Phases	3
Stator Resistance	2.8750 Ω
Stator Inductance	8.5 mH
Flux Linkage	0.175 V.s
No. of Poles	8
Back EMF Flat Area	120^0
Inertia	0.0008 J(kg.m^2)
Stator Voltage	500 V
Rated Speed	3000 r.p.m

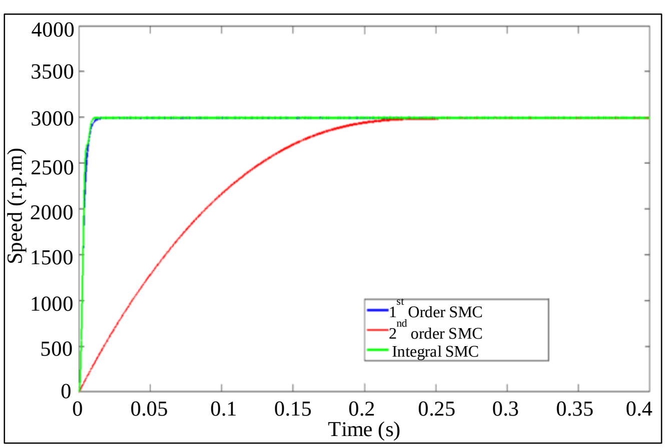

Fig. 4 Rated speed by different SMCs at startup and full load condition

Table 3. System performance at rated speed

Performance	1st SMC	2nd SMC	Integral SMC
Overshoot (%)	0	0	0
Steady-State Value (r.p.m)	2995.1	2990.5	2997.6
Time to Steady State (s)	0.018	0.25	0.012
Steady-State Error (r.p.m)	4.9	9.5	2.4

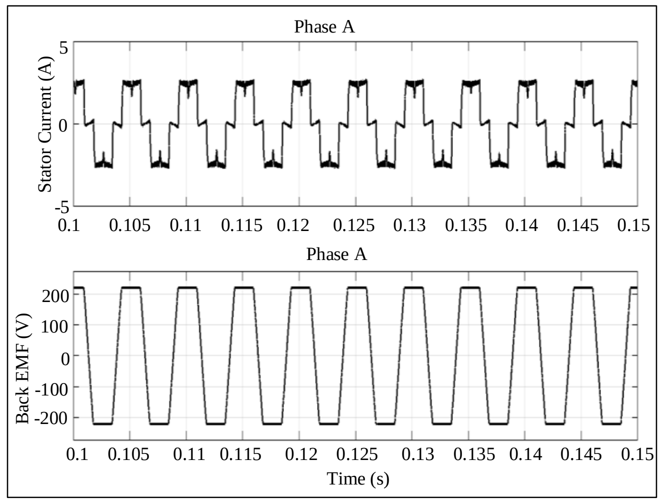

Fig. 5 Stator phase-A current and back EMF

For the sudden change in the desired speed of the BLDC motor, Figure 6 shows the change in the desired speed from 1000 r.p.m to 2500 r.p.m at rated load. Compared with the results shown in Figure 4, the 2nd order still had a slower reaction to the sudden speed change than the other two SMC techniques (1st order and Integral).

At increased speed, the frequency of voltage and current will increase. Also, the current value slightly increases, whereas the voltage (back EMF) will grow higher. During the transient time of the speed change, with the 1st order SMC, the current will dip to -25 A and rise 7.25 A at the speed change instance. In the 2nd SMC, the change in current and back EMF is made so smooth due to the slower performance of the 2nd SMC method.

In the Integral SMC, the current will dip to -50 A and rise to 5.4 A at the speed change instance. Figure 6 also shows the effect of speed change on the electromagnetic T_e torque of the BLDC motor, where the faster response to speed change delivers a higher increase of the T_e value during the transient period.

To study the effect of change in the loading condition, the motor is exposed to a change in the load torque from 0.5 N.m to full load condition, i.e., 3 N.m., as shown in Figure 7. This figure shows that the Integral SMC still performs more than the 1st- and 2nd-order SMC techniques.

After load application and compared with the startup results in Figure 4 and Table 2, the motor speed behaves the same at rated load and speed conditions with the same steady-state error in the speed value.

Figure 7 represents the case for the BLDC performance at sudden changes in the motor speed, but what is the continuous change in the desired speed like the pedal accelerator in the electric vehicles. Figure 8 presents the continuous change of the desired speed from (0 to 3000) r.p.m. at complete load operating conditions between the 2nd order SMC and Integral SMC techniques. In this figure, it can be noted that the rapid response of the Integral SMC to the continuous changes in the reference point is greater than that of the 2nd order SMC technique. In comparison with some of the previous studies concerned with the speed control of BLDC motors, Table 4 lists a significant comparison between them and the present work.

The comparison is made about the speed control method, response to changes in speed and load, and whether their proposed method is compared with other controlling methods. The best results are obtained when the Integral SMC is used among the previously presented speed control methods and the SMC methods presented in this paper.

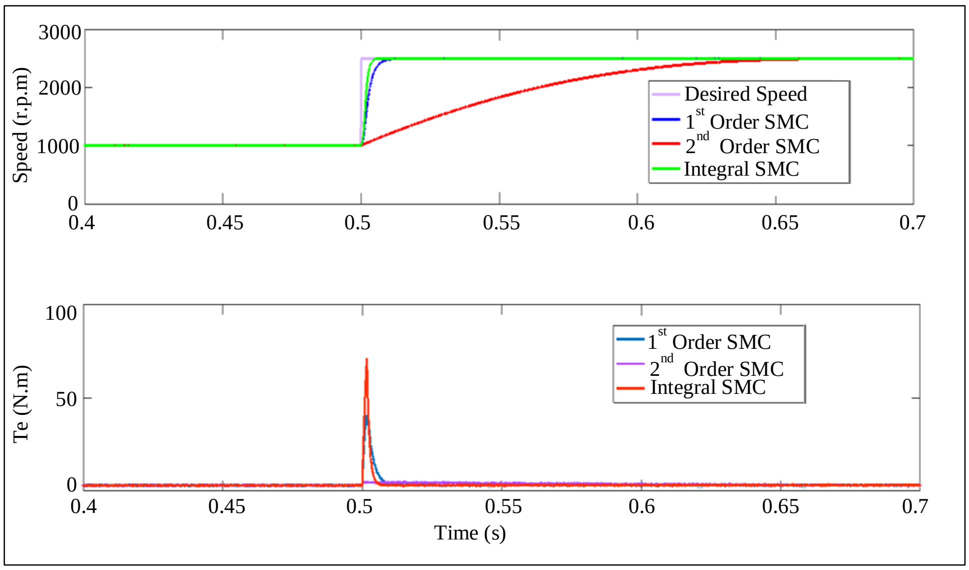

Fig. 6 Change in speed at rated load from (1000 to 2500) r.p.m

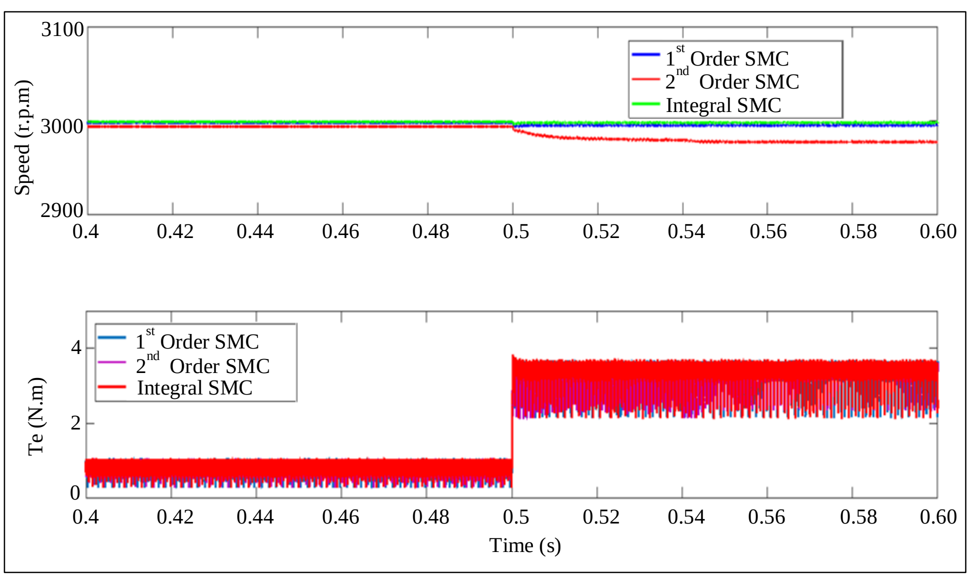

Fig. 7 Load change at rated speed

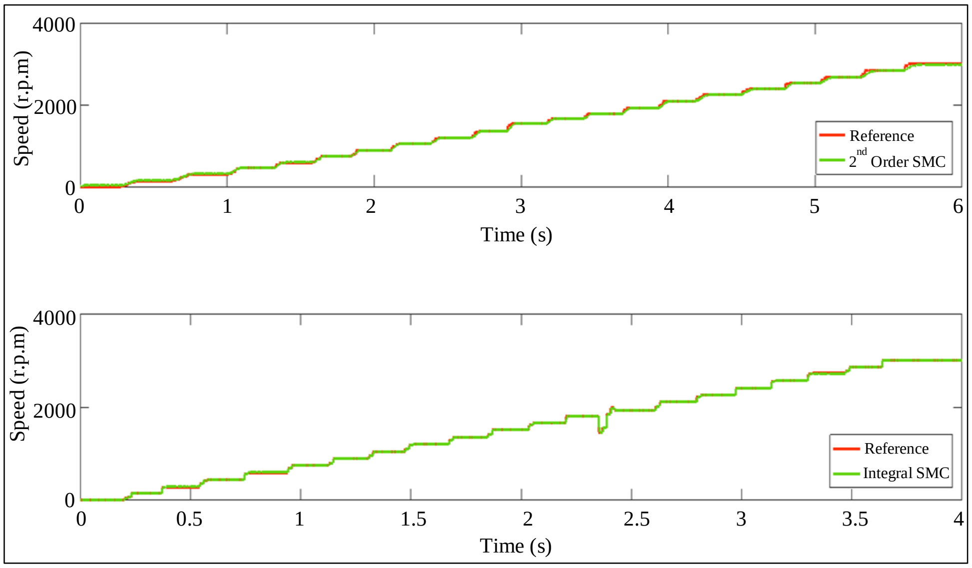

Fig. 8 The motor speed at the continuous changes in reference speed for 2nd order and integral SMC techniques

Table 4. Previous research and present work comparison

Ref. No.	Speed Control Method	Speed Change Response	Load Change Response	Comparison with other Speed Control Methods
[12]	IT2FLPIDC	Good	Good	PID & FLC
[14]	GA-PID-FLC	Good	Good	C-PID, G-PID, T-PID-FLC, and more
[15]	Hybrid PWM Switching	Good	Good	No
[17]	Fuzzy-PID	Good	Good	PID
[19]	FSMC	Good	Good	PID
[20]	New SMC	Moderate	Moderate	PID
Proposed Work	1st order, 2nd Order, Integral SMC	Rapid in ISMC then 1st Order, and Slow at 2nd Order SMC	Rapid in ISMC then 1st Order, and Slow at 2nd Order SMC	Comparison among them

5. Conclusion

This paper presented a performance study of a 1kW 3000 r.p.m BLDC motor, which can be used for electrical vehicle applications. This research compares the system performance for three types of SMC techniques, which are 1st order SMC, 2nd order SMC, and Integral SMC, to regulate the motor rotational speed.

From the results presented, it can be concluded that the Integral SMC has the best performance in handling the BLDC motor speed at various operating conditions rather than the 1st- and 2nd-order SMC techniques. For this fast response, the BLDC motor should be rigid for the high rise in the voltage and current at the transient time of speed or load change.

If the fast response is not the primary concern, or for weak BLDC motors, 2nd order SMC can be employed. For the low power of the used BLDC motor, the proposed SMC methods can regulate the speed of E-bikes, E-tri-cycle bikes, or even vehicles with higher-rated BLDC motors.

References

[1] Shaohua Chen, Gang Liu, and Lianqing Zhu, "Sensorless Startup Strategy for a 315-kW High-Speed Brushless DC Motor with Small Inductance and Nonideal Back EMF," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1703-1714, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[2] Yang Li et al., “A Sensorless Commutation Error Correction Method for High-Speed BLDC Motors Based on Phase Current Integration,” *IEEE Transactions on Industrial Informatics*, vol. 16, no. 1, pp. 328-338, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] J.L. Meza et al., “Fuzzy Self-Tuning PID Semiglobal Regulator for Robot Manipulators,” *IEEE Transactions on Industrial Electronics*, vol. 59, no. 6, pp. 2709-2717, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[4] Masataka Miyamasu, and Kan Akatsu, “Efficiency Comparison between Brushless DC Motor and Brushless AC Motor Considering Driving Method and Machine Design,” *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, Melbourne, Australia, pp. 1830-1835, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[5] Aaron Mohtar, Zorica Nedic, and Jan Machotka, “A Compact and Affordable BLDC Motor Controller for a Microelectronics Remote Laboratory,” *International Conference on Embedded Systems and Applications*, Las Vegas, USA, pp. 75-80, 2008. [Google Scholar] [Publisher Link]

[6] Uzair Ansari, Saqib Alam, and Syed Minhaj un Nabi Jafri, “Modelling and Control of Three Phase BLDC Motor Using PID with Genetic Algorithm,” *2011 UkSim 13th International Conference on Computer Modelling and Simulation*, Cambridge, UK, pp.189-194, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[7] M. Ahmad, “*Development of Speed Control and Monitoring System in BLDC Motor with Hall Sensor*,” Final Project, Electrical Engineering Department of Universitas Sebelas Maret Surakarta, 2020. [Google Scholar]

[8] K. Ogata, “Translation of Automatic Control Techniques (Regulatory System),” vol. 1, 1995.

[9] K. Chandra Sekhar, and K. Vaisakh, “Application of VSC/SMC Controllers for Automatic Generation Control in Deregulated Environment,” *2013 7th International Conference on Intelligent Systems and Control (ISCO)*, Coimbatore, India, pp. 210-218, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[10] M. Ashmi, M. Anila, and K.S. Sivanandan, “Comparison of SMC and PID Controllers for Pneumatically Powered Knee Orthosis,” *Journal of Control, Automation and Electrical Systems*, vol. 32, pp. 1153-1163, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] A.N.K. Nasir, R.M.T. Raja Ismail, and M.A. Ahmad, “Performance Comparison between Sliding Mode Control (SMC) and PD-PID Controllers for a Nonlinear Inverted Pendulum System,” *World Academy of Science, Engineering and Technology*, vol. 71, pp. 122-127, 2010. [Google Scholar] [Publisher Link]

[12] Iraj Faraji Davoudkhani, and Mohsen Akbari, “Adaptive Speed Control of Brushless DC (BLDC) Motor Based on Interval Type-2 Fuzzy Logic,” *2016 24th Iranian Conference on Electrical Engineering (ICEE)*, Shiraz, Iran, pp. 1119-1124, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[13] A. Joseph Godfrey, and V. Sankaranarayanan, “A New Electric Braking System with Energy Regeneration for a BLDC Motor Driven Electric Vehicle,” *Engineering Science and Technology, an International Journal*, vol. 21, no. 4, pp. 704-713, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[14] Huangshui Hu et al., “Speed Control of Brushless Direct Current Motor Using a Genetic Algorithm-Optimized Fuzzy Proportional Integral Differential Controller,” *Advances in Mechanical Engineering*, vol. 11, no. 11, pp. 1-13, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ho-Jin Kim, Hyung-Seok Park, and Jang-Mok Kim, “Expansion of Operating Speed Range of High-Speed BLDC Motor Using Hybrid PWM Switching Method Considering Dead Time,” *Energies*, vol. 13, no. 19 pp. 1-13, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[16] Xinmin Li et al., “A Position Sensorless Control Strategy for BLDCM Driven by FSTPI Based on Flux-Linkage Function,” *World Electric Vehicle Journal*, vol. 13, no. 12, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Hari Maghfiroh et al., “Fuzzy-PID in BLDC Motor Speed Control Using MATLAB/Simulink,” *Journal of Robotics and Control*, vol. 3, no. 1, pp. 8-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Dusa Bhavya, and A. Raghuram, “Solar Interlinking BLDC Motor for Electric Vehicle Charging,” *SSRG International Journal of Electrical and Electronics Engineering*, vol. 10, no. 9, pp. 11-21, 2023. [CrossRef] [Publisher Link]

[19] K. Cherif, A. Sahbani, and K. Ben Saad, *Speed Control for BLDC Motor Using Fuzzy Sliding Mode, Innovative and Intelligent Technology-Based Services for Smart Environments - Smart Sensing and Artificial Intelligence*, CRC Press, 1st ed., 2021. [Google Scholar] [Publisher Link]

[20] Jun Wei Chan, “Sliding Mode Control of Brushless DC Motor Speed Control,” *Malaysian Journal of Science and Advanced Technology*, vol. 2, no. 4, pp. 188-193, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Gopal K. Dubey, *Fundamentals of Electrical Drives*, Alpha Science International Ltd, India, pp. 1-392, 2001. [Google Scholar] [Publisher Link]

[22] Paul Krause et al., *Analysis of Electric Machinery and Drive System*, A John Wiley and Sons Inc., 2013. [CrossRef] [Google Scholar] [Publisher Link]

[23] Bimal K. Bose, *Modren Power Electronics and AC Drives*, Prentice Hall Inc., pp. 1-711, 2002. [Google Scholar] [Publisher Link]

[24] Grzegorz Tarchała, and Teresa Orłowska-Kowalska, “Sliding Mode Speed and Position Control of Induction Motor Drive in Cascade Connection,” *Robust Control - Theoretical Models and Case Studies*, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[25] Axaykumar Mehta, and Brijesh Naik, *Sliding Mode Controllers for Power Electronic Converters*, Springer Nature Singapore Pte Ltd, 1st ed., 2019. [CrossRef] [Google Scholar] [Publisher Link]
[26] R. DeCarlo, and S. Zak, "*A Quick Introduction to Sliding Mode Control and Its Applications*," Universita' Degli Studi di Cagliari, 2008. [Google Scholar]
[27] Yuri Shtessel et al., *Sliding Mode Control and Observation, Springer Science+Business Media*, New York, USA, 1st ed., 2014. [CrossRef] [Google Scholar] [Publisher Link]