IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 14, Issue 4 Ser. II (Jul. – Aug. 2019), PP 35-41
www.iosrjournals.org

A Model-based PI Controller Tuning and Design for Field Oriented Current Control of Permanent Magnet Synchronous Motor

Kenneth C. Odo[1], Sochima V. Egoigwe[2] and Cosmas U. Ogbuka[1]
[1](Department of Electrical Engineering, University of Nigeria, Nsukka Nigeria)
[2](Department of Mechatronic Engineering, University of Nigeria, Nsukka Nigeria)
Corresponding Author: Kenneth C. Odo

Abstract: *This paper presents a model-based PI controller tuning and design for field oriented current control of permanent magnet synchronous motor. A systematic approach is adopted to accurately determine the gains of the PI controller, from first principle, using the mathematical model of the control system. The designed PI controller for field oriented current control was tested on Permanent Magnet Synchronous Motor (PMSM). The accuracy of the design is reflected in the results which show effective tracking of both the d-axis and q-axis reference currents with minimal overshoot. These results clearly represent a superior alternative to the traditional approach of selecting PI controller gains by trial and error with its attendant demerits.*

Keywords: *PI controller, proportional gain, integral gain, PMSM, overshoot*

Date of Submission: 09-08-2019 Date of Acceptance: 23-08-2019

I. Introduction

Proportional Integral (PI) controllers have remained very common in Control Engineering applications [1, 2] but its tuning has continued to be a challenge. PI controllers used in ac machines drives are usually tuned by trial and error methods [3]. One of such methods involves keeping either the proportional gain, Kp, or the integral gain, Ki, constant while the other one is varied until the desired response is obtained. This method is very tedious and time consuming [4].

Many research papers have been published on tuning of PI controllers including the tuning rules in [5] and the manual tuning method explained in [6,7, 8, 9]. In [10], a methodology based on Absolute Value Optimum (AVO) and Symmetric Optimum (SO) was presented for Field Oriented Control (FOC). The shortfall of this method is that it assumes the FOC to be an open loop system while estimating the controller gains.

Unlike the models presented in [6,7,8,9,10,11] which are based on trial and error tuning method, this paper sets-out to adopt a model-based approach to accurately determine the gains of the PI controller, from first principle, using the well-established dq model of the PMSM.

II. PI Controller Design

The dq-axis voltages for a permanent magnet synchronous machine can be written in time domain as[11]:

$$V_d = Ri_d + L_d \frac{di_d}{dt} - \omega L_q i_q \tag{1}$$

$$V_q = Ri_q + L_q \frac{di_q}{dt} + \omega(L_d i_d + \lambda_{pm}) \tag{2}$$

By taking Laplace transform of equation 1 and 2, we obtain the frequency domain equivalent as:

$$V_d(s) = (sL_d + R)i_d(s) - \omega L_q i_q(s) \tag{3}$$

$$V_q(s) = (sL_q + R)i_q(s) + \omega(L_d i_d(s) + \lambda_{pm}) \tag{4}$$

Since we are dealing with field oriented control (FOC) for current, we make the controlled variable (i_q current in this case) the subject of equation 4; i_d current being set to zero in other to maintain constant flux. So from equation 4 we obtain:

$$i_q(s) = [V_q(s) - \omega(L_d i_d(s) + \lambda_{pm})](\frac{1}{sL_q + R}) \tag{5}$$

In block diagram form, equation 5 can be expressed as shown in Figure 1.

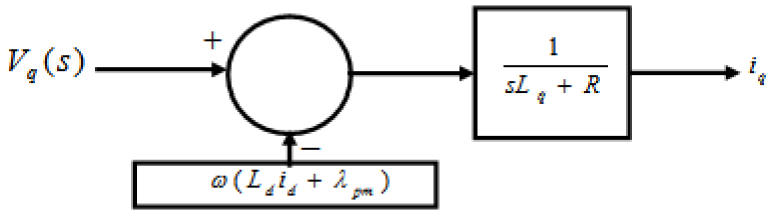

Figure 1: Open loop block diagram of the current control model

It is seen from equations 3 and 4 that the dq current control loops are not independent due to the back-emf terms in both equations. To make the dq current control loops independent, a back-emf decoupling term is introduced. This decoupling term is introduced after the PI controller as a disturbance with the same value but opposite sign of the back-emf term in the motor model. The block diagram of the system now as shown in Figure 2. Since the decoupling term will cancel the effect of the back emf term, Figure 2 reduces to Figure 3. There will be both sensor delay and computation time delay in the system; a first order time delay is introduced to modify Figure 3 as shown in Figure 4

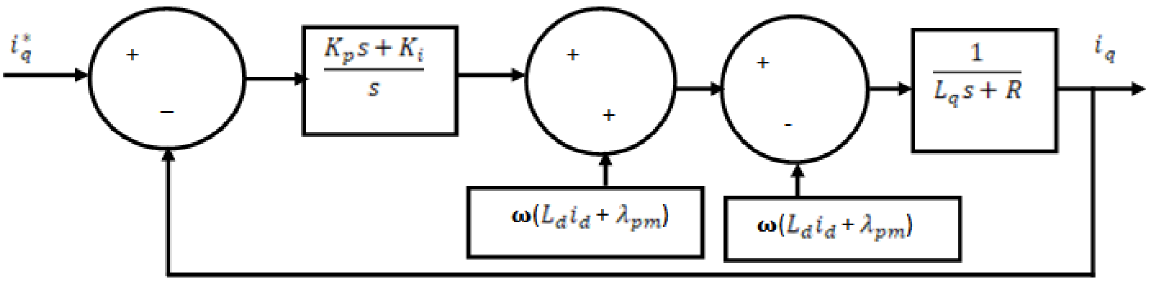

Figure 2: Closed loop block diagram of the decoupled current control model

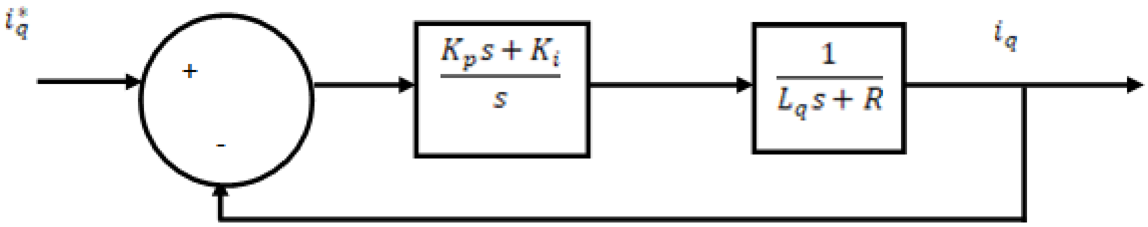

Figure 3: Closed loop block diagram of the current control model

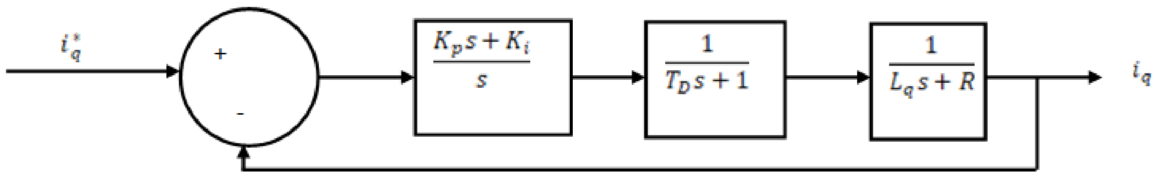

Figure 4: Current control model with time delay

The open loop transfer function, GOL, is given by equation 6 below

$$G_{OL}(s) = \frac{K_p(s) + K_i}{s} \cdot \frac{1}{T_D s + 1} \cdot \frac{1}{Ls + R} \tag{6}$$

Let the PI controller gain ratio $\frac{K_i}{K_p}$ which is equal to the ratio of stator resistance to d or q-axis inductance $\frac{R}{L}$ of the machine be represented as K_{ip}. So that,

$$K_{ip} = \frac{K_i}{K_p} = \frac{R}{L} \text{ or } K_i = K_p K_{ip} \tag{7}$$

Substituting equation 7 into equation 6 gives equation 8 below

$$G_{OL}(s) = \frac{K_p(s) + K_p K_{ip}}{s} \cdot \frac{1}{T_D s + 1} \cdot \frac{1}{Ls + R} \tag{8}$$

Substituting $K_{ip} = \frac{R}{L}$ into equation 8 and simplifying gives:

$$G_{OL}(s) = \frac{K_p}{T_D L} \cdot \frac{1}{s(s + \frac{1}{T_D})} \tag{9}$$

If we let $K = \frac{K_p}{T_D L}$, then equation 9 becomes:

$$G_{OL}(s) = \frac{K}{s(s + \frac{1}{T_D})} \tag{10}$$

The closed loop transfer function, G_{CL}, is given as:

$$G_{CL}(s) = \frac{G_{OL}(s)}{1 + G_{OL}(s)} \tag{11}$$

After substitution and simplification, equation 11 becomes:

$$G_{CL}(s) = \frac{K}{s(s + \frac{1}{T_D}) + K} = \frac{K}{s^2 + \frac{1}{T_D} s + K} \tag{12}$$

The general equation for a second order system is given as [12]:

$$H(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{13}$$

By comparing equation 12 and 13 we obtain:

$$\omega_n = \sqrt{K} \text{ and } \xi = \frac{1}{2T_D\sqrt{K}} \tag{14}$$

Maximum percentage overshoot of a second order system M_p is given as:

$$M_p = e^{-\pi\xi / \sqrt{1-\xi^2}} \tag{15}$$

$K_p = 7.2$ and $K_i = 1314$, where ω_n is the natural frequency and ξ is the damping ratio. So by choosing the maximum percentage overshoot M_p allowed and the value of T_D; K_p *and* K_i can be calculated using equations 14 and 15.

In our case study, by setting $M_p = 2\%$ and $T_D = 0.3ms$; with the machine parameters shown in Table 1, K_p *and* K_i shown above were calculated

Table 1: PMSM parameters

Machine Parameters used Calculation/Simulation		
Rated voltage	V	300V
Stator resistance	Rs	0.9585Ω
d-axis inductance	Ld	0.00525H
q-axis inductance	Lq	0.00525H
Rotor flux linkage	λ_{pm}	0.1827Wb
Inertia	J	0.0006329Kgm^2

Friction factor	B	0.0003035Nms
No. of pole pair	P	4

III. PI Controller Model

From equations 1 and 2:

$$\frac{di_d}{dt} = \frac{1}{L_d}V_d - \frac{R}{L_d}i_d + \omega\frac{L_q}{L_d}i_q \tag{16}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}V_q - \frac{R}{L_q}i_q - \omega\frac{L_d}{L_q}i_d - \frac{\omega\lambda_{pm}}{L_q} \tag{17}$$

The time rate of change of i_d current (i.e. $\frac{di_d}{dt}$) is the same as the error in i_d current, e_d, per sample time.

$$\frac{di_d}{dt} = e_d = i_d^* - i_d \tag{18}$$

Similarly, the time rate of change of i_q current (i.e. $\frac{di_q}{dt}$) is the same as the error in i_q current, e_q, per sample time.

$$\frac{di_q}{dt} = e_q = i_q^* - i_q \tag{19}$$

Substituting e_d and e_q in equations 16 and 17 respectively gives:

$$e_d = \frac{1}{L_d}V_d - \frac{R}{L_d}i_d + \omega\frac{L_q}{L_d}i_q \tag{20}$$

$$e_q = \frac{1}{L_q}V_q - \frac{R}{L_q}i_q - \omega\frac{L_d}{L_q}i_d - \frac{\omega\lambda_{pm}}{L_q} \tag{21}$$

Making V_d and V_q subjects of equation 20 and 21 gives

$$V_d = Ri_d + e_d L_d - \omega L_q i_q \tag{22}$$

$$V_q = Ri_q + e_q L_q + \omega L_d i_d + \omega\lambda_{pm} \tag{23}$$

It is recalled that $K_{ip} = \frac{K_i}{K_p} = \frac{R}{L} \Rightarrow K_i \;\alpha\; R$ and $K_p \;\alpha\; L$

Now $e_d = \frac{di_d}{dt} \Rightarrow i_d = \int e_d dt$

Similarly, $e_q = \frac{di_q}{dt} \Rightarrow i_q = \int e_q dt$

Hence $e_d L_d \;\alpha\; K_p e_d$ and $Ri_d \;\alpha\; K_i \int e_d dt$

Also $e_q L_q \;\alpha\; K_p e_q$ and $Ri_q \;\alpha\; K_i \int e_q dt$

By making appropriate substitutions into equations 22 and 23, it is obtained that:

$$V_d = K_p e_d + K_i \int e_d dt - \omega L_q i_q \tag{24}$$

$$V_q = K_p e_q + K_i \int e_q dt + \omega L_d i_d + \omega\lambda_{pm} \tag{25}$$

Equations 24 and 25 give the relation between current errors and the dq-voltages. Therefore equations 24 and 25 are the mathematical model of the PI controller which can process the current errors to produce the dq-voltages. The block diagram representation of equations 24 and 25 for implementation of the model in MATLAB/Simulink is shown in Figure 5.

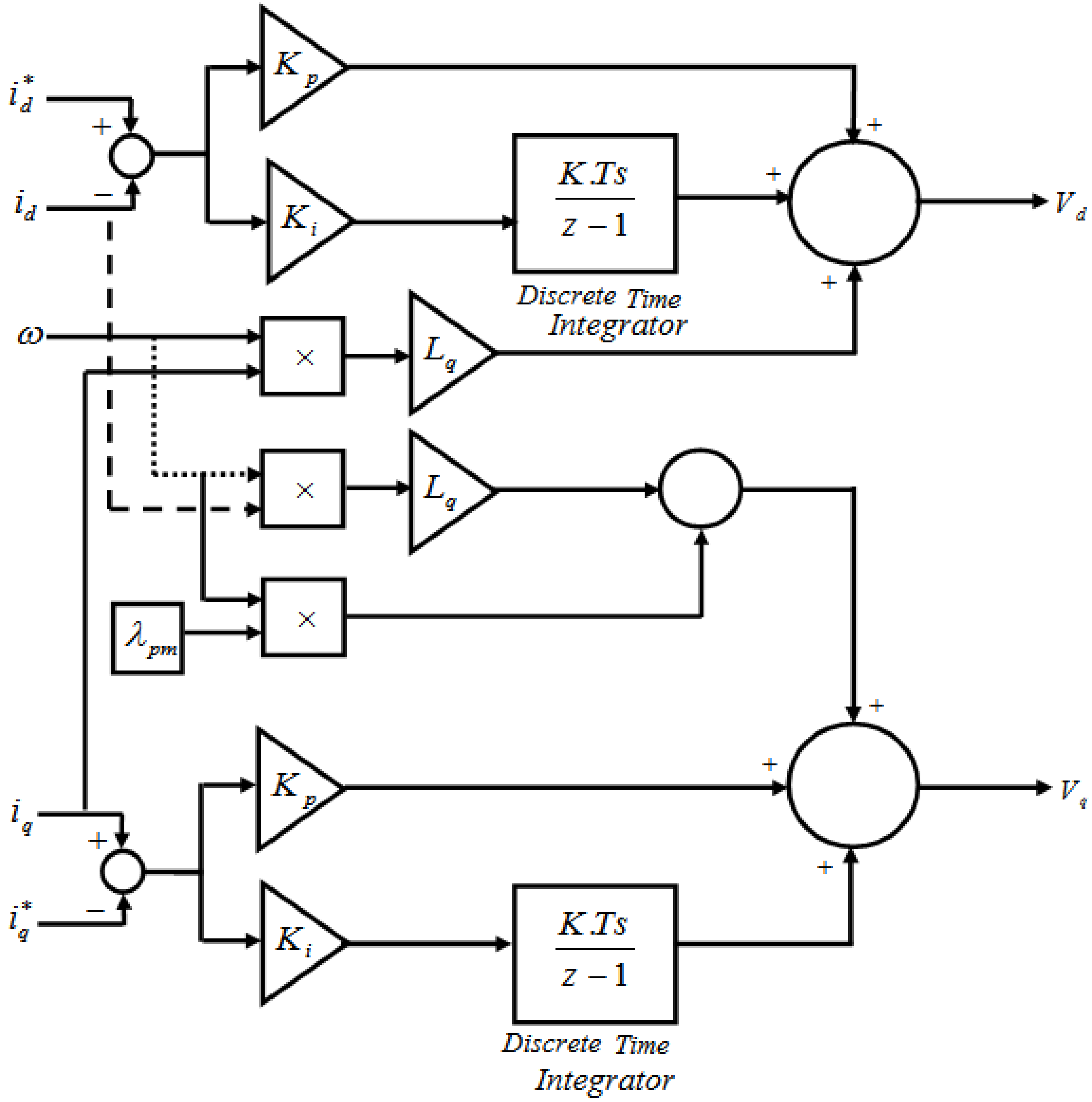

Figure 5: Simulink model of PI controller

IV. Results

The designed PI controller was tested in MATLAB/Simulink environment on a permanent magnet synchronous motor with the parameters shown in Table 1. The calcalated gains of $K_p = 7.2$ and $K_i = 1314.5$ were used in the simulation. The d-axis reference current was kept at zero to ensure constant flux operation while the q-axis reference is a step input with initial value of -5A; final value of 5A and step time of 0.5 seconds for a total simulation time of 1 second. The results show effective tracking of the reference currents (i_d_ref and i_q_ref). A maximum overshoot of ±0.2A was observed. This equals 4% of iq which is slightly higher than the designed 2% maximum overshoot.

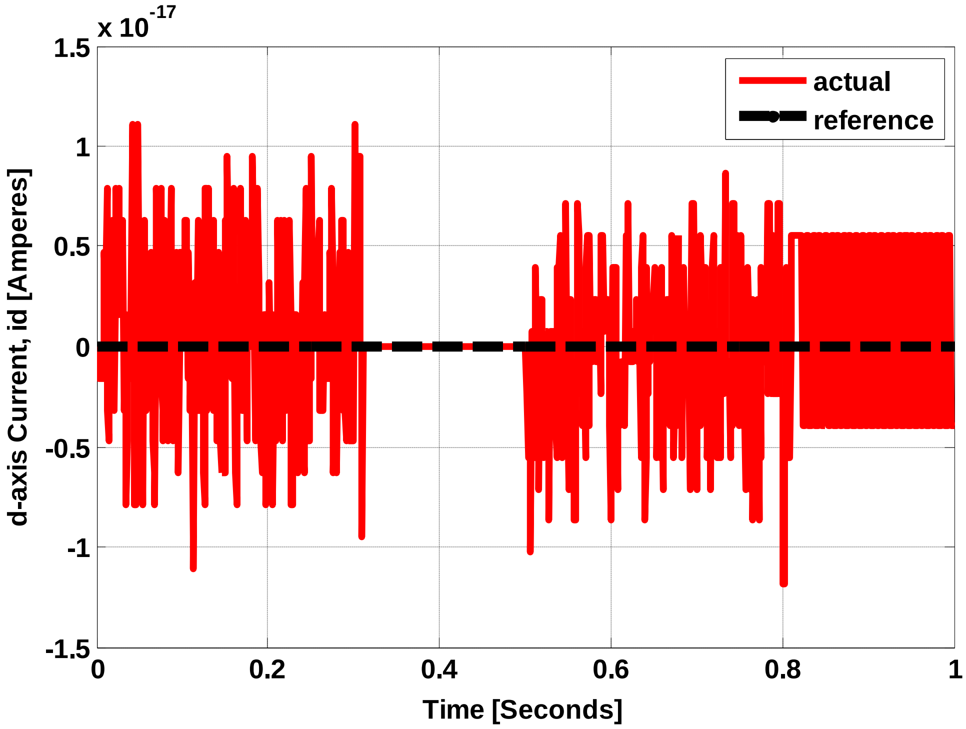

Figure 6: d-axis current response

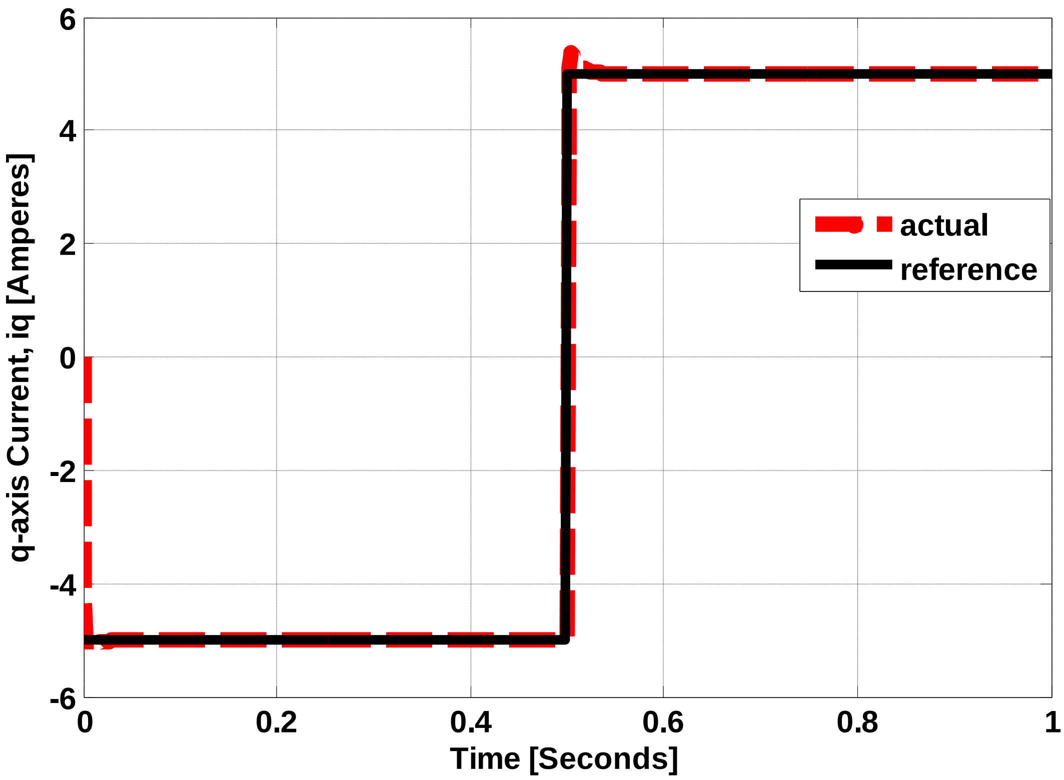

Figure 7: q-axis current response

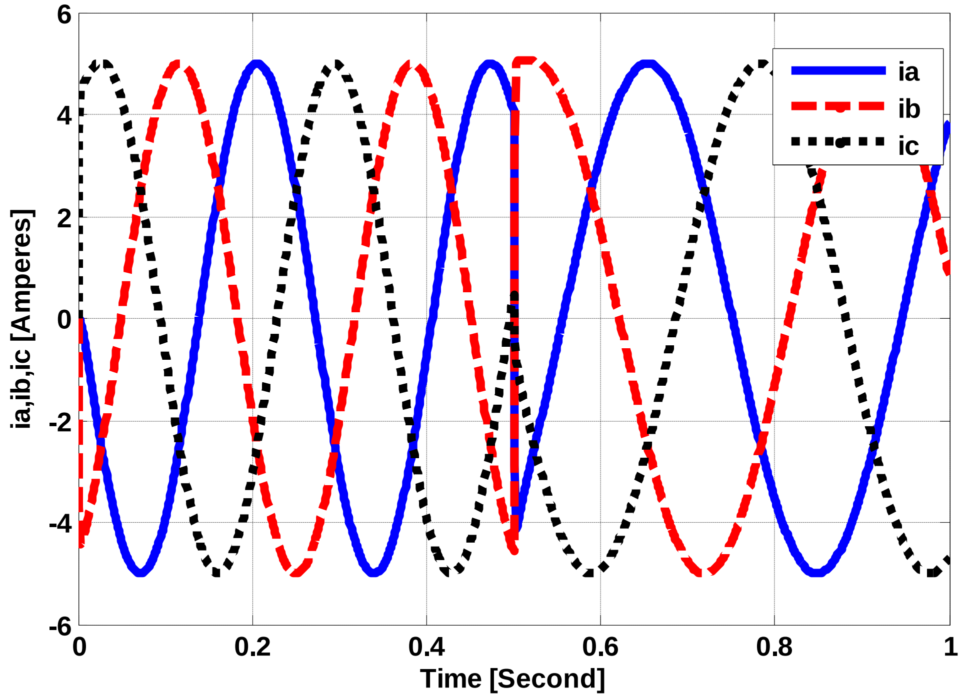

Figure 8: Phase currents for the a,b,c phases

V. Conclusion

This work has successfully determined the gains of the PI controller for FOC using the mathematical model of the control system. The accuracy of the calculated gains is evident in the simulation results which showed effective tracking of the reference currents. The response shows very small overshoot of about 4%, setting time of about 0.015s and a perfect tracking of the reference. These indicate that the tuning method gives satisfactory results. The overall objectives of this work have been achieved.

References

[1]. N. Tan and D. P. Atherton, Design of stabilizing PI and PID controllers, *International Journal of Systems Science, 37(8)*, 2006, 543-554.

[2]. J.C. Basilio and S.R. Matos, Design of PI and PID controllers with transient performance specifications, *IEEE Transactions on Education, 45(4)*, Nov 2002, 364-370.

[3]. R. Kumar and S. Singla, A comparative analysis of different methods for the tuning of PID Controllers, *International Journal of Electronics Communications and Electrical Engineering*, 3(2), February 2013, 1-17.

[4]. C. Gasparovic, E. Eyng, L. Frare, R. Arioli and F. Orssatto, PID tuning by central composite rotational design methodology: a case study of absorption Column for biogas purification, *International Journal of Innovative Computation, Information and Control*, 14(1), February 2018, 15-32.

[5]. S. Skogestad, Probably the best simple PID tuning rules in the world, *Journal of Process Control, 13*, September 2003, 291-309.

[6]. F.A Salem and A.A Rashed, PID controllers and algorithms: selection and design techniques applied in mechatronics systems design- part II, *International Journal of Engineering Sciences, 2(5)*, May 2013, 191-203.

[7]. D.V Lukichev and G.L Demidova, Features of tuning strategy for field-oriented control of PMSM position drive system with two-mass load, *International Journal of Circuits, Systems and Signal Processing, 10*, 88-94.

[8]. C.U. Ogbuka, C. M. Nwosu, M.U. Agu, A fast hysteresis current-controlled permanent magnet synchronous drive based on field orientation, *Journal of Electrical Engineering —Elektrotechnicky Casopis, 67(2)*, March 2016, 69-77.

[9]. C.U. Ogbuka, C.M. Nwosu, M.U. Agu, A high-performance hysteresis current control of permanent magnet synchronous motor drive, *Turkish Journal of Electrical Engineering and Computer Engineering, 25 (1)*, February 2017. Pp. 1-14

[10]. B. Zigmund, A. Terlizzi, X.T. Garcia, R. Pavlanin and L.Salvatore, Experimental evaluation of PI tuning techniques for field oriented control of permanent magnet synchronous motors, *Advances in Electrical and Electronic Engineering, 14*, 114-119.

[11]. C.U Ogbuka, K.C Odo, M.C Odo and C. M Nwosu, Direct torque control of permanent magnet synchronous motor using space vector pulsewidth modulation, Proceedings of the 1st International Conference of the Faculty of Engineering, University of Nigeria Nsukka, 25-28 April, 2018, 181–187.

[12]. C.U. Ogbuka, Performance characteristics of controlled separately excited DC motor, *Pacific Journal of Science and Technology. 10 (1)*, 2009, 67-74.

Kenneth C. Odo, Sochima V. Egoigwe and Cosmas U. Ogbuka " A Model-based PI Controller Tuning and Design for Field Oriented Current Control of Permanent Magnet Synchronous Motor." IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) 14.4 (2019): 35-41.