Journal of Advanced Research in Applied Sciences and Engineering Technology 31, Issue 1 (2023) 110-118

SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Effects of Fractional Order on Performance of FOSMC for Speed Control of PMSM

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ARTICLE INFO

Article history:
Received 26 January 2023
Received in revised form 21 May 2023
Accepted 28 May 2023
Available online 13 June 2023

Keywords:
Permanent magnet motors; sliding mode control; fractional calculus

ABSTRACT

Fractional order sliding mode control has been applied for speed control of PMSM. However, in many previous works, the effects of the controller's parameters have not been studied. This paper investigates the effects of fractional order on performance of FOSMC speed control of PMSM. In this work, fractional order, α and β of FOSMS-PID were varied, and their performances were compared. The simulation and experimental results show that variation of order of fractional order integration, α and order of fractional order differentiation, β can affect the performance of the FOSMC-PID controller. Selection of α and β values determines balancing strategies between integral and differentiation portion of the controller. Proper value selection and combination of these variables can further contribute to obtain optimum speed tracking, disturbance rejection and chattering reduction abilities.

1. Introduction

Speed control in high performance application of PMSM requires not only precise speed tracking but also excellent insensitivity against load disturbances. Various nonlinear controls have been proposed to achieve these properties, which includes sliding mode control, predictive control, backstepping control, adaptive control, automatic disturbance rejection control and artificial intelligence incorporated controllers [1-13]. Among them, sliding mode controller (SMC) has been widely studied as PMSM speed controller. Application of SMC for electric drives was introduced by Utkin [14]. SMC is a robust control method that can exhibit excellent tracking properties regardless of internal parameter variations and external disturbances. Complexity of high order systems is reduced to first order state variables, namely the sliding function and its derivative [15]. However,

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https://doi.org/10.37934/araset.31.1.110118

SMC's remarkable high accuracy and simplicity features are restricted by its chattering phenomenon, which occurs due to high frequency switching within sliding surface boundaries and parasitic dynamics interactions [1,16,17]. Chattering can cause deterioration in control accuracy and high wear of moving mechanical parts [14]. Hence, challenges in SMC design are not only to ensure convergence of system state to sliding surface and achievement of control target on sliding surface, but also to eliminate or reduce chattering during sliding mode.

Due to insufficient performance of conventional SMC design, previous researchers proposed several methods to enhance the controller's performance. Zaihidee *et al.,* [18] has thoroughly reviewed these methods and has categorized them into five approaches taken for SMC enhancement namely sliding surface design modification, higher order SMC, reaching law method, disturbance compensation and artificial intelligence. Sliding surface design modification approach focuses on improving SMC performance by replacing linear sliding surface design in conventional SMC with nonlinear designs. In terminal sliding surface designs, fractional power is introduced to ensure fast and finite-time states convergence during the sliding mode phase. Near the equilibrium point, rate of convergence will speed up which makes this controller preferred for high precision control. On the other hand, integral SMC is proposed by Utkin and Shi [19] to eliminate the reaching phase, therefore, sliding phase is enforced throughout the entire system response. As a result, system robustness can be guaranteed from the initial time. In addition, smaller maximum control magnitude is required for ISMC than conventional SMC since the value is usually bigger during the reaching phase, promoting chattering suppression [20,21].

To further optimize performance of integral speed SMC of PMSM, fractional calculus has been proposed to replace the integer order design. Theory of fractional calculus emerged more than three centuries ago, but just recently has caught researcher's attention to apply it for modelling and control in science and engineering [22]. In this theory, traditional integer order integration and/or differentiation is generalized to non-integer order, which can hold any values between 0 and 1. Incorporation of fractional calculus in SMC aims to improve control accuracy with the extra degree of freedom of integral and differential operators and reduce chattering with its slow energy transfer during switching [16].

For PMSM speed control, integer order integral term is extended by Zaihidee *et al.,* [23] with a fractional order integral term and a fractional order differentiation term to come up with a FOSMC-PID speed controller. Within its own fractional order SMC group, the proposed FOSMC with PID sliding surface has shown its advantages in balancing the individual strength and weaknesses of FOSMC-PI and FOSMC-PD [16,24]. The proposed FOSMC reduces overshoot contributed by the integral portion and at the same time reduces steady state error contributed by the differential portion. The combination of PID also improves speed loss when the load torque is applied, compared to speed loss of the FOSMC-PI and FOSMC-PD individually, ensuring optimum performance during transient mode as well as under external load disturbances. However, in their work, fractional order values are fixed. Hence, extra degree of freedom claimed to be offered by fractional calculus terms are not clearly identified. This work investigates how speed tracking and robustness change as fractional order values are varied in PMSM drive system with FOSMC-PID speed controller.

The rest of the paper is organized as follows. Fractional order sliding mode speed controller design for PMSM is presented in Section 2. Then, in Section 3, simulation and experimental results for variable fractional order values of the FOSMC are analyzed and discussed. Finally, conclusion and future works are presented.

2. FOSMC-PID Speed Controller for PMSM

Design of the speed controller is based on indirect field-oriented control of PMSM, as illustrated in Figure 1. Speed controller in the outer loop responses to speed error, which is the difference between actual speed and reference speed. Output of speed controller provides q-axis current reference value for execution of q-axis current regulation in inner loop that is responsible of controlling the torque of PMSM. On the other hand, d-axis current controller corresponds to flux control. Output of both current controllers define reference voltages for PWM in dq-coordinates. Inverse Clarke and Park transformation converts them into abc-coordinates required by PWM to generate appropriate switching signals to the three phase two level VSI inverter.

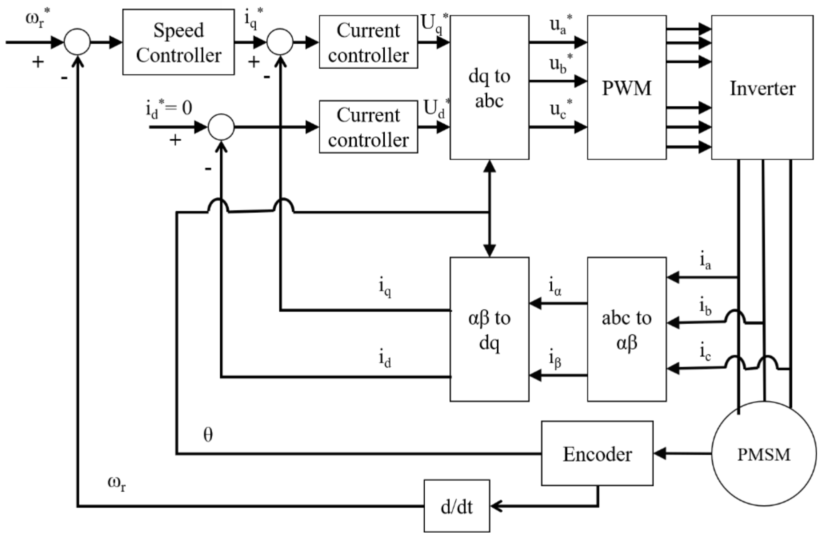


Fig. 1. Block diagram of indirect field-oriented control of PMSM

Fractional PID ($PI^{\alpha}D^{\beta}$) sliding surface design used in this work is shown in Eq. (1). Eq. (2) defines the equivalent control law obtained for the sliding mode speed controller of PMSM [23].

$$s(t) = k_p e(t) + k_i \, {}_0D_t^{-\alpha} e(t) + k_d \, {}_0D_t^{\beta} e(t) \tag{1}$$

$$i_q^*(t) = \left(bk_p\right)^{-1} \begin{bmatrix} k_i \, {}_0D_t^{1-\alpha} e(t) + k_d \, {}_0D_t^{\beta+1} e(t) + (w-a)k_p e(t) + k_p \phi(t) \\ +wk_i \, {}_0D_t^{-\alpha} e(t) + wk_d \, {}_0D_t^{\beta} e(t) + k_s sign(s) \end{bmatrix} \tag{2}$$

3. Effects of Fractional Order Selection on FOSMC-PID Speed Controller Performance

Sliding surface design of the FOSMC-PID as shown in Eq. (1) consists of two fractional order terms namely fractional integration and fractional differentiation. Both terms are identified by the order assigned to them, which can hold any real values between 0 to 1. This section investigates changes in speed response that occur when values of α and β are manipulated. The parameters of FOSMC-PID were chosen as in Table 1. Performance evaluation was executed in MATLAB/Simulink environment. Then, simulation results were further verified through hardware implementation using a closed-loop PMSM drive prototype, as shown in Figure 2. A 1.93kW interior PMSM with encoder was used in this work with nameplate data and parameters tabulated in Table 2 and Table 3 respectively. C code of the designed controller, coordinate transformations and PWM was generated in MATLAB/Simulink and was uploaded to DS1104 controller board. Inputs and outputs to and from the controller were obtained and distributed respectively using CP1104 connector panel. Switching signals produced by the PWM were fed to the inverter. The inverter produced the appropriate output voltages for the motor. Encoder signals was fed to the controller as feedback through a signal conditioning circuit. From these signals, the position of the rotor and the motor speed were extracted. Other than that, output currents to the motor were measured using current transducers and were fed back to the current controller. Load torque was applied to the system by a hysteresis brake, which was controlled by a dynamometer controller.

Table 1
FOSMC-PID controller parameter values

Parameter name	Parameter value
Order of fractional order integration, α	varies
Order of fractional order differentiation, β	varies
k_p	0.08
k_i	0.6
k_d	0.01
w	80
k_s	0.08

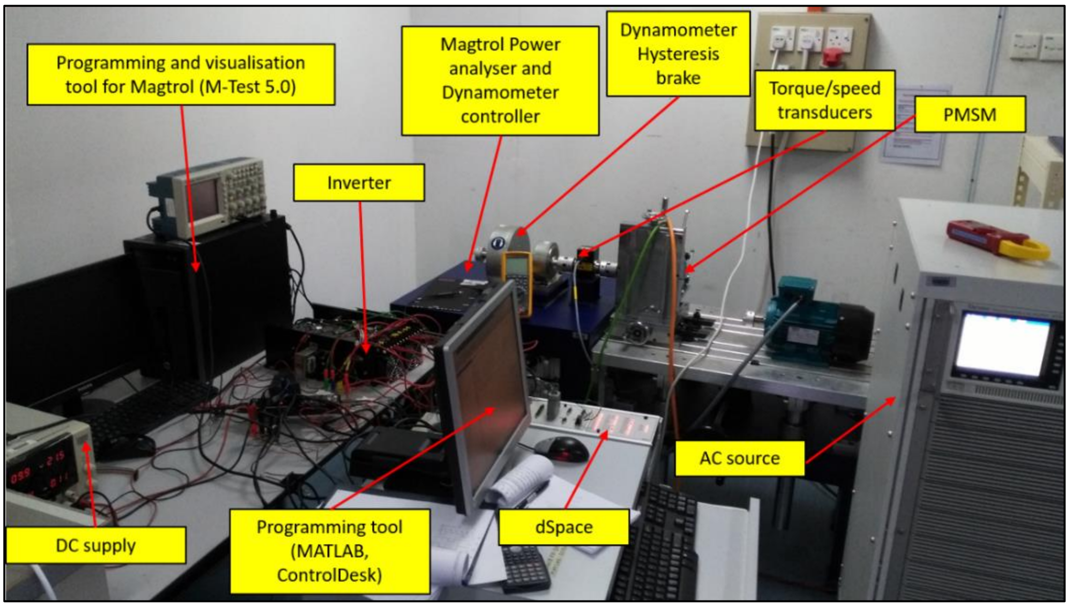


Fig. 2. Closed loop PMSM drive prototype

Table 2
Motor nameplate data

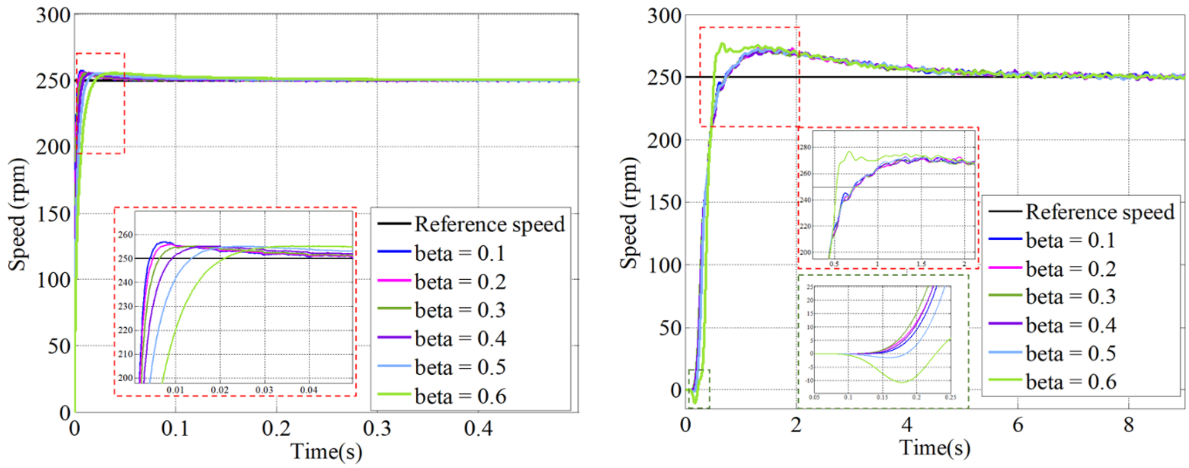
Motor parameter	Symbol	Motor data
Nominal output power	PN	1.93kW
Maximum voltage	Umax	480Vrms
Maximum current	Imax	17.1Arms
Maximum mechanical speed	nmax	6000min^{-1}
Continuous stall torque	M0	5.8Nm

Table 3
PMSM parameters

Motor parameter name	Symbol	Motor parameter value
Stator resistance	R_s	1.2Ω
d-axis stator inductance	L_d	6mH
q-axis stator inductance	L_q	6.75mH
Number of poles	p	8
Inertia	J	2.31 kgcm^2
Back emf constant	K_e	77 Vrms/krpm
Torque constant	K_t	0.9Nm/A

3.1 Various Order of Fractional Order Differentiation, β

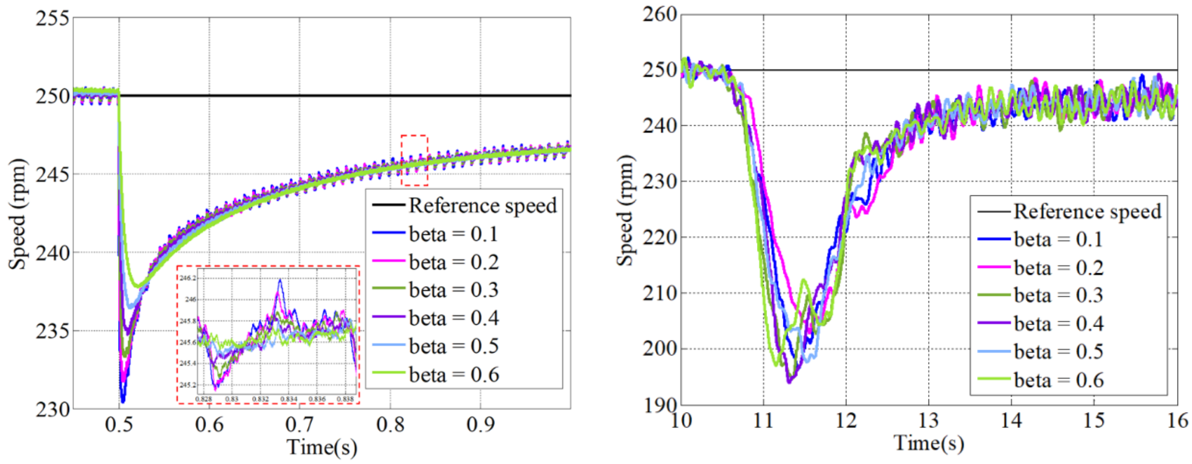
Initially, order of fractional order differentiation, β is varied with fixed value of α at 0.5 (middle value between 0 and 1). 250 rpm of speed reference is given to the drive system. Simulation results in Figure 3(a) show that time taken for the motor to reach reference speed increases as β increases. In contrary, speed transient overshoot reduces as β increases. Unfortunately, these relations cannot be clearly identified in experimental validation, as shown in Figure 3(b). In addition, a peculiar transient reverse motor rotation is recorded for $\beta > 0.5$.



(a) (b)

Fig. 3. Speed response comparison of FOSMC with various order of fractional order differentiation, β at no load (a) simulation (b) experiment

Speed tracking properties are then analysed when the system is burdened with load torque of 0.5Nm. Higher β values result in lower speed drop and lower speed ripple during simulation run, as indicated in Figure 4(a). On the other hand, although small differences can be identified from experimental results in Figure 4(b), relation between β values and speed drop or speed ripple cannot be concluded.

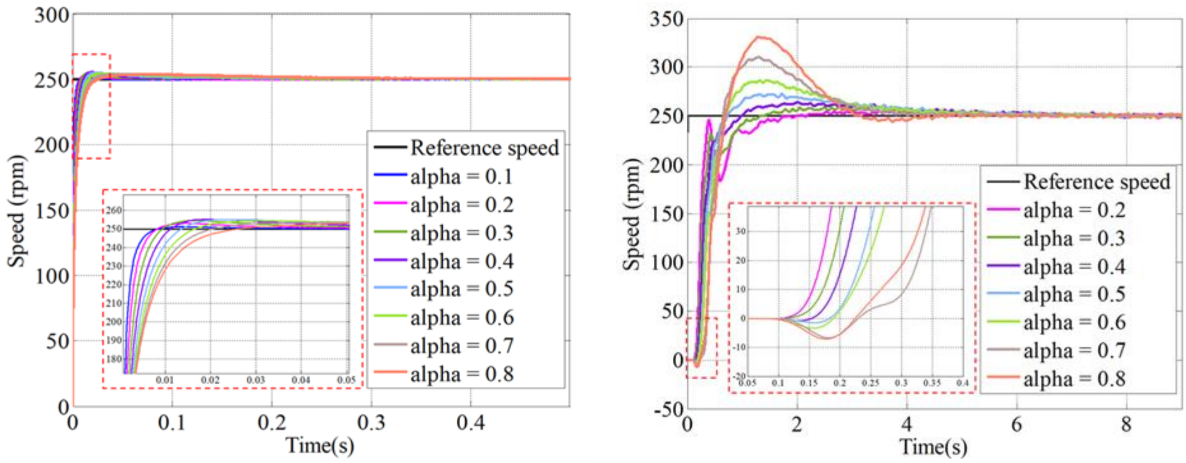


(a) (b)

Fig. 4. Speed response comparison of FOSMC with various order of fractional order differentiation, β with applied load of 0.5 Nm (a) simulation (b) experiment

3.2 Various Order of Fractional Order Integration, α

Secondly, order of fractional order integration, α is varied with fixed value of β at 0.5 (middle value between 0 and 1). Same speed reference of 250 rpm is given to the drive system. Increasing α values causes increment in rise time, as shown in simulation results in Figure 5(a). In contrary, experimental results in Figure 5(b) show that as α increases, rise time decreases. However, similar to previous case, reverse motor rotation during transient mode is recorded for $\alpha > 0.4$. In terms of overshoot, the value increases for α between 0.1 and 0.4, then decreases for $\alpha > 0.4$ in simulation case. In experimental case, gradual overshoot increment is experienced by the system as α increases.



(a) (b)

Fig. 5. Speed response comparison of FOSMC with various order of fractional order integration, α at no load (a) simulation (b) experiment

Under load torque of 0.5Nm, higher values of α causes higher speed drop in simulation, as shown in Figure 6(a). Similar trend is also recorded during experiment. During steady state, systems with higher α values experience lower steady state speed error in both simulation and experimental run. In addition, experimental results in Figure 6(b) show that a significant speed oscillation occurs in steady state for $\alpha > 0.7$.

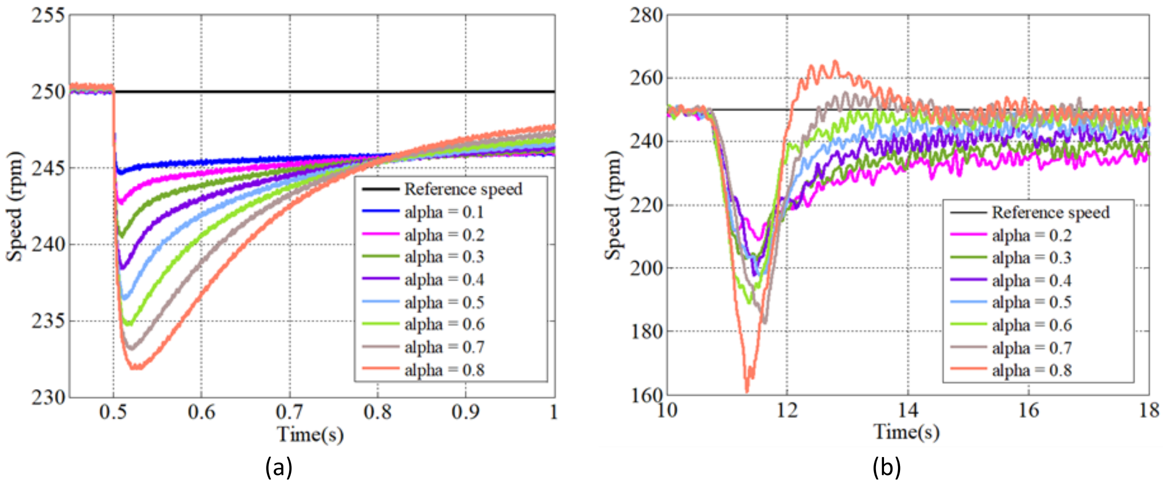


Fig. 6. Speed response comparison of FOSMC with various order of fractional order integration, α with applied load of 0.5 Nm (a) simulation (b) experiment

The presented results show that variation of order of fractional order integration, α and order of fractional order differentiation, β can affect the performance of the proposed FOSMC-PID controller. Both additional variables of fractional calculus incorporated in the SMC design provides extra degree of freedom for the SMC. Selection of α and β values determines balancing strategies between integral and differentiation portion of the controller. Proper value selection and combination of these variables can further contribute to obtain optimum speed tracking, disturbance rejection and chattering reduction abilities. This improvement will then result in more energy efficient use of motor drives, which will ensure country's future energy security, as elaborated in Khattak *et al.,* [25].

4. Conclusion and Future Works

Simulation and experimental results in this work proves that selection of fractional order integration, α and order of fractional order differentiation, β plays an important role in determining the performance of the proposed FOSMC-PID controller in terms of speed tracking, disturbance rejection and chattering reduction abilities. In future work, optimization algorithm e.g., using PSO should be incorporated into the proposed FOSMC-PID speed controller of PMSM to tune the parameters α and β [26]. Although fractional order sliding mode controller is a promising enhancement, selection of order values is crucial to avoid not only insignificant result, but in worse case, causes deteriorative effects to the system.

Acknowledgement
This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS Grant FRGS/1/2021/TK0/UPSI/02/1).

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