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Speed drives control using particle swarm optimization for PMSM drives

Jurifa Mat Lazi, Md Hairul Nizam Talib, Hyreil Anuar Bin Kasdirin, Mohd Ruzaini Bin Hashim, Azrita Alias
Department of Electrical Engineering, Faculty of Electrical Technology and Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Malaysia

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ABSTRACT

The paper presents a contemporary method for controlling the speed of a permanent magnet synchronous machine (PMSM) by optimizing the parameters of a proportional-integral (PI) controller using the particle swarm optimization (PSO) algorithm. This approach aims to enhance the robustness and dynamic performance of the drive system, resulting in improved accuracy and sensitivity to load changes and wide range of speed. The study evaluates two tuning techniques for the PI controller, which are the traditional trial-and-error method and the PSO optimization method. The performance of the PMSM is assessed based on speed response performance, including rise time, overshoot, and settling time. The PSO-tuned controller significantly minimizes overshoot compared to the trial-and-error method. And also achieves a shorter settling time, indicating a more stable response. However, the rise time is slightly longer with the PSO-tuned controller compared to the conventional tuning method just for the medium speed. For the rated speed, PSO still having shorter rise time compared to trial-and-error PI method. These findings imply that while the PSO method may result in a longer rise time, its overall advantages in reducing overshoot and settling time make it a more effective option for speed control in PMSMs. This is consistent with other research suggesting that PSO can outperform traditional methods in optimizing control parameters across various applications.

Corresponding Author:

Jurifa Mat Lazi
Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, Durian Tunggal, Melaka, 76100, Malaysia
Email: jurifa@utem.edu.my

1. INTRODUCTION

Permanent magnet synchronous motor (PMSM) is widely used in industries involving motor usage. PMSM is popular due to high power density and large torque according to inertia ratio, high efficiency and speed of the motor can be controlled. The criteria required in the high performance drive system used in robotics, rolling mill, and machine tools are fast and accurate system response, and not sensitive parameters to variation [1]-[5]. Not only eliminating the torque and flux that make the system respond quickly, PMSM drives that using the vector control scheme also make control tasks be easy [6], [7]. To fulfil the criteria required to improve drive performance, the speed controller plays a very important role. The usage of controllers such as proportional integral (PI) and proportional integral differential (PID) has been widely used to control DC and AC motors [8]-[10]. Traditional control methods like PID controllers or field-oriented control (FOC) may not always deliver optimal performance, especially under varying load conditions or system uncertainties. These controllers are difficult to design if the model system is not available. Another weakness for this controller is unknown load dynamics and other factors such as noise, temperature, and saturation. Affect the performance of these controllers for wide range of speed operations.

Some ways have been used to improve PMSM performance such as, fuzzy logic controller (FLC) FLC are increasingly employed in the control of PMSM due to their ability to manage nonlinearities and provide adaptable control solutions. However, they also come with certain limitations that may restrict their effectiveness in specific applications such as design complexity, absence of systematic design methodologies, and sensitivity to change which can limit their suitability for certain applications [11]-[14]. Other than that, researchers trying to use optimization technique such as genetic algorithm (GE). GE offers considerable advantages for optimizing PMSM drive control, their high computational costs, sensitivity to parameter settings, and potential for slow convergence may limit their effectiveness in real-time applications or scenarios requiring immediate action [15]-[17]. Then, researchers come with artificial bee colony (ABC) method to optimize the PMSM drives. ABC algorithm provides effective and straightforward optimization capabilities for PMSM drive control but, its slower convergence, sensitivity to parameter settings, and potential for stagnation may limit its effectiveness in real-time situations [18]-[20].

Other optimization method is PSO for determining the optimize and the best gain for KP and KI in PI controller, which is not accurately determine by using conventional PI controller. PSO, inspired by the social behavior of birds flocking or fish schooling, is a nature-inspired optimization algorithm. It has gained popularity in recent years due to its simplicity, ease of implementation, and ability to handle nonlinear and complex optimization problems. Utilizing PSO for PMSM control indicates a shift towards more adaptive and intelligent control techniques [21]-[26]. PSO is capable of adjusting control parameters dynamically, making it suitable for handling the nonlinear characteristics and parameter variations of PMSM drives. Unlike conventional controllers that may get stuck in local optima, PSO can search for the global optimum solution, potentially leading to better performance in terms of reduced overshoot, settling time, rise time and steady-state error. PSO-based controllers can adapt to changing operating conditions, making them robust against disturbances and uncertainties that might degrade the performance of traditional control strategies. Therefore this current study proposes that speed drives control of PMSM is using the PSO algorithm to improve PI-controller parameters such as KP and KI gains.

2. METHOD

Method of this project started with mathematical model of PMSM drives. Followed by equivalent circuit of permanent magnet sysnchronize machine and then the steps for particle swarm optimization (PSO) method. The method of using PSO for PMSM drives involves applying the PSO algorithm to optimize the control parameters of the PMSM speed control system, such as the parameters of the PI controller or other control strategies. This optimization process helps in achieving better speed regulation, minimizing overshoot, reducing settling time, and enhancing overall system stability [21].

2.1. Mathematical model of PMSM drives

Figure 1 shows the d-q rotor reference frame. From the Figure 1, we can see that, the rotor reference axis creates an angle θ_r at every certain time t, with constant stator axis. There is an angle α between stator mmf and rotor d-axis. Moreover, the stator mmf revolves at the similar speed with rotor axis.

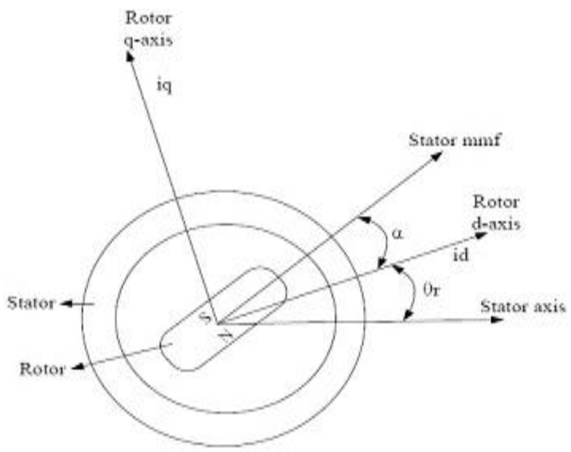


Figure 1. The d-q rotor reference frame

The PMSM model for exclude damper winding already developed based on rotor reference frame by using a few assumptions which are, the saturation is ignored, the signal of EMF is sinusoidal, the hysteresis losses and eddy current are ignored and it does have not field current dynamics.

The equation for voltage of stator in *d-q* axis:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \tag{1}$$

$$V_d = R_s i_d + \omega_r \lambda_q + \rho \lambda_d \tag{2}$$

where I_q and I_d are current of stator in dq axis flux linkage equation:

$$I_q = L_q i_q \tag{3}$$

$$I_d = L_d i_d + \lambda_f \tag{4}$$

where λ_q and λ_d are fluxes linkage of stator in *d-q* axis while λ_f is flux linkage of PMSM. Sub (3) and (4) into (1) and (2).

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + r L_q i_q \tag{5}$$

$$V_d = R_s i_d + \omega_r L_q i_q + r (L_d i_d + \lambda_f) \tag{6}$$

Form a matrix from (5) and (6), the developed torque is (7):

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q + \lambda_q i_d) \tag{7}$$

with applied i_d and reluctance torque with zero, the higher efficiency and torque per amp with linear characteristics can be achieved. In (8) for mechanical torque.

$$T_e = T_L + B\omega_m + j\frac{d\omega_m}{dt} \tag{8}$$

From the (9),

$$\omega_m = \frac{2}{P}\omega_r \tag{9}$$

where ω_r is electrical speed of rotor while ω_m is mechanical speed of rotor.

2.2. Equivalent circuit of PMSM

By using equation of stator voltage, the equivalent circuit can be obtained from dq modelling of the motor. Since PMSM has rotor d axis is equivalent with a constant current source as shown in the (10). The equivalent circuit for PMSM is shown in Figure 2.

$$I_f = L_{dm} i_f \tag{10}$$

Were, λ_f is field flux linkage, L_{dm} is magnetizing inductance in d axis, I_f is field current for equivalent PMSM.

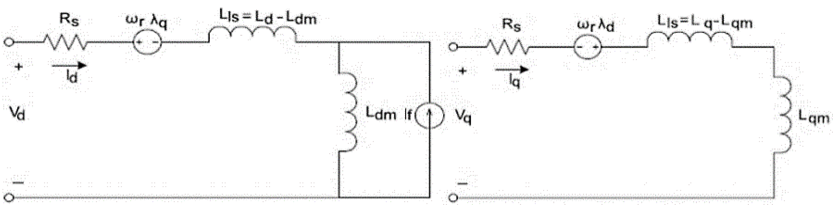


Figure 2. Equivalent circuit of PMSM

3. PARTICLE SWARM OPTIMIZATION

PSO is an optimization algorithm was demonstrated from the imitation of societal performance of birds in the group. When the pears were updated, PSO will make ready a clutch of haphazard units and will examinations for the bests. For every unit, the performance will be taken from how close by the unit is since the worldwide optimal. This performance will be restrained by via a suitability, purpose which be influenced by on the optimization cases as below;

- The particles will be initialized.
- For each particle, the fitness values will be calculated.
- When personal best is better than current fitness, the current fitness will be assigned as new personal best.
- If the personal best is not better than current fitness, the personal best will be used same like previous.
- Best particle's the personal best will be assigned a value to food's coordinate.
- The velocity for each particle will be calculated.
- To update its data values, each particle's velocity will be used.
- Determine the target of maxi maximum epochs either reached or not.

PSO has two main operators, which are position and velocity. Throughout each iteration, every possible solution is elevated toward their last best position and their global best position. At every iteration, a new velocity value for each possible solution determined primarily based on its current velocity, the gap from its last best position, and the gap from the global best position. Current best velocity value is then uses to calculate the following position of the possible solution within the search area. This procedure is then iterating a set quantity of time or until an optimum solution is accomplished. A particle in the search space is playing role as an individual in swarm system in PSO [21]. Every particle serves as a possible solution to the problems. The new position after an iteration is based on its personal best location and the global best position within the search space. Particle position x_i are adjusted using;

$$(t+1) = (t) + v_i(t+1) \tag{11}$$

wherein the velocity component, v_i, represents the step size. For the next operator of PSO, velocity, v_i:

$$v_{i,j(t+1)} = \omega v_{i,j(t)} + c_1 r_{1,j(t)}(y_{1,j(t)} - x_{i,j(t)}) + c_2 r_{2,j(t)}(\check{y}_{i(t)} - x_{i,j(t)}) \tag{12}$$

wherein w is the inertia weight to control the velocity of the possible solutions, c_1 and c_2 are the cognition and social behaviour coefficients, r_1, r_2, j random position of possible solution, $\check{i}$ and $\check{y}_i$ is the global best position of particle $\check{y}$. The global best position of particle $\check{y}_i$ depends on search space used [10]. $\check{y}_i$ is the new global best if the personal best is farther than the global optimum value:

$$\check{y}_{i(t)} \in \{y_{0(t)}, y_{1(t)} \ldots\ldots y_{s(t)}\} = min\{f(y_{0(t)}), f(y_{1(t)} y_{s(t)})\} \tag{13}$$

wherein s is the size of population.

In this project, it has well thought-out that use PSO provided that extra supply by combining the technique of bearing in mind numerous information, although isolated character of every single information was kept. From the results of this project, particle swarm produces an extension that will tolerate it to be the better as an optimization technique. Figure 3 shows the Flowchart of the PSO method.

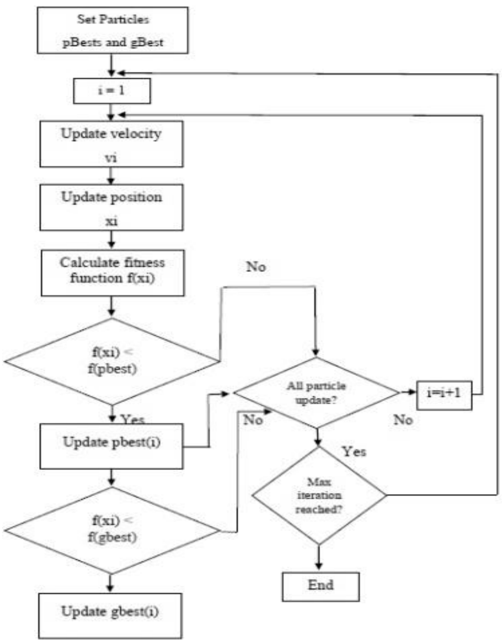


Figure 3. Flowchart PSO method

4. SIMULATION RESULTS

The performance of PMSM will be evaluated based on the speed response produced by different tuning methods. The rise time, overshoot and settling time will be recorded for making comparison. The comparison between the simulation outcomes will be presented in this section. The load was be used is 3 Nm at t=0.03s. Figure 4 shows the Simulink block diagram for PMSM drives using PSO method.

4.1. Performance PMSM drive for rated speed 1,500 rpm

Figure 5 shows the comparison speed responses using different tuning method. The detail of values of overshoot, rise time, and settling for both technique methods are shown in Table 1. Comparison that can be derived from the value obtained is value of overshoot and settling time for PSO technique has lower than trial and error method except the value of rise time. Moreover, the system that applying PSO technique has more stable compare to conventional method.

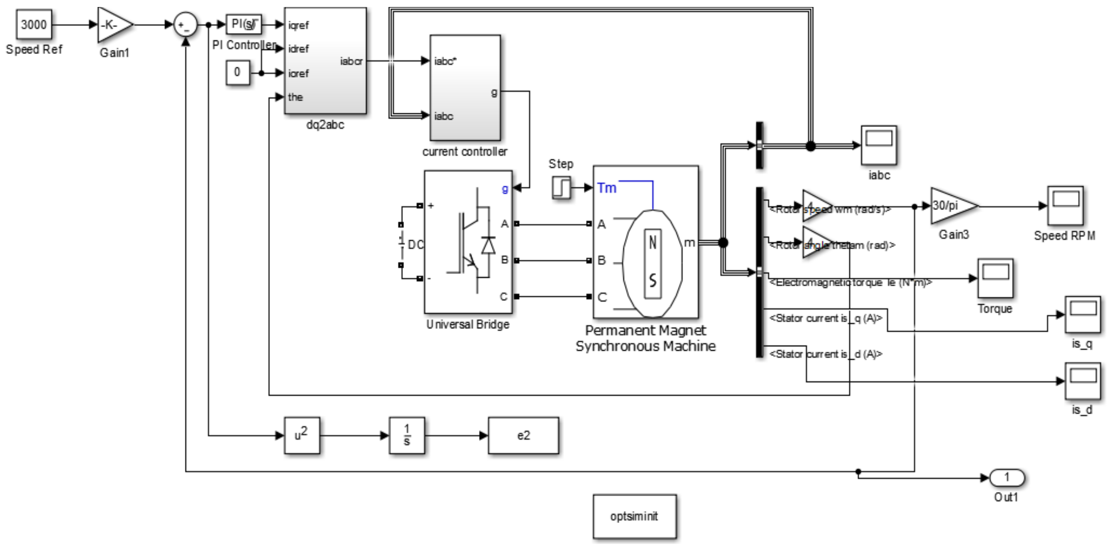


Figure 4. Simulink block diagram for PMSM drives

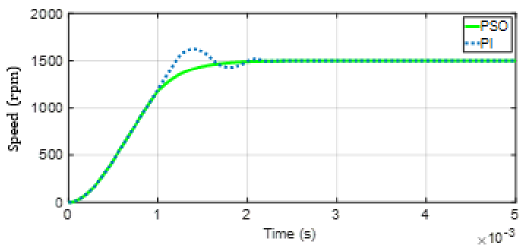


Figure 5. Speed response using PI controller method and PSO method

Table 1. Comparison tuning method at 1,500 rpm

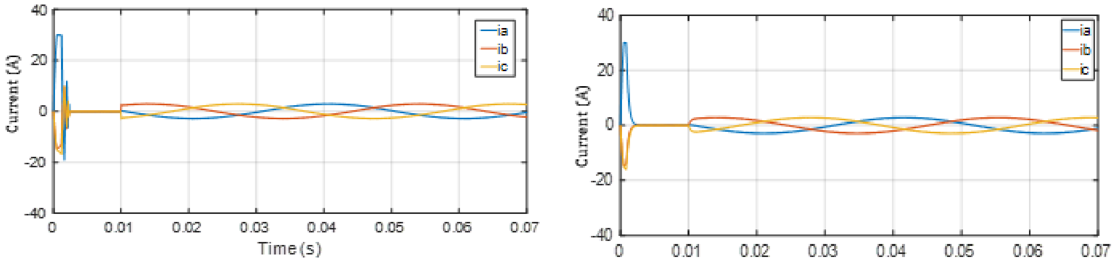
Types	Tr (msec)	Ts (ms)	OS (%)
PSO	686.102	0.866	0.894
PI	414.083	1.165	15.625

A. I_{abc} for 1,500 rpm using trial and error (PI) and PSO method

Figure 6 shows comparison for I_{abc} by using different tuning methods. The load applied is 3N.m at t=0.01s. From Figures 6(a) and 6(b), both of the tuning method produce the same waveforms. The different between both tuning methods is, at range time t=0 until t = 0.07s, ripple current I_{abc} for trial-and-error method is higher than PSO method as shown in Figures 6(a) and 6(b) respectively. From t = 0s until t = 0.01s the signal of I_{abc} current is close to zero. This is because no load was applied at that time. While at t = 0.01s until t = 0.07s, the waveform of I_{abc} current has maximum and minimum values 3A and -3A. This is because the I_{abc} current is influenced by the existence of load 3 Nm.

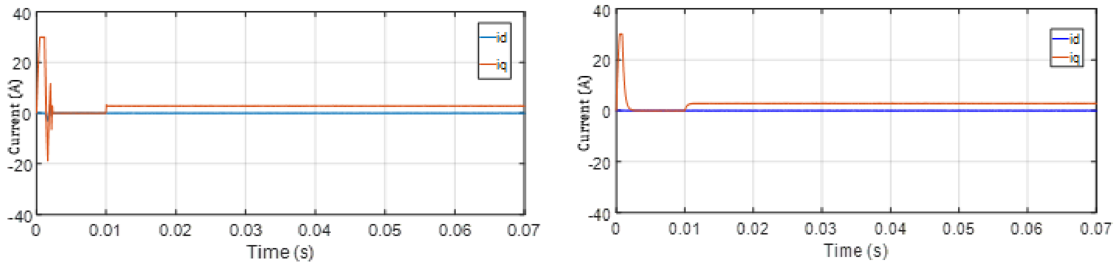
B. Stator current I_d I_q for 1,500 rpm using trial and error (PI) and PSO method

Figure 7 shows comparison for stator current I_d I_q by using different tuning methods. The load was applied is 3 Nm at t=0.01s. The comparison can be made from graph obtained is, for stator current I_d I_q without applying PSO has ripple current at small range time only. For overall, the properties of stator current I_q is the same with I_{abc}, which is the stator current I_q is influenced by the existence of load 3Nm. It can be seen that, from Figure 7(a), for trial-and-error method, the stator current I_d experienced a sharp rise and a sharp decrease with the amplitude around 5A and -4A at the beginning. But the increase is in a small-time range. From the Figures 7(a) and 7(b), the stator current I_d is not affected by the existence of the load. This is because when the load is applied, stator current I_d value is still approaching to zero. But when the load is applied at t = 0.03s, the value of steady state current I_q increases about to 3A. But the decrease is in a small-time range only. By applying the PSO method as in Figure 7(b), the stator current I_q had been improved where, the oscillated current at range time t=0.003 until t= 0.005 is eliminated.



(a) (b)

Figure 6. Three-phase stator current using (a) I_{abc} – trial-and-error (PI) controller method and (b) current I_{abc} using PSO – 3 Nm



(a) (b)

Figure 7. I_d I_q stator current using (a) I_d I_q – trial-and-error (PI) controller method and (b) current I_d I_q using PSO – 3 Nm

4.2. Performance PMSM drive for rated speed 3,000 rpm

The performance of PMSM drive in rated speed 3,000 rpm will be discussed in this subchapter. Analysis will be done by applying load and no load to the motor. Performance of PMSM drive is evaluated by obtains the value of overshoot, rise time, and settling time from the simulation. The detail of values of overshoot, rise time, and settling for both technique methods are shown in Table 2.

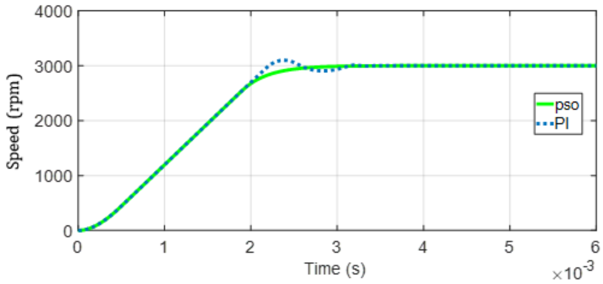


Figure 8. Speed response for 3,000 rpm using PI controller method and PSO method

Figure 8 shows the comparison speed responses using different tuning method for 3,000 rpm. Comparison that can be derived from the value obtained is value of overshoot and settling time for PSO technique has lower than trial and error method except the value of rise time. Moreover, the system that applying PSO technique has more stable compare to conventional method. The detail of values of overshoot, rise time, and settling for both technique methods are shown in Table 2.

Table 2. Comparison tuning method at 3,000 rpm

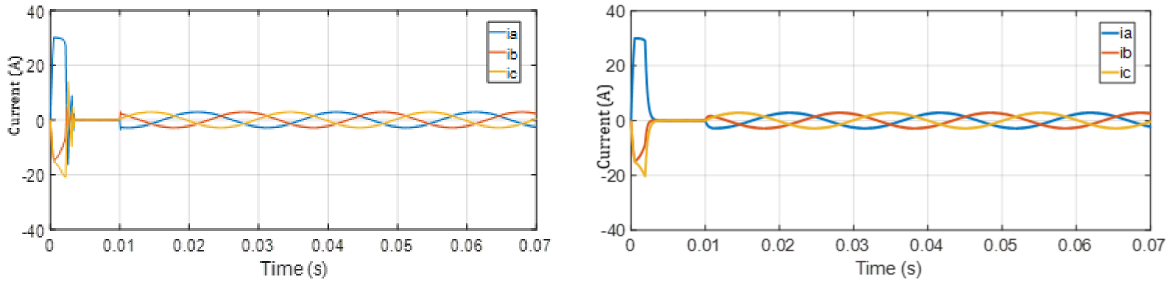
Types	*Tr (msec)*	*Ts (ms)*	OS (%)
PSO	1.277	1.083	0.648
Trial and error	992.821	1.471	5.883

A. I_{abc} for 3,000 rpm using trial and error (PI) and PSO method

From the Figures 9(a) and 9(b), both of the tuning method produce same waveform. Same as previous I_{abc}, the different between both tuning method is, at range time t=0 until t= 0.01, ripple current I_{abc} for trial-and-error method is higher than PSO method as shown in Figures 9(a) and 9(b) respectively. From t = 0s until t = 0.01s the signal of I_{abc} current is close to zero. This is because no load was applied at that time. While at t = 0.03s until t = 0.07s, the waveform of i_{abc} current has maximum and minimum values 3 and -3. This is because the I_{abc} current influenced by the existence of load 3 Nm. The different between applying speed 3,000 rpm and 1,500 rpm is the frequency for I_{abc} for 3,000 rpm is higher than 1,500 rpm.

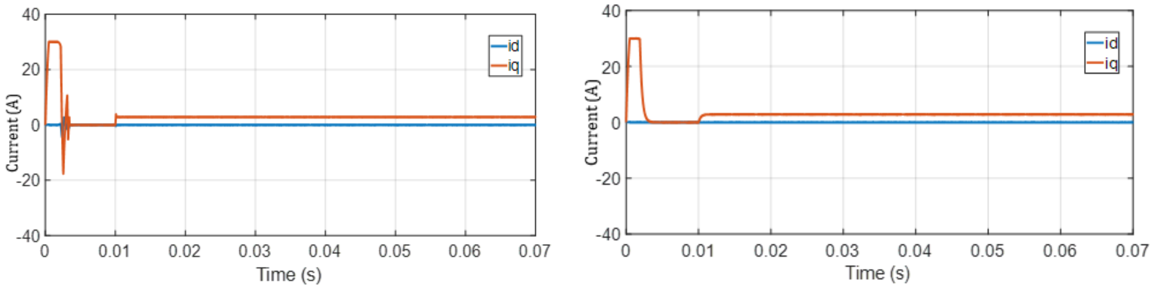
B. Stator current Iq for 3,000 rpm using trial and error (PI) and PSO method

Figure 10 shows comparison for stator current I_d I_q by using different tuning methods. The load was applied is 3 Nm at t=0.01s. Figure 10(a) shows the stator current I_d I_q for 3,000 rpm using trial and error method. At the beginning, the stator current I_d experienced a sharp rise and a sharp decrease with the amplitude around 4A and -4A. But the increase is in a small-time range only. From the Figure 10(a), the stator current I_d is not affected by the existence of the load. This is because when the load is applied, stator current id value is still approaching to zero. By applying the PSO method as shown in Figure 10(b), the stator current I_q had been improved where, the ascending current at range time t=0.004s until t= 0.005s is eliminated and effect of load on current at t=0.01s is also eliminated.



(a) (b)

Figure 9. Three-phase stator current I_{abc} using (a) I_{abc} – trial-and-error (PI) controller method and (b) current I_{abc} using PSO – 3Nm PSO



(a) (b)

Figure 10. I_d I_q stator current using (a) I_d i_q – trial-and-error (PI) controller method and (b) current I_d I_q using PSO – 3Nm

5. CONCLUSION

This project is successfully implementing the PI controller using PSO method as a speed controller for PMSM drives. The system for PMSM drives has successfully developed by using Simulink/MATLAB. Furthermore, the results of this project were analyzed by comparing the performance of PMSM drives by using different tuning methods such as conventional trial and error PI and PSO methods. The execution of the PSO method for tuning a PI controller has been ended up being superior to the conventional method. From the simulation outcomes, the PI controller utilizing the PSO method demonstrates better execution over the conventional method specifically for overshoot, settling time and rise time for wide range of speed.

Although PSO method requires more complex algorithms, it is highly adaptive to changing conditions, more robust and capable of handling uncertainties and superior for nonlinear and complex systems. And even though PSO is relatively simple to implement, the real-time application of PSO in control systems might require substantial computational resources, especially for high-speed or high-precision applications.

For conclusion, the use of PSO for PMSM speed drives is a significant advancement in motor control strategies, particularly for systems with nonlinearities or variable operating conditions. It offers clear advantages in terms of adaptability and optimal performance so that it can has better dynamic performance such as lower overshoot, fast settling and rise time for wide range of speed. However, challenges related to computational complexity and convergence issues must be carefully addressed to fully harness its potential. Comparing it to traditional methods, PSO shows superior performance in complex and dynamic environments, making it an exciting and valuable research direction in the field of motor control especially for PMSM drives.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Jurifa Mat Lazi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	
Md Hairul Nizam Talib		✓			✓		✓					✓		
Hyreil Anuar Bin Kasdirin		✓	✓	✓										
Mohd Ruzaini Bin Hashim		✓	✓	✓		✓		✓		✓	✓	✓		✓
Azrita Alias			✓	✓			✓			✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].

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BIOGRAPHIES OF AUTHORS

Jurifa Mat Lazi received her Bachelor's degree in Electrical Engineering from Universiti Teknologi Malaysia in 2001. She then obtained her Master of Science degree in Electrical Power Engineering from University Universiti Teknologi Malaysia, in 2003. She received her Ph.D. degree from University Universiti Teknikal Malaysia Melaka in 2016. She has served as an academic staff at Universiti Teknikal Malaysia Melaka (UTeM) since 2001 and she is currently a senior lecturer. Her research interests include Machine Drives especially in Sensorless and PMSM drives, Power Electronics and Power Systems. She can be contacted at email: jurifa@utem.edu.my.

Md Hairul Nizam Talib was born in Malaysia, in 1976. He received his B.S. in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Johor, Malaysia, in 1999, M.S. in Electrical Engineering from the University of Nottingham, Nottingham, UK, in 2005 and Ph.D. from the Universiti Teknikal Malaysia Melaka (UTeM), Malaysia in 2016. He is currently a senior lecturer at UTeM. His main research interests include power electronics, fuzzy logic control and motor drives. He can be contacted at email: hairulnizam@utem.edu.my.

Hyreil Anuar Bin Kasdirin was born in Malaysia, in 1979. He received his B.S. in Electrical Engineering from the Institut Teknologi Mara, Malaysia in 2003, M.S. in Electrical Engineering from the University of Sheffield United Kingdom, in 2006 and Ph.D. from the University of Sheffield United Kingdom, in 2016. He is currently a senior lecturer at UTeM. His main research interests include control system, fuzzy logic control and optimization. He can be contacted at email: hyriel@utem.edu.my.

Mohd Ruzaini Bin Hashim earned his B.Sc. (Hons.) in Electrical (Electronic) from Universiti Teknologi Mara (UiTM), Shah Alam, Malaysia, followed by an M.Sc. in Electrical and Electronic Engineering from the University of Leeds, U.K., and a Ph.D. in Automation and Control Systems Engineering from the University of Sheffield, U.K., completed in 2005, 2009, and 2018, respectively. He is currently a Senior Lecturer at Universiti Teknikal Malaysia Melaka, Melaka, Malaysia. His research focuses on the computation of optimization algorithms and their applications across various domains. He can be contacted at email: ruzaini@utem.edu.my.

Azrita Alias was born in Malaysia, in 1978. She received her B. Eng in Electrical (Control and Instrumentation) (Hons) and M. Eng (Electrical) from the Universiti Teknologi Malaysia, in 2000 and 2003, respectively, and her Ph.D. from University of Malaya in 2015. She is a senior lecturer at the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM). Her main research interests are in modeling, control systems analysis, power electronics application engineering systems and OBE. She can be contacted at email: azrita@utem.edu.my.