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Design of Fractional Order Proportional-integrator-derivative Controller for Current Loop of Permanent Magnet Synchronous Motor

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ABSTRACT

Performance improvement of permanent magnet synchronous motor is of great concern for researchers in controllers loop due to their high reliability performance and high power density for industrial drives. Because of the importance of this issue, in this paper to improve the behavior of permanent magnet synchronous motor, such as reducing the rise time, settling time and overshoot to step input in current loop control, fractional order PID controller is designed. Then, this improved behavior is compared to the fractional order PI controller in MATLAB simulation software. The results of simulations show the improvement of the behavior of synchronous permanent magnet synchronous motor by fractional order PID controller in its current loop.

Keywords: Behavior improvement, Current loop controller, Fractional order Proportional-Integrator-Derivative Controller (FOPID), Permanent magnet synchronous motor (PMSM).

I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) as variable speed drives have been replacing induction motors in industrial applications due to good features like low volume, low weight, high efficiency, high standalone torque density and easy of control [1-3]. PMSMs are now widely used as high performance starter such as industrial robots and machining tools [4].

In the recent decades, meaningful progress is achieved for speed control techniques. Control methods such as adaptive control, fuzzy control and neural networks are presented [5-7]. However, PID controllers are widely used that are tuned based on the proportional, integrator and derivative variables.

Proportional-Integrator and Derivative controllers are designed by researchers to improve the behavior of permanent magnet synchronous motors (PMSM) for the current loop which is schematically shown in Figure 1. For each of the three speed controllers, the d and q currents need proper coefficients *kp*, *ki* and *kd* to achieve the best steady state and transient response of the system. As these coefficients are dependent to the electrical and mechanical parameters of machine like stator resistance and inductances and also the control diagram of system is non-linear, there is no specific mathematical method to calculate above mentioned coefficients and some methods such as diagram linearization as possible and elimination of interior loops to reach these coefficients are used [8].

In recent years, fractional order controllers and systems are considered by researchers due to proper modeling of dynamic control structures, robust, effective and explicit control design, reasonable achieving

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by approximation [9-13]. For example, in the paper [14], superiority of proportional-integral fractional order controller is shown over full order controller. To improve the behavior of permanent magnet synchronous motor in the current loop with respect to the fractional order proportional-integrator (FOPI) controller of paper [14].

This paper presents a fractional order proportional-integrator-derivative (FOPID) controller. This improvement in the behavior is compared with the FOPI controller in MATLAB simulation software. The results indicate that the FOPID controller proposed in this paper to the unit step input of permanent magnet synchronous motor in current loop, has better performance such as the amount of rise time, overshoot and settling time compared with FOPI controller.

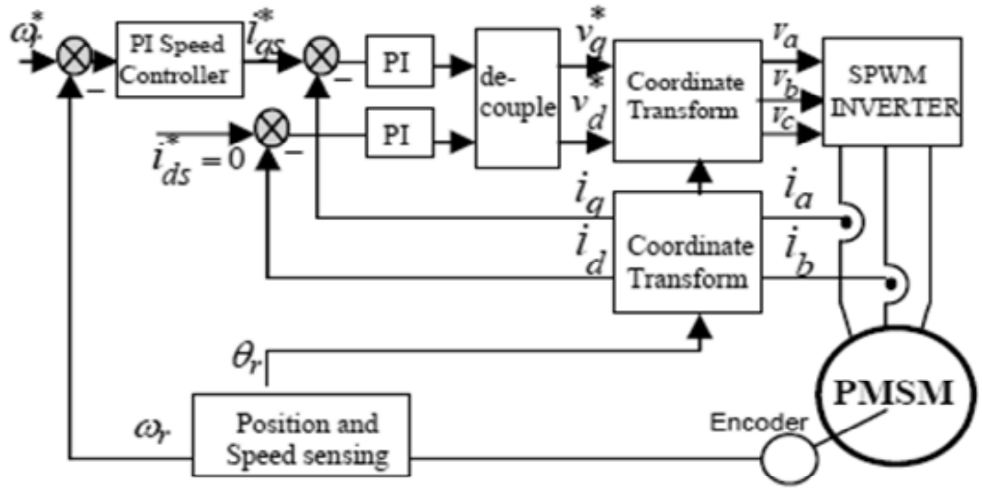

Figure 1: Schematic of control loops for permanent magnet synchronous motor

II. FRACTIONAL ORDER PROPORTIONAL-INTEGRATOR-DERIVATIVE CONTROLLER

In the frequency domain, the control functions are in the feedback mode that has an impact on the behavior of the system. These operators are proportional, derivative and integrator and their main influences on the behavior of the controlled system are as follows [15]:

1) Increase the response speed, decrease the steady-state error and relative stability for proportional operator
2) Increase the relative stability and sensitivity to noise for the derivative operator
3) Eliminate steady state error and reduce the relative stability for the Integrator operator

Proportional, Integrator and Derivative (PID) controllers are well known and widely used due to their simple implementation, efficacy in industry, robustness against uncertainties in system and ease of parameters tuning.

Generalized of a PID controller is a FOPID controller in which integral and derivation order are fractional. To develop the fractional order controller, [16] has presented general form of a FOPID as follows:

$$u(t) = k_p e(t) + k_i D_t^{-\lambda} e(t) + k_d D_t^{\mu} e(t) \tag{1}$$

And it is shown in the frequency domain as:

$$C_{FO}(s) = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \tag{2}$$

As shown in equation (2), this controller includes a λ-order integrator and ì-order derivative. These two parameters increase the degree of freedom of the system and cause the FOPID controller to be superior to full order controller. Some of these superiorities are more design parameters increase in degree of freedom for design of a stable and tolerant controller and also by improved ability to track the desired input, reduction of the steady-state error and overshoot and increase in the speed of response are obtained. For more information, refer to [17].

III. CURRENT LOOP OF PERMANENT MAGNET SYNCHRONOUS MOTOR

Current controller design is usually based on linear control system methods such as Bode diagram, root locus or by optimization functions. Current loop controller design is very important for permanent magnet synchronous motor drives in high performance applications. Current controller, which is usually a PI controller, can be designed based on the self-inductance and stator resistance for each phase of the motor [18]. Figure 2 shows a simplified form of q axis current loop of permanent magnet synchronous motor [14].

It is noted that these indices can be calculated for the whole system or any part of it or even a specific feeder.

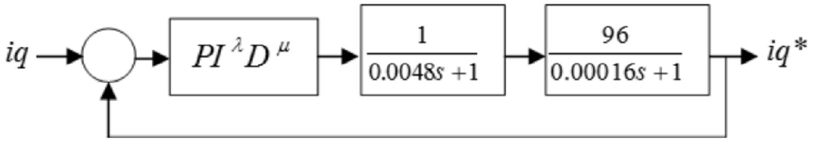

Figure 2: Simplified diagram of q axis current loop

IV. SIMULATION AND RESULTS

In this paper, the simulation results of the proposed method of permanent magnet synchronous motor current loop model proposed in [14] is used and the transfer function of the system in current loop is as:

$$G(s) = \frac{96}{(0.00048s)(0.00016s)} \tag{3}$$

Figure 3 shows the output of transfer function (3) with respect to a unit step input without controller mode.

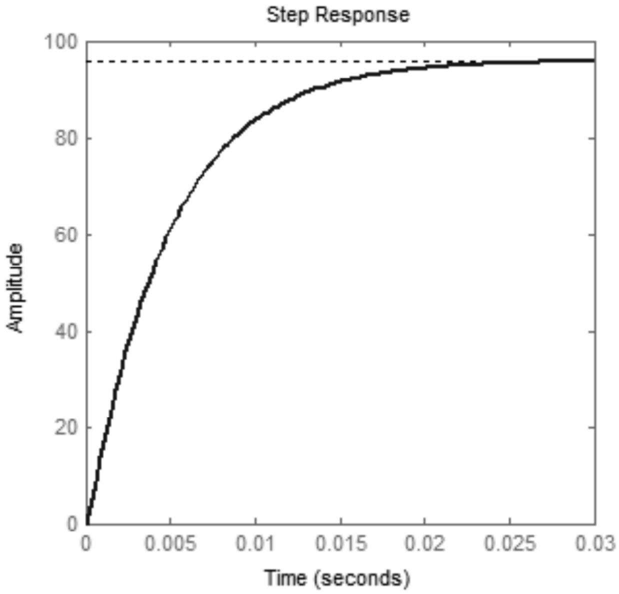

Figure 3: Motor current loop output waveform without controller

Several methods are proposed for obtaining the coefficients of proportional-integrator-derivative fractional order controller [19-21]. In this paper, the method presented in [17] is used to obtain the coefficients.

In this method, design criteria specified in this field are as follows:

1) Phase margin criterion (φ_m) and gain pass frequency (ω_{cg})

Phase margin and gain margin are used as significant values of stability. Equations of phase margin and gain pass frequency are as follows.

$$\left|C(\mathrm{j}\omega_{cg})\mathrm{G}(\mathrm{j}\omega_{cg})\right|_{dB} = 0dB \tag{4}$$

$$\arg(C(\mathrm{j}\omega_{cg})\mathrm{G}(\mathrm{j}\omega_{cg})) = -\pi + \varphi_m \tag{5}$$

2) Gain margin criterion (φ_m) and phase pass frequency (ω_{cg})

The below equation shows the equation of gain margin and phase pass frequency:

$$\frac{1}{\left|C(\mathrm{j}\omega_{cp})\mathrm{G}(\mathrm{j}\omega_{cp})\right|} = A_m \tag{6}$$

3) Stability for changing the values of system gain

For stability criterion of changing the values of system gain, equation (7) is used:

$$\left(\frac{d(\arg(C(\mathrm{s})\mathrm{G}(\mathrm{s}))}{d\omega}\right)_{\omega=\omega_{cg}} = 0 \tag{7}$$

4) A criterion for eliminating the noise effect in high frequencies

$$\begin{aligned} &\left|T(j\omega) = \frac{C(j\omega)G(j\omega)}{1+C(j\omega)G(j\omega)}\right|_{dB} \le AdB, \\ &for \\ &\omega \ge \omega_t rad/s \rightarrow |T(j\omega_t)|_{dB} = AdB \end{aligned} \tag{8}$$

5) A criterion for eliminating the disturbance effect in low frequencies

$$\begin{aligned} &\left|\mathrm{S}(j\omega) = \frac{1}{1+C(j\omega)G(j\omega)}\right|_{dB} \le BdB, \\ &for \\ &\omega \le \omega_s rad/s \rightarrow \left|\mathrm{S}(j\omega_s)\right|_{dB} = BdB \end{aligned} \tag{9}$$

In this paper, in order to achieve the 5 above mentioned criteria (4-9) and considering 5 parameters in the controller k_p, k_i, λ, k_d, μ criteria (4) has to be considered as optimization function and the 4 other criteria are considered as its constraints.

Nelder and Mead minimization method [22] is used for solving the above criteria and parameters.

Parameters obtained by the Nelder and Mead FOPID optimization method and parameters calculated in the paper [14] are given in Table (1) with the following characteristics of the motor:

Table I
Values of Parameters

Parameters	*FOPI*	*FOPID* [a]
k_p	0154	0.5775
k_i	3.04	0.63072
λ	0.62	0.48093
k_d	0	0.96085
μ	0	0.49775

$$\omega_{cg} = 3000\ rad/s$$

$$\varphi_m = 70^\circ$$

$$A = -20\ dB$$

$$B = -20\ dB$$

By observing Figure 4, it is shown that the proposed method gives better response. For a more detailed comparison, Table 2 shows the step response from different indices perspective.

As shown in Figure 4 and Table 2, the proposed method provides better unit step response.

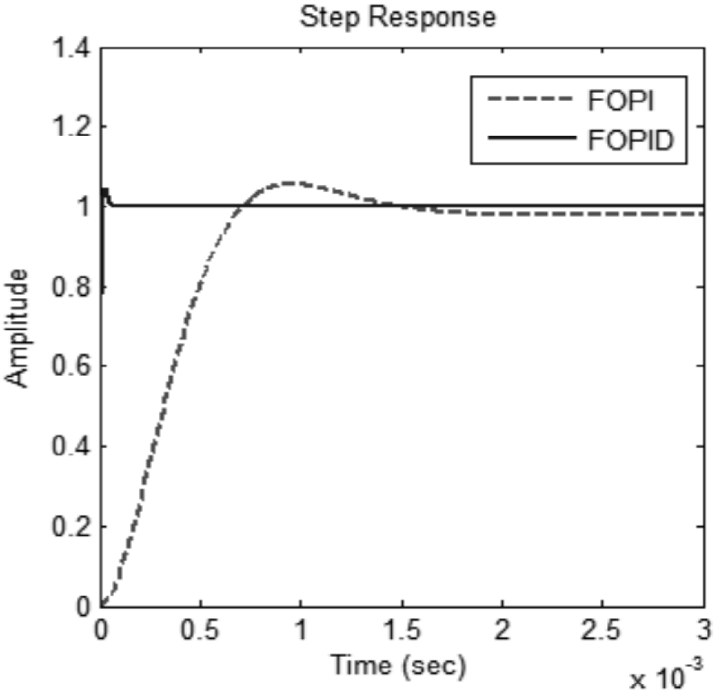

Figure 4: The output waveform of the motor to the unit step input with controller

Table II
Values of Parameters

Parameters	*FOPI*	*FOPID* [a]
Rise Time (s)	0.00045139	0.000013596
Setteling Time (s)	0.0015	0.00004384
Over Shoot	7.8267	4.8330

CONCLUSION

The method presented in this paper (design of a FOPID controller) presents better response for current loop control system of permanent magnet synchronous motor because of more design parameters.

The response reduces the cost and complexity of system controller design. This method is designed to reduce the complexity of the proportional-integrator-derivative controller. As shown in simulation, improvement of the behavior of permanent magnet synchronous motor by FOPID controller on its current loop was better with respect to the FOPI controller and shows the superiority of this kind of fractional order controller.

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