MJSAT

Malaysian Journal of Science
and
Advanced Technology

journal homepage: https://mjsat.com.my/

Sliding Mode Control of Brushless DC Motor Speed Control

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KEYWORDS

Brushless DC Motor
PID Controller
Sliding Mode Controller
Speed Control

ARTICLE HISTORY

Received 10 July 2022
Accepted 21 October 2022
Available online 22 October 2022

ABSTRACT

Over the years, development in control industry has brought a conventional controller, Proportional-Integral-Derivative (PID) controller as Brushless DC (BLDC) motor speed regulator. The PID controller suffers from lengthy design time due to the large number of rules and parameter tuning. Thus, this paper proposes a newly developed Sliding Mode Controller (SMC) to be used as the BLDC motor speed controller. SMC is a modern speed controller which is also a non-linear speed controller where it can show high performance controlling non-linear plant like BLDC motor. SMC gives a speed performance comparable to the PID but with much robust speed performance in terms of small overshoot and short settling time. The motor performance with SMC is evaluated through simulation and experimental approach in terms of speed response under several test conditions. The performance is then compared with the motor performance with PID speed controller. Overall, SMC is outperformed PID controller in terms of speed performance with no overshoot and less settling time.

1. INTRODUCTION

A motor is a device that transfers electrical energy into mechanical energy and is sometimes referred to as a power delivery machine. There is various type of motors are in common use in the industrial. Some of the common DC motor are Brushed DC Motor, Brushless DC Motor (BLDC) and Stepper Motor. At the same time, there are also AC motor such as Induction Motor and Synchronous motor. Variable-frequency drives are required to regulate the speed and torque of AC motors. On the other hand, DC motors use speed controller such as Proportional-Integral-Derivative (PID) controller, Sliding Mode Control, Fuzzy Controller and so on to vary the voltage sent to the motor [1].

Brushless DC motors do not use brushes as their name implies. The rotor of a brushless DC motor is permanently magnetised, and the coils are locked in place on the stator rather than rotating. Since the coils are not moving, thus, there is no need for brushes. Brushless DC motors have a high performance because they can regulate at max rotating force constantly (torque). Furthermore, it is adaptable in terms of adjusting output speed, since it makes use of feedback systems to precisely supply the appropriate torque and rotation speed. Brushless DC motors are also more durable and produce less electric noise owing no brushes and at the same time it also does not need high level of maintenance [2].

DC motor systems are inherently unpredictable and nonlinear, which has an impact on controller efficiency. V. I. Utkin et al.[3] once said SMC is a prominent control strategy and powerful control technique for dealing with nonlinear uncertain systems for these reasons. It's commonly used to solve terrible control scenarios such as external disturbances, parametric perturbations with lower and upper limits, stick-slip friction, and so on. It does not require precise dynamic models, and its control methods are simple to implement. According to [4], the robustness of the sliding mode control, on the other hand, is highly dependent on the parameters used

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in the construction of the sliding function. There are two control signals in SMC, specifically, in reaching and sliding modes. According to [5], The switching control (u_sw)is necessary in reaching mode to convey the system's state to a sliding surface. There is also an equivalent control (u_eq)in the sliding mode state to ensure the system's stability. By getting the system state to the sliding surface and subsequently to the centre point.

2. METHODOLOGY

2.1 Flowchart

First, in the determination of the defectiveness of proposed SMC speed control vs PID speed control, the comparison will be done in software and hardware based. A software BLDC system with SMC and PID controller will be developed using MATLAB. The information data collected and analysed would help to identify the effectiveness of SMC speed control vs PID speed control and also provide an aid of design to build the hardware prototype. The final part will be testing the hardware prototype with both SMC and PID controller and validate the output from software and hardware.

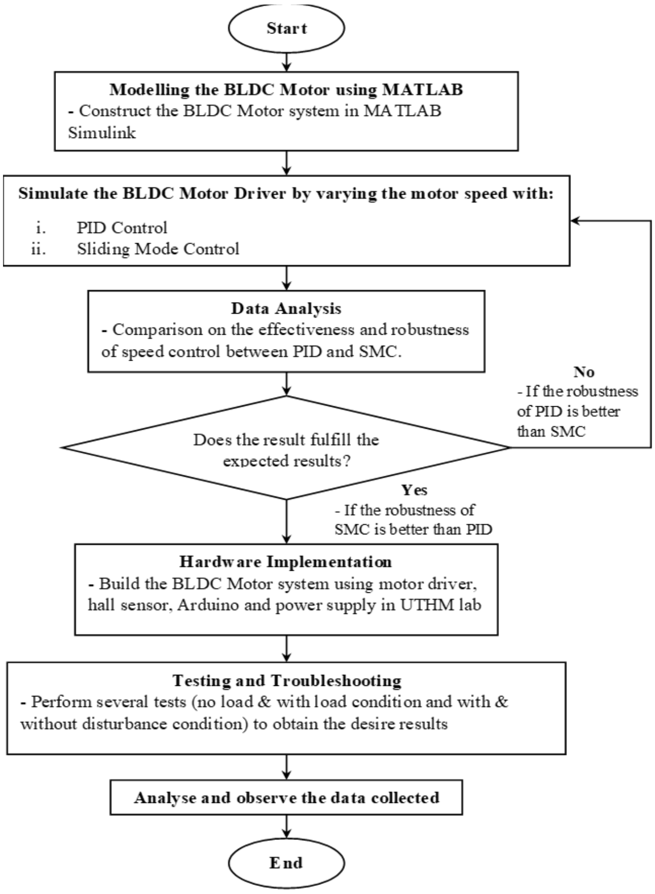

Fig. 1. Flow chart of the methodology

2.2 Study Area

The study was conducted at the laboratory in Universiti Tun Hussein Onn Malaysia (UTHM), main campus Parit Raja. The laboratory chosen is the Power Electronic Lab (POWERE), located at F1-001-10 and it is the laboratory under Faculty of Electrical and Electronic Engineering (FKEE). POWERE laboratory consists of the equipment required for this study such as 4 Channel Digital Oscilloscope, DC Bench Power Supply, Soldering Workstation, True RMS AC/DC Clamp Meter and etc.

2.3 Mathematical Modelling of BLDC motor

In this stage, a transfer function block will represent the BLDC motor itself. Therefore, a mathematical equation for BLDC motor is required to be derived. According to [6], there are two common kinds of BLDC motor models, which are first order model and second order model. In our study, second order model of BLDC motor is chosen.

However, there are several types of equations representing the second order model and the equation selected in this study is referring to [7]'s mathematical equation. The mechanical and electrical time constants, according to the author, are critical modelling parameters for BLDC motors. Equation can be used to calculate the mechanical time constant of a BLDC motor (2)

$$\boldsymbol{\tau_m = \sum \frac{RJ}{K_e K_t} = J \sum \frac{R}{K_e K_t}} \qquad (1)$$

And the electrical time constant,

$$\boldsymbol{\tau_e = \sum \frac{L}{R}} \qquad (1)$$

Because the arrangement is symmetrical and three-phase, the mechanical and electrical time constants are:

$$\boldsymbol{\tau_m = \frac{3RJ}{K_e K_t} \; and \; \tau_e = \frac{L}{R}} \qquad (2)$$

As a result, the BLDC motor equation can now be stated in terms of its respective time constants as follows:

$$\boldsymbol{G(s) = \frac{\omega_m}{V_s} = \frac{\frac{1}{K_t}}{\tau_m \tau_e s^2 + \tau_m s + 1}} \qquad (3)$$

Where,

ω_m= Angular Velocity (RPM)

V_s = Supply Voltage

K_t =Torque Constant

τ_m= Mechanical Time Constant

τ_e= Electrical Time Constant

2.4 Mathematical equation of Sliding Mode Control

The SMC model will be designed before constructed the Simulink model. The SMC model need to be derived in mathematical equation so that it can be built in the Simulink model.

The first step is to design a sliding surface for the sliding mode controller. The sliding surface is as follow [8].

$$\boldsymbol{s} = (\frac{\boldsymbol{de(t)}}{\boldsymbol{dt}} + \boldsymbol{C} \cdot \boldsymbol{e(t)})^{\boldsymbol{n-1}} \tag{5}$$

Where the sliding surface is s, e will be the signal calculated from the reference and actual speed , C is a constant with only positive value that defines the bandwidth of the system, n is the degree, and. Because the BLDC motor's transfer function is second degree, the sliding surface is as follows when the speed is substituted.:

$$\boldsymbol{s} = \frac{\boldsymbol{d\omega_e}}{\boldsymbol{dt}} + \boldsymbol{C} \cdot \boldsymbol{\omega_e} \tag{6}$$

The error signal is described as the variation in between reference signal as well as the process variable, and ω_e, is the rotational speed. After the sliding surface has already been identified, the following step is to form a control signal that will allow the sliding surface to be achieved and maintained. This is contingent on:

$$\boldsymbol{s} \cdot \dot{\boldsymbol{s}} > \boldsymbol{0} \tag{7}$$

The theory of the discontinuous control signal is obtained using the sign function., in which the parameter is the sliding surface's instantaneous value and K is a constant positive value, in order to satisfy this criterion:

$$\boldsymbol{u} = \boldsymbol{K} \cdot \boldsymbol{sgn}(\boldsymbol{s}) \tag{8}$$

In (8), the sign function can be expressed as

$$\boldsymbol{s} = \begin{cases} \boldsymbol{-1}, & \boldsymbol{s} < \boldsymbol{0} \\ \boldsymbol{1}, & \boldsymbol{s} \geq \boldsymbol{0} \end{cases} \tag{9}$$

The application of the sign function can cause chattering, which can destroy the motor, thus SMC must take precautions to avoid it. One way to avoid chattering would be to use the pseudo function instead of the sign function :

$$\boldsymbol{u} = \boldsymbol{K} \cdot \frac{\boldsymbol{s}}{|\boldsymbol{s}| + \boldsymbol{\delta}} \tag{10}$$

where δ is a small positive constant used to prevent chattering and is called a tuning parameter [5]. The value of d is important because if it is too tiny, chattering may still occur, but if it is too large, the controller may have trouble reaching the reference value [9].

2.5 Simulation using MATLAB Simulink

With a complete BLDC motor system software prototype, the next step, simulation can be run. Usually, a simulation in MATLAB Simulink required some preparation before running the system. For instance, some parameter has to be defined by running the MATLAB coding as well as some tuning of speed controller. With all preparation done, the simulation can be started. The output of the simulation will be observed and collected. What define the output in BLDC motor system is the output speed in rad/s and the output waveform will be observed at the oscilloscope. The settling time, maximum and minimum overshoot in either steady state and transient mode will be observed and compare between two speed controllers in this study: PID and Sliding Mode Control. Figure 2 and 3 shows the Simulink model of PID and SMC.

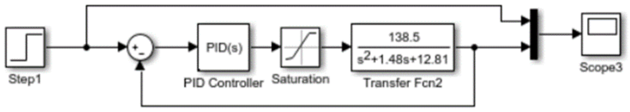

Fig. 2. Simulink model of DC motor with PID

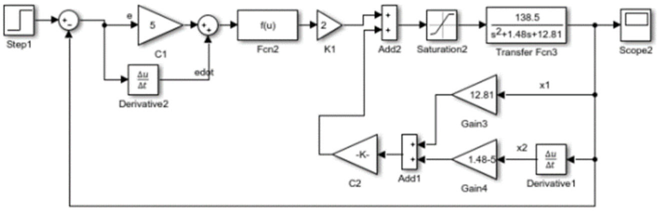

Fig. 3. Simulink model of DC motor with SMC

3. RESULTS AND DISCUSSIONS

This section discusses on the software simulation of BLDC motor with PID speed controller. The experiment has been carried out to test the robustness of PID controller when handling non-linear system like BLDC motor. In section 3.1 shows the simulation of a BLDC motor system with PID speed controller and SMC using MATLAB Simulink. The output system is tested with step response to compare the reference speed and the output speed. While the hardware results will be presented in section 3.2.

3.1 Software Simulation Results

A. Unit step response test with PID and SMC

The output of the system is measured using the scope and the signal is being controlled under no disturbance condition. Figure 4 shows the performance of unit step response with PID and SMC. The PID controller clearly has a very fast rise time as observed from the waveform. However, due to oscillation before reaching the steady state, the settling time is short. On the other hand, it is clearly seen that the PID response has a huge a 22.48% overshoot. It can be seen that SMC response did not have an overshoot. As a result, the SMC controller outperforms the PID controller. The data collected is shown in Table 1.

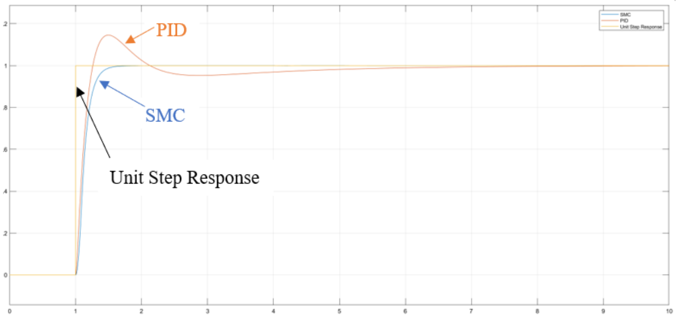

Fig. 4. Performance of unit step response with PID and SMC

Table 1. Performance for unit step response with PID controller

Control method	Rise Time	Settling Time	Overshoot %
PID	0.1830	6.3084	6.989
SMC	0.6070	0.8013	0

B. Signal tracking test with PID controller and SMC

The next test is signal tracking test. In this test, setpoint are changing from initial 0 to 1 and from final 0f 1 to. Figure 5 shows the results of the test. PID has a very quick rise time, as can be shown from the same findings as unit step response. However, it oscillates before reaching a steady-state condition, lengthening the time it takes to settle. When the setpoint reduces from 1 to 0.5, PID oscillated before steady, while SMC has not oscillated. Performance for signal tracking is showed in Table 2. It can also be shown that when the setpoint is reduced, SMC has no overrun, but PID has a significant overshoot of 13.4468%.

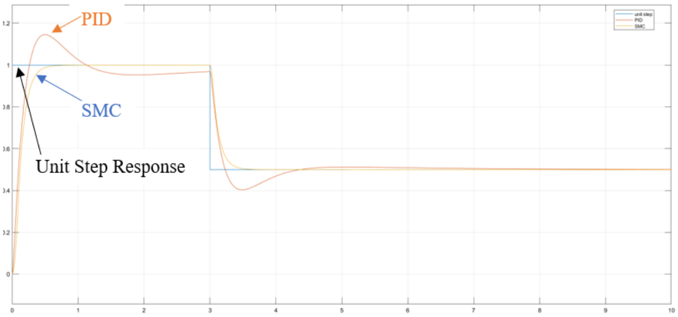

Fig. 5. Performance of signal tracking with PID and SMC

Table 2. Performance for signal tracking with PID controller

Control method	**Rise Time**	**Settling Time**	**Overshoot %**
PID	1.2704	5.4630	13.4468
SMC	0.6070	0.8013	0

C. Performance of PID and SMC with disturbance

The next test is to add a -0.5 value of disturbance is introduced after 5 seconds of simulation. The results from Figure 6 shows that PID controller still has a faster rise time than SMC and when the disturbance is being introduced after 5 seconds, the PID response oscillated after recovered from the disturbance, however, SMC response recovered back steadily without oscillating. The data collected in Table 3 shows that PID has an overshoot of 17.059%, while SMC only has a little overshoot of 0.48%.

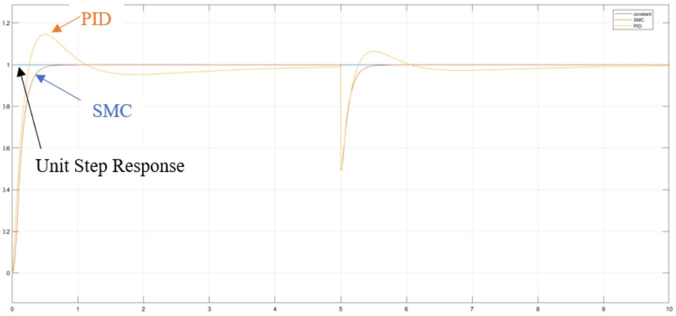

Fig.6. Performance of PID and SMC with disturbance

Table 3. Performance of PID and SMC with disturbance

Control method	Rise Time	Settling Time	Overshoot %
PID	1.3742	5.4630	17.059
SMC	0.2298	0.8013	0.480

3.2 Hardware Results

A. Open loop speed control using PWM method

Pulse Width Modulation (PWM) is a common microcontroller-based approach for controlling DC motors. The electric motor's speed is determined by the modulator voltage. When the voltage is higher, an electric motor turns quicker [10]. There is no feed-back system since the actual motor speed is not recorded in this way. Only reference speed is utilised to regulate the motor speed when the PWM duty cycle is updated. PWM open loop speed control will only adjust the output speed of BLDC motor by turning the knob of potentiometer.

At no load condition, the BLDC motor is run at full PWM, and it achieved 760 rpm as shown in Figure 7. The PWM duty cycle is then decrease to 85% and 55% and the speed waveform is showed in figure 8 and 9. The data is then recorded in table 4. The data and waveform show that the output speed is decreasing when the PWM duty cycle is reduced which indicates that the open loop speed controller using PWM method is working, and the output waveform looks steady when the speed is constant.

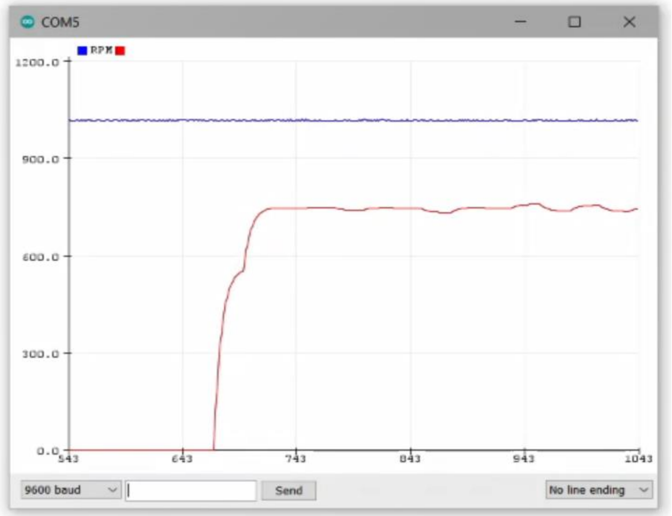

Fig.7. BLDC motor at speed = 760 rpm, PWM = 100%

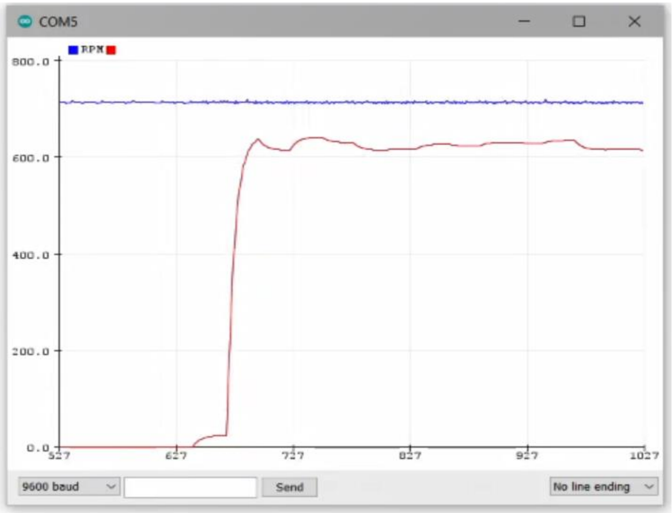

Fig.8. BLDC motor at speed = 645 rpm, PWM = 85%

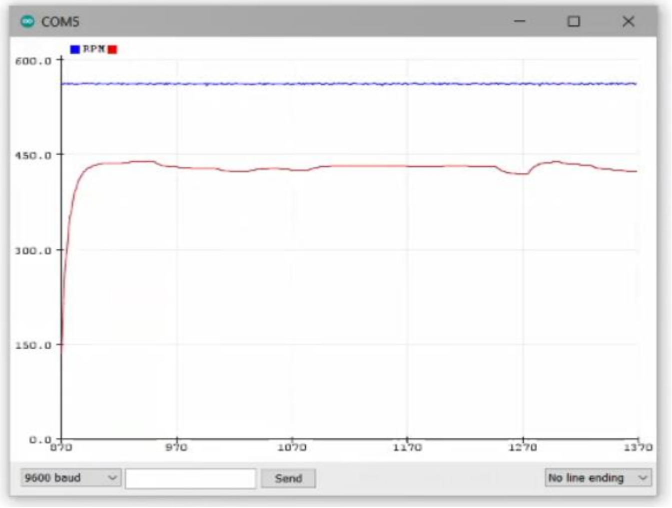

Fig. 9. BLDC motor at speed = 430 rpm, PWM = 55%

Table 4. Data on PWM Duty Cycle Correlation and Motor Speed

PWM	Speed (rpm)	Duty cycle (%)
255	760	100
217	645	85
139	430	55

B. Closed loop speed control using PID controller

PID controller is applied as the closed loop control system for BLDC motor. The PID equation has been introduced before and manual tuning method is chosen to tune the system until it is stabilised. The finalised parameters for PID are P = 0.5, I = 1 and D = 0.5. These parameters are the most suitable parameters after several attempts.

By using the serial plotter feature in Arduino IDE, the output speed waveform can be observed, and it is presented in Figure 10. From the plotting, PID controller has a very fast rise time, but the overshoot is huge as well as the settling time is long. The observation is almost same as the simulation in section 2. According to N. N. Baharudin, slower reaction, oscillation, and higher overshoot are all downsides of the PID controller [11]. Peak overshoots and settling time issues can be filtered out with a PID controller, but the gains (value of P) need to be tuned again, which means one of the two characteristics such as by reducing overshoot, settling time will be increased, and vice versa, need to be compromised either one of them.

However, the real root cause that PID controller has not likely smooth outcome been PID as a linear controller is not suitable to control such dynamic and complex system like BLDC motor.

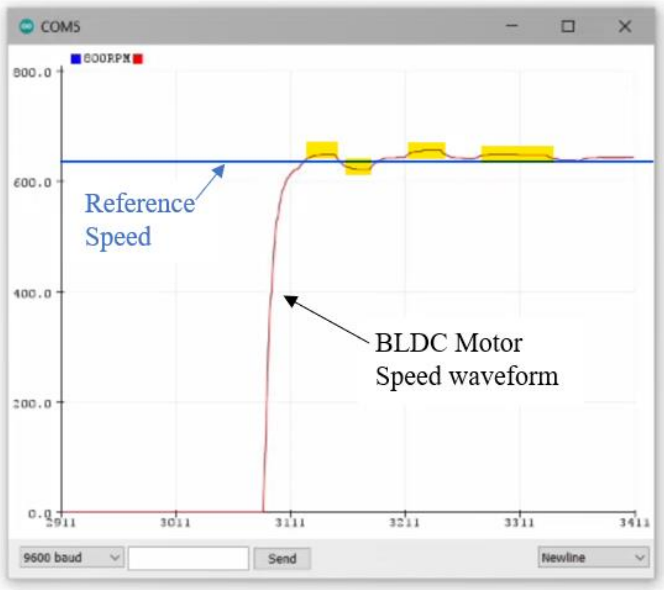

Fig. 10. Performance of BLDC motor with PID controller

4. CONCLUSION AND FUTURE RECOMMENDATIONS

In this paper, The PID controller and SMC are the closed loop speed controller of a BLDC motor. In simulation mode, both with and without disturbance, SMC is found to be superior to PID controller. When disturbance is introduced, the PID response is shown to be decreased while the SMC response remains unaltered. Besides, for unit step response and signal tracking test, when compared to PID controllers, SMC offers better speed performance in terms of overshoot, settling time and rise time. When a disturbance is applied, the PI response is impaired, but the SMC response is unaffected.

However, the hardware implementation has only conducted for PID controller under constant speed and without disturbance. The results showed that PID response has similar waveform as in simulation such as fast rise time, big overshoot and long settling time. The output of PID waveform can be perfected by increasing the amount of manual tuning. Due to time constraint factor, several tests for PID controller could not be conducted such as step response, signal tracking and performance with disturbance. The only results obtained from PID controller in hardware implementation is the closed loop speed control under constant speed.

There are some imperfect sides in this paper and some recommendations will be given to improve the findings. The BLDC motor control in this paper is using the most common hall-based control as known as six-step commutation. A basic method for detecting Hall sensors and consecutively activating coils is six-step commutation. For many motors, this approach has the disadvantage of sacrificing some efficiency and being less smooth than more sophisticated ways. whenever the hall sensor received a signal and a new Hall state will be read per 60 electrical degrees, the switching signal for each MOFET will be activating the current to flow through the coils [12]. Therefore, a recommendation to improve the BLDC control is to propose another more effective motor control, Field Oriented Control (FOC).

FOC is a mathematically advanced method of regulating three-phase DC motors and stepper motors to improve efficiency and position control at greater speeds. FOC allows BLDC motors to run more effectively, with a higher power factor and greater light load efficiency, as well as more smoothly, with fewer torque ripples and quicker dynamic response to load and speed variations. To achieve the maximum electromagnetic torque, FOC control aligns the magnetic fields of the stator and rotor [13].

Chuck Lewis has conducted one experiment to observe the performance improvement from FOC versus Hall-based commutation. From the experiment, FOC model run the BLDC motor with faster speed than Hall-based model and it is about 64% faster [12]. The author concluded that FOC, in comparison to Hall-based approach, can provide significant performance gains at high speeds.

REFERENCES

[1] Bradley, "AC and DC Motors: Differences and Advantages | Types of Electric Motors," Gainesville Industrial Electric, 2021. https://www.gainesvilleindustrial.com/blog/ac-dc-motors/ (accessed Dec. 08, 2021).J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Renesas, "What are Brushless DC Motors | Renesas," 2021. https://www.renesas.com/us/en/support/engineer-school/brushless-dc-motor-01-overview (accessed Dec. 08, 2021).K. Elissa, "Title of paper if known," unpublished.

[3] V. I. Utkin, "Survey Paper: Variable Structure Systems with Sliding Modes," IEEE Transactions on Automatic Control, vol. 22, no. 2, pp. 212–222, 1977, doi: 10.1109/TAC.1977.1101446.

[4] Christopher Edwards and Sarah K. Spurgeon, Sliding Mode Control: Theory And Applications - C Edwards, S Spurgeon - Google Books, 1st ed., vol. 1. 1998. Accessed: Dec. 08, 2021. [Online].

[5] H. Maghfiroh, A. Sujono, M. Ahmad, and C. H. B. Apribowo, "Basic Tutorial on Sliding Mode Control in Speed Control of DC-motor," Journal of Electrical, Electronic, Information, and Communication Technology, vol. 2, no. 1, Apr. 2020, doi: 10.20961/jeeict.2.1.41354.

[6] Yusai Zheng, Zhenwei Cao, and Song Wang, "Comparative Study of BLDC Motor Modeling," 2018.

[7] Surendra Singh Patel, B.A.Botre, Krishan K., and kAUSHAL k., "Modeling and implementation of Intelligent Communitation System for BLDC Motor in Underwater Robotic Applications," 2016.

[8] Anita Mary and Dr.L.Padma Suresh, Comparative performance analysis of different controllers for a nonlinear multivariable system. 2016.

[9] E. H. Dursun and A. Durdu, "Speed Control of a DC Motor with Variable Load Using Sliding Mode Control," International Journal of Computer and Electrical Engineering, vol. 8, no. 3, pp. 219–226, 2016, doi: 10.17706/IJCEE.2016.8.3.219-226.

[10] M. W. Fatma and M. I. Hamid, "PWM speed control of dc permanent magnet motor using a PIC18F4550 microcontroller," in IOP Conference Series: Materials Science and Engineering, Sep. 2019, vol. 602, no. 1. doi: 10.1088/1757-899X/602/1/012017.

[11] N. N. Baharudin and S. M. Ayob, "Brushless DC motor drive control using Single Input Fuzzy PI Controller (SIFPIC)," in 2015 IEEE Conference on Energy Conversion, CENCON 2015, 2015, pp. 13–18. doi: 10.1109/CENCON.2015.7409506.

[12] Chuck Lewin, "Field Oriented Control (FOC) - A Deep Dive," 2021. https://www.pmdcorp.com/resources/type/articles/get/field-oriented-control-foc-a-deep-dive-article (accessed May 31, 2022).

[13] Texas Instruments, "Field Oriented Control (FOC) Made Easy for Brushless DC (BLDC) Motors Using TI Smart Gate Drivers," 2021. [Online]. Available: www.ti.com