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Current PI-Gain Determination for Permanent Magnet Synchronous Motor by using Particle Swarm Optimization

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Abstract

This paper proposes the modern approach using Particle Swarm Optimization (PSO) algorithm in determining the ideal value of Proportional Integral (PI) gain for current controller of Permanent Magnet Synchronous Motor (PMSM). Controlling the torque of PMSM and optimizing the PI-gain are the main objectives of this project. The PI controller is employed to control the speed and the torque of the PMSM with the implementation of Field Oriented Control (FOC) method. This new proposed PSO technique proved that the ability in reducing the torque ripple compared to conventional heuristic method. The ideal PI-gain acquired from the PSO was included into current PI controller. From the result obtained, it shows that the viability of the PSO technique is the best to determine PI-gain for current controller.

***Keywords**: PI, FOC, PMSM, PSO*

1. Introduction

The fact that PMSM is generally utilized as a part of robotic system, Computer Numerical Control machine, electric drive system and etc. because of its capabilities in power density, favorable circumstances in effectiveness and reliability. Proportional-integral (PI) control strategy could still be disputed in ensuring adequate accuracy for PMSM control system [1]. The principal weakness of sinusoidal commutation is that it attempts to control motor currents that are in time variant. The limited bandwidth of the PI controller which makes the speed and frequencies goes up. Thus, this problem is solved by implementing FOC, which control the current space vector specifically in the d-q reference axis.

FOC control technique has been dedicated in PMSM system due its simplicity and straightforward execution, strength in operation and simple cognizance of its guideline compared with other strategy utilizing the PI controller [2-4]. Other advantages are quick reaction and little torque swell as well as ease in the implementation are the benefits of FOC. Other strategies that make used of PI controller for tuning are such as: 1) Heuristic method, 2) Process Reaction Curve methods, 3) Continuous cycling method, 4) Cohen-Coon method, 5) Ziegler-Nichols method.

PI controller has been significantly utilized as a part of modern segment for PMSM framework due to best execution when it is ideally tuned [5]. Nonetheless, without correct model, it is hard to track down the global best value. This will cause problem to locate the ideal gain in which will limit the dynamic execution of the system. This issue can be resolved by using current control of PMSM. This system will focus on controlling the current of the PMSM by using PI controller. To achieve an efficient speed control, PSO technique was executed to optimize the PI parameters. The scope of this project focusing on the current control of PMSM. Torque current will be controlled in PI controller to reduce the overshoot and ripples of the torque and flux current that increase efficiency and fast response.

There are various types of optimization technique such as Differential Evolution (DE), Genetic Algorithm (GA), Evolutionary Programming and etc [6] Due to numerous types of optimization technique, this project focused on the controlling current loop of FOC control method by using PSO technique. The designed system was validated by using Matlab/Simulink Software.

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2. Research Method

The main goal of this project is to design the PSO algorithm that can be executed into PI current controller. Literature review focusing on the FOC method and PSO optimization technique were carried out. Next the FOC for PMSM is modelled and PSO is executed into FOC block model on the MATLAB Simulink software. Finally the response of current and torque were analysed.

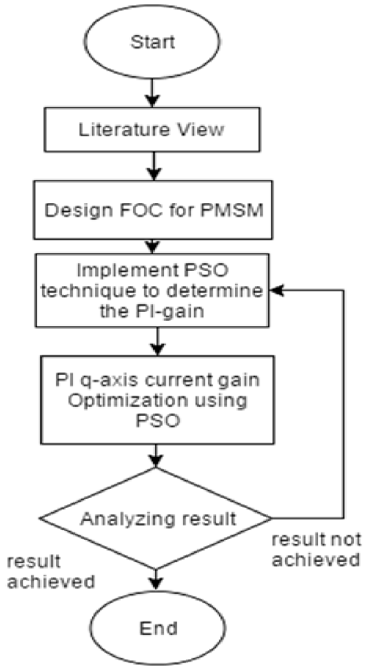

Figure 1. Project's Methodology Flowchart

2.1. Mathematical Modelling of PMSMS

Mathematical model of the PMSM was derived in this section. The current control by using FOC was briefly explained. Generally, PMSM can be classified into two components that consist of mechanical and electrical components. These two components can be derived by nonlinear differential equations. The electrical component is fundamentally comprised of the stator stage windings [7]. Controlling of the stator current is subjected on the projections that change time and speed into two axes called d-q coordinate that incorporate the flux, voltage, mechanical movement and torque.

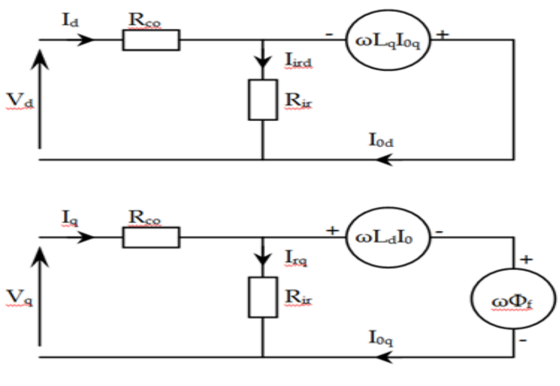

Figure 2. PMSM equivalent circuit for d-q axis

Figure 2 shows the equivalent circuit of PMSM in the d-q axes. Torque and flux variables can be derived in the equations as shown:

$$\varphi_{ds} = L_d i_{ds} + \varphi_j \quad (1)$$

$$\varphi_{qs} = L_q i_{qs} \quad (2)$$

$$V_d = r_s i_{ds} - \omega_r \varphi_{qs} + p\varphi_{ds} \quad (3)$$

$$V_q = r_s i_{qs} + \omega_r \varphi_{ds} + p\varphi_{qs} \quad (4)$$

For the electromagnetic torque, the equation can be expressed as follows [6]:

$$T_e = (\frac{3}{2})(\frac{P}{2})\lambda_m i_{qs} \quad (5)$$

2.2. Mathematical Modelling of PMSMS

Figure 3 shows closed loop current control of a PMSM using FOC method. Torque and flux current are decoupled to generate the free torque and flux control. Both torque and flux are decoupled to create torque that can be controlled comprehensively. This process is to increase the performance of the system.

1) FOC Transformation Block:

The mathematical modelled design of FOC block in the Simulink software is based on the equation below. Park Transformation is shown in Equation 6 and 7:

$$i_{sd} = i\alpha \cos(\vartheta) + i_\beta \sin(\vartheta) \quad (6)$$

$$i_{sq} = -i\alpha \sin(\vartheta) + i_\beta \cos(\vartheta) \quad (7)$$

Inverse Park Transformation is shown in Equation 8 and 9:

$$i_\alpha = i_{sd} \cos(\vartheta) - i_{sq} \sin(\vartheta) \quad (8)$$

$$i_\beta = i_{sd} \sin(\vartheta) + i_{sq} \cos(\vartheta) \quad (9)$$

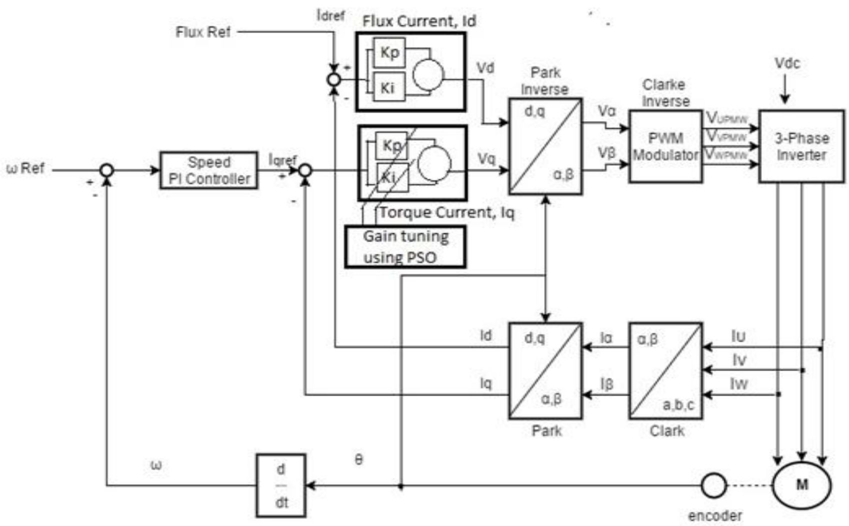

Figure 3. FOC modelling

2) FOC Current Loop of PI Controller:

Generally, PI controller is traditionally used to control the motor in terms of speed, torque, position, current or voltage. Nevertheless, the expectation of these signals can contain large noise makes the PI controller without the derivative part more appropriate[8]. In designing the PI controller, both Kp and Ki gain of PI controller need to be choosen correctly to ensure the ability of fast response of the system. Current PI controller consists of q-axis current and d-axis current. In this project, the main focus is to control the torque current, Iq.

Figure 4 shows the basic block diagram of a PI current controller that being used in FOC method. The ripple error straightforwardly sent to the current PI regulator. An integrator built up a redundant output if the large value of error detected.

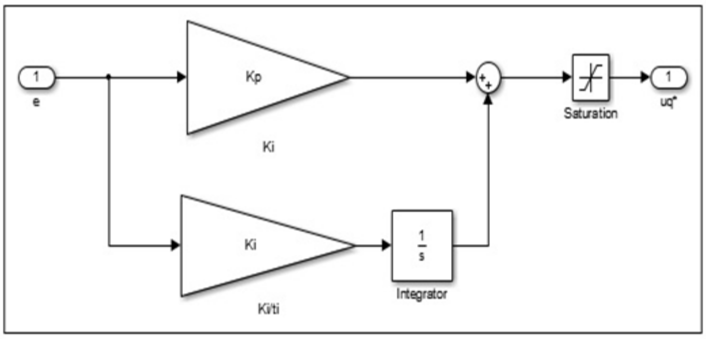

Figure 4. PI Controller Block Diagram

A plant of current control loop is described by the transfer function. The following equation shows the transfer function of the PI controller for d-axis current loop:

$$C(s) = K_c(1 + \frac{1}{\tau_1^d s}) \tag{10}$$

The proportional gain Kc and the integral time constant τ_1^d or (τ_1^q) are determined in the controller design by using pole-assignment controller design. The proportional control gain and the integral times constant are calculated by the guidance of the design approach:

$$K_c^d = L_d(2\xi\omega_n - \frac{R_s}{L_d}) = 2\xi\omega_n L_d - R_s \tag{11}$$

$$\tau_1^d = \frac{2\xi\omega_n - \frac{R_s}{L_d}}{\omega_n^2} = \frac{2\xi\omega_n L_d - R_s}{L_d\omega_n^2} \tag{12}$$

The PI controller parameters for the q-axis current are calculated as:

$$K_c^q = 2\xi\omega_n L_q - R_s \tag{13}$$

$$\tau_1^q = \frac{2\xi\omega_n - R_s}{L_q\omega_n^2} \tag{14}$$

2.3. Current PI-PSO

From the improvement of speed response and quality of solution found by PSO, different essential varieties had been made [9]. The PSO algorithm was designed and executed to the FOC block model to optimize the current PI-gain after the FOC block model had been designed. The optimization process will stop searching if the stopping criterion is achieved by the optimization technique. The stopping criterion is rely either on the number of iterations or the fitness best value [10]. The program can be set to stop at maximum iteration or to stop when certain parameters are achieved. The optimization procedure will locate its ideal value by fulfils the fitness function until it achieved the stopping criterion. According to Figure 5, the process for any numbers of iteration will be maintained at the same condition as long as the process had not reached it maximum iteration that had been established.

Figure 5 shows the PSO process from beginning until it was implemented into the PMSM model. It can be summaries that the PSO fundamentally comprised of seven stages as follows:

1. Data Declaration Process
2. Particles Initialization Process
3. Particle Position and Velocity Updating Process
4. Topology Related Process
5. PMSM Model Execution Process
6. Objective and Fitness Function Evaluation Process
7. Pbest and Gbest Updating Process

The objective function is to reduce the torque ripple of the motor. It is shown in Equation 15.

$$\tau_{ripple} = \tau_{\max} - \tau_{\min} \tag{15}$$

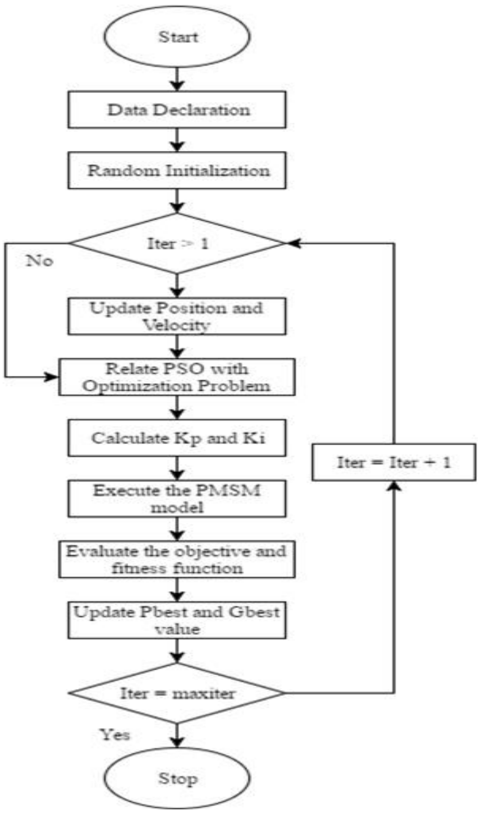

Figure 5. PSO flowchart

2.4. Simulink Implementation

Figure 6 shows Simulink block model that used in this project. FOC control method was employed in this block model. There are two basic loops in this FOC which are speed and current loop. There are two transformation blocks that act as importance role for the FOC control method as depicted in Figure 7 and Figure 8. In the current loop, there are two components which are q-axis current and d-axis current. This project focused on the q-axis current in the current loop of the FOC control method. The value of Kp and Ki gain in the q-axis current PI parameters will be taken from the value of global best and it will be inserted into each PI controller of the q-axis current loop.

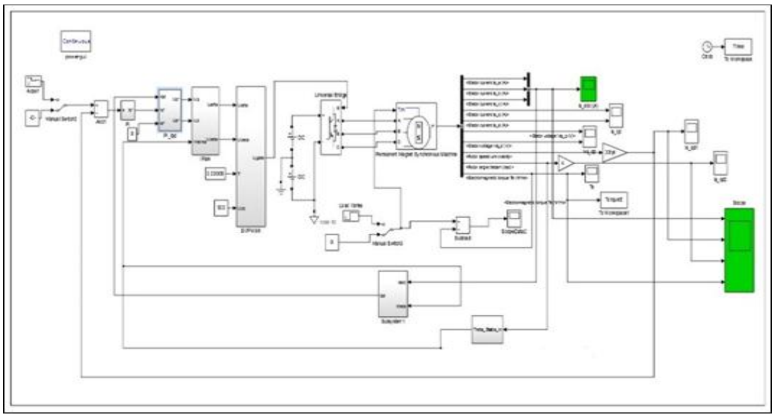

Figure 6. PMSM Simulink Model

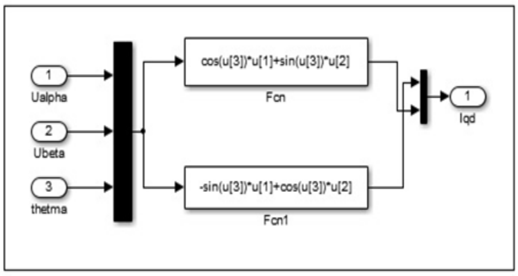

Figure 7. Park transformation block

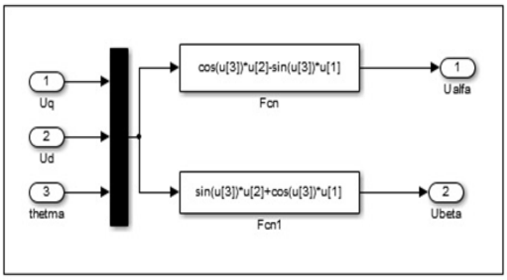

Figure 8. Inverse Park transformation block

The transformation block of Park transformation was designed by referring to eqn. (6) and (7). The α and β input signals were being transformed into d-axis and q-axis form as shown in Figure 7 [11]. The output signal for this transformation converted into the input signal of the PI current controller. Then output of the PI current controller was the input of the Inverse Park transformation.

Then, the Inverse Park transformation block in rotating frame was transformed to orthogonal stationary references, α and β [12] as depicted in Figure 8. Inputs for this dq-axis output current were acquired from the current PI controllers and the angle from the PMSM theta, θ as shown in Figure 8. These blocks were modelled according to the eqn (8) and eqn (9).

PSO technique was utilized into the PI speed controller after all the transformation block of the FOC control method and the PMSM block model being developed in the Matlab/Simulink software.

3. Results and Analysis

The model for this project was developed by using Matlab/Simulink software as shown in Figure 6. The value of torque ripple is presented to compare the different of the ripple between the implementation of PSO technique and by manually tuned the PI-gain. The system was tested in a several conditions of PMSM. The PMSM and PSO parameter were tabulated in Table 1 and Table 2 respectively.

Table 1. PMSM Model Parameter

Parameters	Physical Meanings	Values
Id	d-axis current	0.0085A
Iq	q-axis current	0.0085A
Rs	Armature Resistance	2.8750 Ω
J	Moment of Inertia	0.0008kg.m2
P	Number of Poles	4
F	Frequency	50Hz
S	Speed	1500rpm

Table 2. PSO Parameter

Parameters	Values
Number of iteration	30
Cognitive constant, c1	2.05
Social influence constant, c2	2.05
Swarm Size	15

3.1. Torque Reference, 0 Nm

The system© was examined with a reference speed of 1500© rpm with 0 Nm electromagnetic© torque. The optimal value for Kp and Ki gain of torque current obtained from PSO were Kp = 5 and Ki = 5.

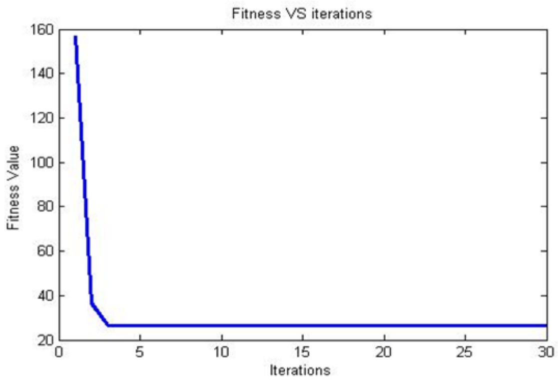

Figure 9. Fitness value of 0 Nm torque reference

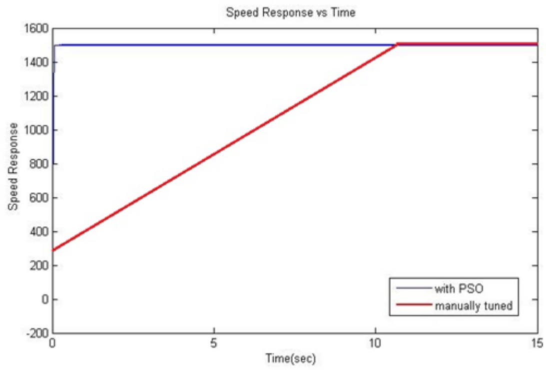

Figure 10. Speed response of 1500 rpm speed reference at 0 Nm

In this analysis, the values for Kp and Ki for d-axis current were set to be constant which were 10 and 50. While the value of q-axis current for manually tuned was set at 100 and 50 for Kp and Ki respectively. Figure 9 shows that the graph of fitness vs iterations. By using the PSO technique, electromagnetic torque ripple shows the result converge for the particle of the swarm found the optimal value at 3rd iteration.

Figure 10 shows the speed response for the speed reference of 1500 rpm at 0 Nm electromagnetic torque value. It shows that the speed achieved it referenced speed tremendously faster by using PSO method compared to the manually tuned method.

Figure 11 shows the electromagnetic torque ripple and Figure 12 shows the zoom in view of electromagnetic ripple. It can be seen that the torque ripple has been reduced drastically. The value of torque ripple was being compared with manually tuned PI controller and tabulated as in Table 3 and the reduction of torque ripple is almost 95% in comparison to manually tuned.

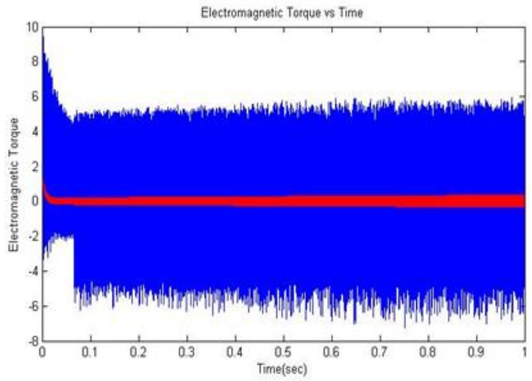

Figure 11. Electromagnetic torque of 0 Nm torque reference

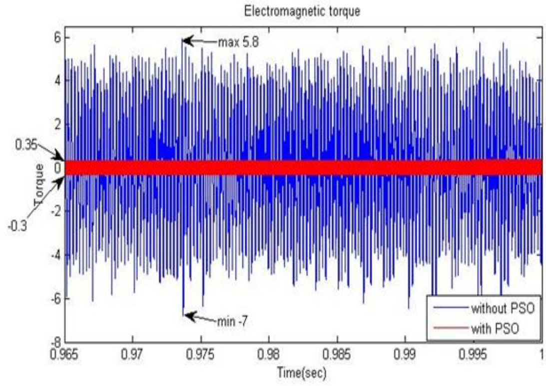

Figure 12. Electromagnetic torque of 0 Nm torque reference when zoom in

Table 3. Torque Ripple at 0 NM

Torque ripple	Without PSO	With PSO
T_{max} - T_{min}	12.8	0.65

3.2. Torque Reference, 2 Nm

The system was tested with a reference speed of 1500 rpm and the electromagnetic torque value was adjusted to 2 Nm. The ideal value for Kp=53.0659 and value for Ki=71.4123.

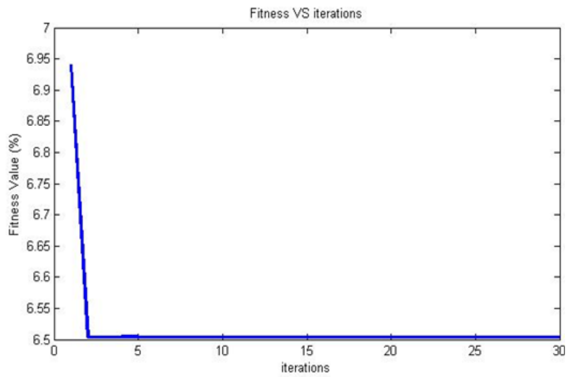

Figure 13. Fitness value of 2 Nm torque reference

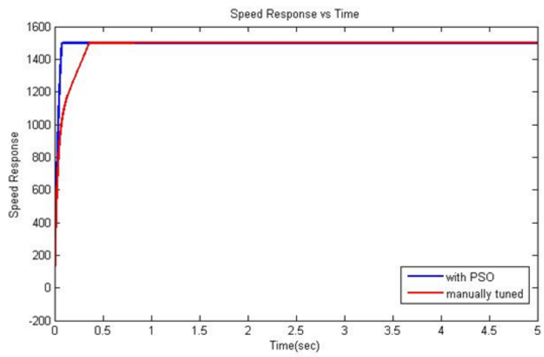

Figure 14. Speed response of 1500 rpm speed reference at 2 Nm

In this analysis, the values for Kp and Ki in flux current were set to be constant which were 10 and 50 respectively. Time range was set for 0.3 sec. Figure 13 shows the graph© of fitness value for the torque value of 2 Nm. After applying PSO technique, the convergence results for the fitness value and the particle of the swarm found the optimal value at 5th iteration.

Figure 14 shows the speed response for the speed reference of 1500 rpm at 0 Nm electromagnetic torque value. It shows that the speed response achieved it referenced speed faster using PSO method compared to the manually tuned method.

Figure 15 shows the electromagnetic torque ripple and Figure 16 shows electromagnetic ripple when zoom. All graphs show the comparison between with and without PSO technique. The value of torque ripple was being compared with manually tuned PI controller and tabulated as in Table IV, which also proves the capability of PSO to find the optimal value of Kp and Ki in order to reduce the torque ripple.

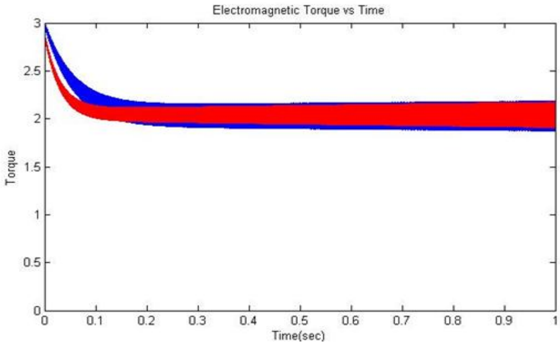

Figure 15. Electromagnetic torque of 2 Nm torque reference

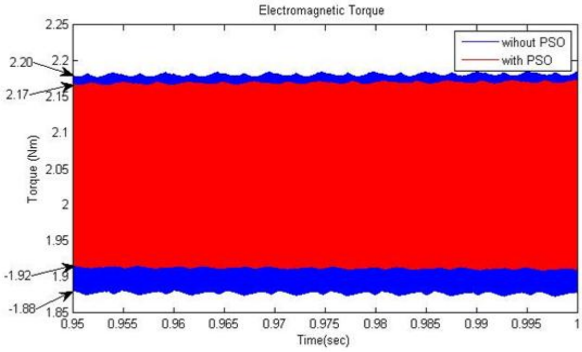

Figure 16. Electromagnetic torque of 2 Nm torque reference when zoom in

Table 3. Torque Ripple at 2 NM

Torque ripple	Without PSO	With PSO
$\tau_{max} - \tau_{min}$	0.32	0.25

The comparison between PSO technique and manually tuned PI controller made to verify the effectiveness of PSO technique. From Table 3 until Table 4, it clearly demonstrated that the proposed method can reduce the electromagnetic torque ripple close to its reference value using PSO technique by finding its ideal value without sacrificing the speed of the motor.

The drawbacks in terms of more time consuming and high value of torque ripple had made the manually tuned PI controller method less effective and can cause deterioration performance of the machine.

4. Conclusion

Particle Swarm Optimization (PSO) technique had been selected rather than using traditional trial and error method to optimize the PI gain. By using this method, the swarm optimizer can adjust the PI controller parameters to get best result for the torque and current controller. The results were based on the analysis over the condition of the electromagnetic torque value. It proved that by using PSO technique ideal value of the PI parameters can be determined after a few iterations which is less than five iterations. It also gives a more effective performance in terms of minimizing torque ripple of the PMSM.

Moreover, the system is more robust, highly efficient and also can increase performance of the machine by optimizing the system parameters. To minimize or maximize any other objectives it is recommended to use the multi objectives function of PSO to ensure the effectiveness of a system. Provide a statement that what is expected, as stated in the Introduction chapter can ultimately result in Results and Discussion chapter, so there is compatibility. Moreover, it can also be added the prospect of the development of research results and application.

Acknowledgment

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