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Performance index for optimization method based on PMSM drives using ABC and PSO

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ABSTRACT

The permanent magnet synchronous motor (PMSM) is commonly used in industrial and home appliances for its high efficiency and dynamic performance. In this research, a PMSM drive based on field-oriented control (FOC) is designed and simulated using MATLAB/Simulink. The speed controller of the drive is tuned using the trial-and-error method. However, the method requires more time for testing and adjustment of the speed controller to generate an optimal output response. Thus, particle swarm optimization (PSO) and artificial bee colony (ABC) algorithms, which require less computational effort and effectively produce good responses, are used to optimize the speed controller of the drive. PSO and ABC also offer an attractive optimization framework because of their independent, agnostic model structures, global searching capability, and low-load real-time calculation. In this study, the results obtained from different tuning methods are compared to determine the best optimization method of the speed controller in the PMSM drive under different operations. Other than that, performance measures such as integral square error (ISE), integral absolute error (IAE), and integral time absolute error (ITAE), which are commonly used to measure the effectiveness of a controller, are also discussed. The results show that the PMSM drive based on the ITAE criterion using the ABC algorithm gives better performance under different conditions.

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1. INTRODUCTION

A permanent magnet synchronous motor (PMSM) is a three-phase alternating current (AC) synchronous electric motor that runs at synchronous speed with the supply of an AC source. It is popular due to its fast response, high efficiency, high power density, high dynamic performance, and ability to maintain full torque at low speed [1], [2]. PMSM is widely used in many applications such as electric vehicles, robotics, servo drives, large power systems, and some home appliances. In order to make the tasks of PMSM easily controlled or reduce the ripples of torque in PMSM, some control schemes are required. In general, the control techniques of motor drives to eliminate torque ripples can be categorized as scalar control and vector control [3], [4]. Vector control, such as field-oriented control (FOC) and direct torque control (DTC), is commonly used to control the output performance of PMSM. Generally, most of the PMSM drives use proportional-integral (PI) or proportional-integral-differential (PID) controllers to control the output performance [5], [6]. In order to adjust the controller parameters, there are many techniques, such as conventional tuning methods or stochastic optimization algorithms, that can be used [7]. The conventional methods, such as trial and error and Ziegler-Nichols, are easy to understand and use for controller tuning [8], [9]. However, conventional methods require a longer time for testing and adjustment of the controller parameters. In addition, the controller parameters obtained using conventional methods are no longer suitable to generate optimum performance if the speed or condition changed where it may cause the performance of PMSM drives to degrade. Thus, optimization algorithms such as particle swarm optimization (PSO), genetic algorithm (GA), differential evolution (DE), artificial bee colony (ABC) algorithm, and so on, which are simple, effective, and faster, can automatically tune the controller gains based on different operations. In the previous study [10], PSO optimization and Ziegler-Nichols' method are used to obtain the PI parameters for minimizing the steady-state error of the speed of the PMSM drive.

The particle swarm optimization (PSO) is a metaheuristic algorithm that was invented by Kennedy and Eberhart. It is based on the idea of swarm intelligence, skilled to solve compound mathematical problems in the engineering field. A random global search through an n-dimensional problem was executed to improve an objective function of the problem by keeping informed of the swarm location and velocity [11], [12]. This technique can usually be used for an objective function that cannot be derived. Its operation is very simple and has strong convergence to the optimum solution. Another research study in [13] used the PSO algorithm combined with the deep deterministic policy gradient (DDPG) algorithm to track the speed control of the PMSM drive. The results showed that the transient response of the PMSM drive has improved when a load is applied. Based on the research [14], [15] showed that the PSO algorithm can find the optimum PI gains to produce better speed performance in steady-state error of the PMSM drive when compared to the heuristic method. Preview study [16] used a PI controller that is adjusted using two approaches: manual tuning and then using the PSO method. The systems are tested under different operating conditions. The simulation results demonstrate a good response with short recovery time and align with experimental testing. In [17] and [18], the PMSM drives, tuned by optimization such as PSO, are also controlled by the fuzzy logic controller (FLC). In [17], the proposed method is a combination of symbiotic organism search (SOS), PSO, and sewing trainee-based optimization (STBO), named SPS-FC-TMFS. While the FLC with tuned and deformed membership functions (TMFS) is called FC-TMFS. Based on the results, it can be concluded that advanced development can be accomplished by using a standard FLC or tuned using innovative or state-of-the-art optimization algorithms. Other than PSO, a swarm-based meta-heuristic algorithm that uses the intelligent searching behavior of honey bees, which was introduced in 2005 by Karaboga [19] and it is known as the ABC algorithm.

Preview study [20], the ABC algorithm is used to optimize the matrix gain that influences the output of the linear quadratic gaussian (LQG) controller, producing a better closed-loop system transient response in a large antenna servo control system. The results showed that the control effect of weight optimization for an LQG system using the ABC algorithm on a large antenna servo is better than that of the conventional trial-and-error method, with improved rapidity, stability, and overshoot in the system. Besides that, the types of performance measures that are used for selection and tuning of controller parameters are also important. The performance measures, also called performance indices, are used to compare the quality of controlled responses in order to determine which performance measure is more suitable used in different controlled systems.

In this research, the main purpose is to model the PMSM drive using optimization tuning based on the ABC algorithm. Then, verify the effectiveness of the proposed improvement method using the ABC algorithm compared to the conventional trial-and-error method and PSO. After that, determine the suitable performance measures or error criterion used for tuning the speed controller in the PMSM drive. Since the development of the arrangement for surface-mounted PMSM is easier and has high reluctance as well as large and effective uniform air gaps, which make the saliency effect negligible, this research is focused on the operation of a surface-mounted PMSM drive.

This study demonstrates the significance of PSO and ABC algorithms as efficient optimization frameworks for electric motor drive systems. By enabling the optimization of controller parameters in an offline or semi-offline operation, PSO and ABC effectively address nonlinearities, parameter uncertainties, and conflicting performance objectives without increasing online computational burden. Their model-agnostic nature further enhances robustness compared to predictive and learning-based controllers. The novelty of this work:

- Systematic comparison of PSO- and ABC-based optimization with different performance indices such as ISE, IAE, and ITAE that are commonly used in measuring the effectiveness of PMSM drive performance.
- Demonstration of improved performance–complexity trade-offs without online optimization.

- A flexible optimization framework applicable across different motor types and control optimization algorithms.

This study establishes PSO and ABC as practical and scalable alternatives for advanced motor drive optimization.

2. MODELLING OF PMSM DRIVE

Figure 1 presents the equivalent circuit of the PMSM in the d-q reference frame. Based on the equivalent circuit, the equations of V_q and V_d are shown in (1) and (2) [1].

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

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

The flux linkage is expressed by (3) and (4).

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

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

Where R_s refer to stator resistance, i_d and i_q refer to the stator current in the d-q rotating frame, ω_r refer to the electrical speed of the rotor, λ_d and λ_q refer to stator flux linkages in the d-q rotating frame, L_d and L_q refer to inductance in the d-q axes and λ_f refer to the permanent magnet flux linkage. By substituting (3) and (4) into (1) and (2).

$$\begin{aligned} V_q &= R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho (L_q i_q) \\ &= R_s i_q + \rho L_q i_q + \omega_r L_d i_d + \omega_r \lambda_f \\ &= (R_s + \rho L_q)\, i_q + \omega_r L_d i_d + \omega_r \lambda_f \end{aligned} \tag{5}$$

$$\begin{aligned} V_d &= R_s i_d - \omega_r (L_q i_q) + \rho (L_d i_d + \lambda_f) \\ &= -\omega_r L_q i_q + R_s i_d + \rho L_d i_d + \rho \lambda_f \\ &= -\omega_r L_q i_q + (R_s + \rho L_d) i_d + \rho \lambda_f \end{aligned} \tag{6}$$

When (5) and (6) are arranged in matrix form.

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_d & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \tag{7}$$

The torque equation is shown in (8).

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)(\lambda_d i_q - \lambda_q i_d) \tag{8}$$

Since $\lambda_d = L_d i_d + \lambda_f$ and $\lambda_q = L_q i_q$ where $\lambda_f = L_m i_f$,

$$\begin{aligned} T_e &= \frac{3}{2}\left(\frac{p}{2}\right)((L_d i_d + L_m i_f) i_q - L_q i_q i_d) \\ &= \frac{3}{2}\left(\frac{p}{2}\right)(L_d i_d i_q + L_m i_f i_q - L_q i_d i_q) \\ &= \frac{3}{2}\left(\frac{p}{2}\right)(L_m i_f i_q + (L_d - L_q) i_d i_q) \\ &= \frac{3}{2}\left(\frac{p}{2}\right)(\lambda_f i_q + (L_d - L_q) i_d i_q) \end{aligned} \tag{9}$$

The selected PMSM type is surface-mounted; therefore, $L_q = L_d$.

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)(\lambda_f i_q) \tag{10}$$

The mechanical torque is given as (11).

$$T_e = T_L + \mathrm{B}\omega_m + \mathrm{j}\frac{d\omega_m}{dt} \tag{11}$$

Therefore, the mechanical speed is given by (12):

$$\omega_m = \int(\frac{T_e = T_L + \mathrm{B}\omega_m}{J})\mathrm{dt} \tag{12}$$

and

$$\omega_m = \omega_r(\frac{2}{p}) \tag{13}$$

where J = rotor inertia, B = mechanical damping, and T_L = mechanical load torque.

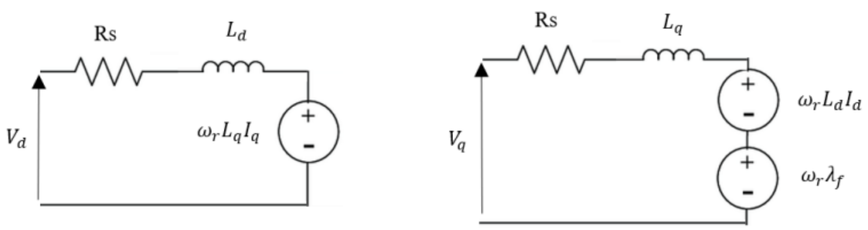

Figure 1. Equivalent circuit for PMSM model in d-q reference frame

2.1. Simulink and parameter design of the PMSM drive

Figure 2 depicts the schematic diagram of the PMSM. Proportional and integral (PI) controller is a feedback control loop that calculates the control signal by comparing output and reference signals. It is important to achieve zero steady-state error without significantly affecting the transient response in a control system. There are some methods used to tune the parameters of a PI controller, such as conventional trial and error or the Ziegler-Nichols method. In this research, the trial-and-error method is used to obtain the controller gains for getting an optimum response. However, it requires a large number of trials and time to obtain optimal controller gains; thus, another technique that can automatically and effectively optimize the controller gains, such as GA, PSO, and ABC algorithms, is suggested. Another significant process in PMSM drive is the transformation of the d-q rotating frame to the three-phase reference. Based on the mathematical modelling and equivalent circuit of PMSM, the system is operated in the *d-q* frame due to its simplicity, because an AC three-phase synchronous motor having windings that are separated by 120° apart is more complex. The amplitude of current, voltage, and flux linkage of a stationary three-phase reference is time-varying, which leads to difficulty and challenging on system modelling [21]. Thus, the *d-q* frame is suggested, which focuses on flux- and torque-producing currents. In this process, the Park transformation is used to convert three-phase voltage and current to *dq0* axis variables, whereas the inverse Park transformation is used to change the voltage and current in *dq0* axis variables to an AC three-phase signal.

Based on the research in [10], there are two conditions. First, when the rotating d-q frame is aligned along the A-axis at t = 0, the equations of the park and inverse park transformations are given by (14) and (15). The second condition is when the *d-q* frame is rotated 90° behind the A-axis; the equations of the park and inverse park transformations are given by (16) and (17). In this research, the setting of the d-q rotating frame is aligned 90° behind the A-axis; thus, the equation used in the block that converts *d-q* current to a three-phase signal is based on (17). The setting of dq0 to three-phase current is done using (18)-(20).

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ -\sin\theta_r & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r & 1 \\ \cos(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r - \frac{2\pi}{3}) & 1 \\ \cos(\theta_r + \frac{2\pi}{3}) & \sin(\theta_r + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\theta_r & \sin(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r + \frac{2\pi}{3}) \\ \cos\theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \sin\theta_r & \cos\theta_r & 1 \\ \sin(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & 1 \\ \sin(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} \quad (17)$$

$$i_a = i_q \cos\theta + i_d \sin\theta \quad (18)$$

$$i_b = i_q \cos(\theta - \frac{2\pi}{3}) + i_d \sin(\theta - \frac{2\pi}{3}) \quad (19)$$

$$i_c = i_q \cos(\theta + \frac{2\pi}{3}) + i_d \sin(\theta + \frac{2\pi}{3}) \quad (20)$$

Next, the hysteresis controller is used to control the current flow in the inverter. It produces a reference signal for the current within a hysteresis band to keep the current from straying outside the reference. In addition, the performance measure, also called the cost function, can affect the output response of the PMSM drive. It is used to measure the effectiveness of a potential solution. There are many types of performance criteria, such as keeping the maximum deviation error as small as possible, achieving a shorter settling time, and minimizing the integral of errors in order to achieve the desired set point. Performance indices, also known as measures of control system performance, are used to compare the quality of controlled responses [20]. In this research, the output of the PMSM drive is focused on the steady-state error of the output speed. The widely used performance measures are integral square error (ISE), integral absolute error (IAE), and integral time absolute error (ITAE) [22]. ISE is a measure that can eliminate large errors faster through integration of the square of the error over time, and this will provide a fast response for the control system. IAE is a measure that can produce less sustained oscillation or can eliminate the small error by integrating the absolute error over time. ITAE is a measure that can produce systems that settle more quickly than ISE and IAE by integrating the absolute error multiplied by time over time. The equations of the performance measures for the steady-state error are shown in (21)-(23) [22].

$$\text{ISE} = \int_0^\infty e^2(t)dt \quad (21)$$

$$\text{IAE} = \int_0^\infty |e(t)|dt \quad (22)$$

$$\text{ITAE} = \int_0^\infty t|e(t)|dt \quad (23)$$

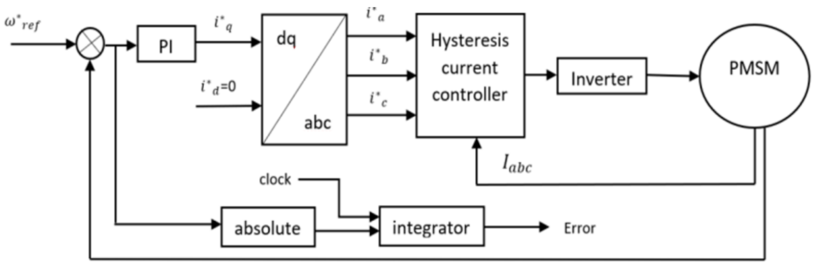

Figure 2. Design of PMSM drive [18]

In this research, the PI controller is tuned by the conventional trial-and-error method. The PI gains are randomly adjusted to figure out the suitable value that can produce a better transient response of the speed. Since the trial-and-error tuning method requires a longer time for testing and adjustment, it is not effectively used to tune the PI parameters under different operations or different rated speeds. Hence, the ABC algorithm and PSO algorithm are selected to optimize the parameters of the controller to obtain an optimum response effectively in this research. For the parameters of the PMSM drive components, the settings are shown in Table 1.

Table 1. Parameters of PMSM drive system

Number of phases	3-phase
Vdc	220 V
Number of pole pairs	4
Stator phase resistance, Rs	2.875 Ω
Armature inductance, L	0.00153 H
Inertia, J	0.0008 Kg.m^2
Viscous damping, F	0 N.m.s
Rated torque, T_L	10 Nm
Speed range	1000 rpm, 1500 rpm, 2000 rpm, 3000 rpm

2.2. ABC algorithm

The ABC algorithm consists of three (3) main components, which are employed bees, unemployed bees, and food sources [19], [20], [24]. It can also categorize the bees as employed bees, while the onlooker and scout bees are unemployed bees. The number of employed bees is similar to the number of sources because of the assumption that one employed bee is only for one source. The employed and unemployed bees search for the food source that is near their colony. The concept of the bees searching for food is that they will produce positive feedback when foragers find an abundant food source, but they will produce negative feedback when foragers give back by abandoning poor food sources [24]. Thus, the employed bees search for the food source, then come back to their hive to dance to the onlooker bees. Onlooker bees will choose the best source of food based on the dances of employed bees. In a more detailed understanding, the employed bees move to the food source that is in their memory and search the closest neighboring food source. Then, they will evaluate the nectar amount on the food source and dance at the hive in front of onlooker bees. The onlooker bees watch the dance and choose the best food source, which is an abundant amount of nectar. Other employed bees that abandon the food source will become scout bees and continue searching for a new food source.

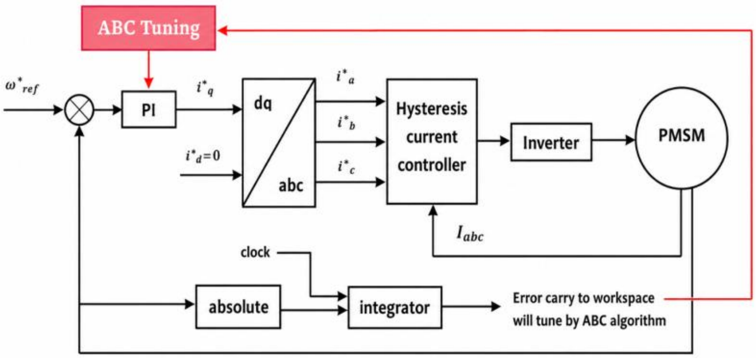

Figure 3. Block diagram that carried error signal for optimization controller gains using ABC algorithm

Figure 3 shows the error signal obtained from the PMSM drive is carried to the workspace in MATLAB to optimize the PI parameters using the ABC algorithm. First, ABC initialize the food source or population of SN with a random distribution in a search space where the SN is the population size. Let the i^{th} solution in the population with dimension n which is also the employed bees are represent by $x_i = \{x_{i,1}, x_{i,2}, \dots\dots, x_{i,n}\}$. Every employed bee x_i will search and generate a new or better solution v_i in neighbouring source from existing location with equation $v_{i,k} = x_{i,k} + \Phi_{i,k} x(x_{i,k} - x_{j,k})$ where $v_{i,k}$ is randomly selected solution (i is not equal to j), k is randomly selected dimension index between 1 to n and $\Phi_{i,k}$ is randomly selected number between [-1, 1]. Next, if the fitness of v_i is better than x_i, the position x_i will update to v_i. Otherwise, it will remain its original x_i. This is the process of employed bees to search for a new source. After that, they will share the information of the food source through waggle dance. The onlooker bees will choose the better source (solution) based on the evaluation of the nectar amount of the source with (24) [25]:

$$P_i = \frac{fit_i}{\sum_{m=1}^{SN} fit_i} \tag{24}$$

and the fitness can be calculated with (25) [24].

$$fit_i = \begin{cases} \frac{1}{1+fit_i} & if\ fit_i \geq 0 \\ 1 + abs(fit_i) & if\ fit_i < 0 \end{cases} \quad (25)$$

fit_i represents the fitness value of the i^{th} solution in the population. When the onlooker bees select a better food source, the previously explored food sources of certain employed bees are abandoned, and those employed bees are converted into scout bees. The scout bees then continue searching for new food sources to replace the abandoned ones according to (26).

$$x_{i,k} = lb_k + \Phi_{i,k} \text{ x } (ub_k - lb_k) \quad (26)$$

Where $\Phi_{i,k}$ is a randomly generated number within the range [0,1] following a normal distribution, lb_k is the lower boundary of k^{th} dimension. The process is repeated until all iterations are completed or the optimum solution is achieved.

2.3. PSO algorithm

The PSO algorithm operates by having a swarm of particles that move around in the search space. The travels of elements are guided by their local best position (P_{best}) in the search space, as well as by the global best position (G_{best}) [11]. When the particles find an improved or optimal position, they will become a new guide for the movement of the particle swarm. The particles will automatically update the new position and velocity. This process is repeated with numerous iterations until an optimal solution is achieved.

Figure 4 shows that the error signal obtained from the PMSM drive is carried to the workspace in MATLAB to optimize the PI parameters using the PSO algorithm. At iteration t, the i^{th} particle is characterized by a vector ${X_i}^t$ to represent its position. The vector ${V_i}^t$ is used to illustrate its velocity. Initially, when iteration t = 0, the positions and the velocities of the particles are assumed randomly from the search space. Each particle will change its position ${X_i}^t$ per iteration by using (27) [11].

$${X_i}^{t+1} = {X_i}^t + {V_i}^{t+1} \quad (27)$$

The updated velocity of the particles depends on the current velocity ${V_i}^t$ and the weighted difference of vectors (P_{best} - ${X_i}^t$) and (G_{best} - ${X_i}^t$) which is presented in (28).

$${V_i}^{t+1} = \omega {V_i}^t + c_1 r_1 (P_{best} - {X_i}^t) + c_2 r_2 (G_{best} - {X_i}^t) \quad (28)$$

The parameters of r_1 and r_2 are chosen randomly between 0 and 1, while the parameters of c_1 and c_2 as individual acceleration coefficient and global acceleration coefficients are commonly set between 0 and 2. The particles will update their local best position (P_{best}) if the existing new position ${X_i}^t$ is better or smaller than P_{best}. The G_{best} will also be updated if the current P_{best} of the i^{th} particle is better than the G_{best}. This process is repeated until all iterations *t* that have been set in the algorithm.

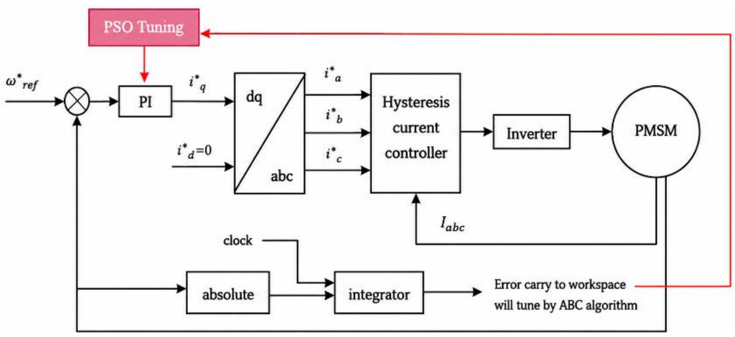

Figure 4. Block diagram that carries the error signal for optimization of controller gains using PSO algorithm

3. RESULTS AND DISCUSSION

The PMSM's reference speed range is 1000 to 3000 rpm. The PMSM drive is operated under different conditions. First, the PMSM drive is tested under forward and reverse operating conditions. Then, the transient responses, such as percentage overshoot (%OS), rise time (Tr), and settling time (Ts), are monitored. Finally, the optimization performance indices, including ISE, IAE, and ITAE, are analyzed using the ABC and PSO algorithms

3.1. Forward and reverse operation

Figure 5 shows the speed performance of the PMSM drive after tuning using the trial-and-error method, the PSO algorithm, and the ABC algorithm under forward and reverse operation. The transient response of the PMSM drive speed is tabulated in Table 2. The input signal is set to zero initially and increases to 1000 rpm after a delay of 0.03 s. After 0.08 s, the reference speed of the PMSM returns to zero. Based on the result in Figure 5, the speed of the PMSM drive can follow the reference speed, where the reference speed is varied. Based on the data in Table 2, the percentage of overshoot, %OS, obtained from the speed optimized by different methods is the same. However, the PSO algorithm can generate the output speed of the PMSM drive with lower settling time, T_s, and rise time, T_r. Therefore, tuning of the speed controller for the PMSM drive using the PSO algorithm is better for coping with the instruction where the rated speed is suddenly changed.

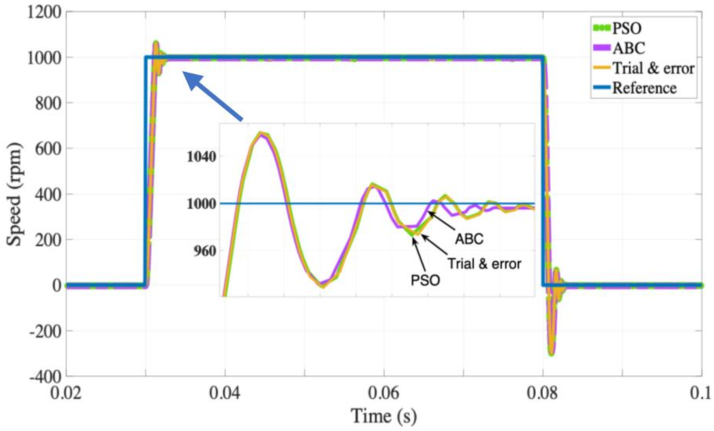

Figure 5. Speed of PMSM drives under forward and reverse operation

Table 2. Transient responses obtained by different techniques under forward and reverse operation.

Tuning method	Kp	Ki	%OS	Ts	Tr
Trial and error	30	10	6.081%	1.520ms	805.154µs
PSO	23.1981	0.7743	6.081%	1.112ms	800.897µs
ABC	30	29.9271	6.081%	1.492ms	803.951µs

3.2. Performance index using ABC algorithm

By changing the arrangement of the block diagram, the performance measures can be changed. The changes to the Simulink block of the PMSM drive system are depicted in Figure 6. The same ABC coding is then used to obtain the PI parameters, which can achieve zero or very small steady-state error. At the end of the simulation, the final values of PI parameters, average objective function value, transient response, and steady-state error obtained are presented in Table 3.

In this research, the most important result focuses on the steady-state error produced in the speed performance. Since the PI controller of the PMSM drive is optimized using the ABC algorithm, a suitable performance measure needs to be identified to obtain the output speed of the PMSM with low steady-state error. Based on the data obtained in Table 3, the PMSM drive based on the ITAE criterion can generate the output speed with less steady-state error when compared to the ISE and IAE performance measures. Although it produced a response with higher overshoot, settling time, and rise time when compared to the responses obtained based on the ISE and IAE error criteria, it can achieve a closer approach to the rated speed of the PMSM drive. In this section, the PMSM drive based on the ISE performance index gives the worst response in terms of steady-state error, whereas the PMSM drive based on the ITAE performance index can produce a better response in terms of steady-state error when the system is optimized by the ABC algorithm. Since the simulation is carried out for 50 iterations, the data of the global minimum, which is known as the objective function value or the error, are analyzed as shown in Figure 7.

Figure 7 shows the average objective function value where the PMSM drive is optimized by the ABC algorithm based on ISE, IAE, and ITAE error criteria. As the reference speed increases, the objective function value is higher. Based on the outcomes from Figure 7, it can be concluded that the control measure

ITAE is more suitable for the parameter tuning of the PMSM drive. This is because it can give very small objective function values in every iteration compared with the control measures of ISE and IAE. Therefore, it can better control the output speed of the PMSM drive, following its rated speed with zero or very small steady-state error compared to the other 2 control measures.

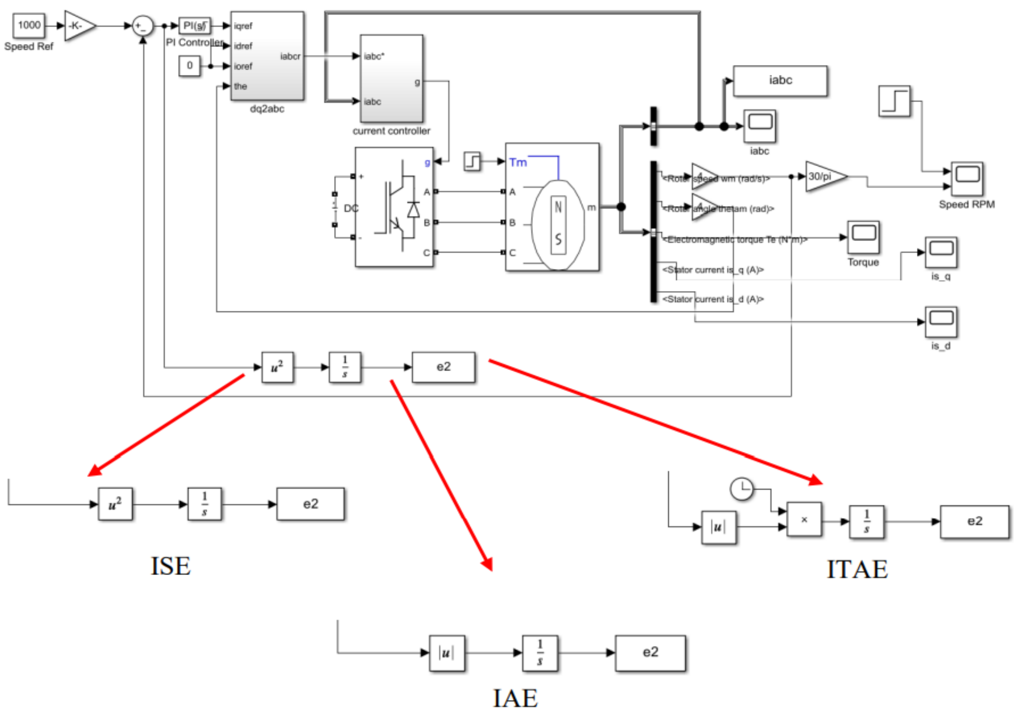

Figure 6. The changes in Simulink blocks based on different error criteria [18]

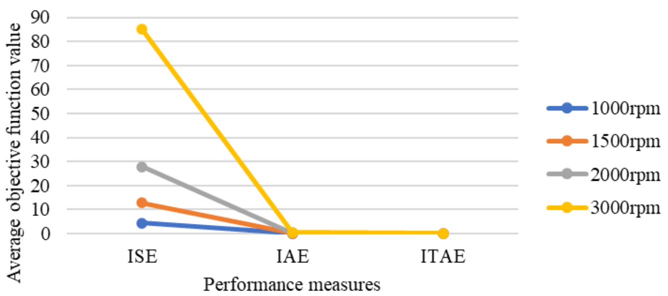

Figure 7. Average objective function values obtained from ABC optimization

Table 3. Transient responses for the ABC algorithm

Rated speed (rpm)	Performance measure	Ave. obj. function value	Kp	Ki	%OS (%)	Ts (ms)	Tr (ms)	e_{ss} (rpm)
1000	ISE	4.407675	2.9183	9.9996	9.341	3.496	0.568	22
	IAE	0.063294	6.2030	9.9864	13.068	1.183	0.573	12
	ITAE	0.000043	9.9980	9.9657	26.042	3.541	0.290	8
1500	ISE	12.824852	2.8422	10	5.851	3.314	0.812	21
	IAE	0.117331	5.0763	10	6.989	1.066	0.824	13
	ITAE	0.000071	9.9657	10	13.281	3.364	0.555	7
2000	ISE	27.833164	2.8595	10	3.646	0.930	1.071	19
	IAE	0.188440	4.7502	9.9767	5.851	0.975	1.078	13
	ITAE	0.000121	9.9480	10	5.851	1.451	1.081	8
3000	ISE	85.122300	3.9228	10	2.577	1.235	1.597	12
	IAE	0.388348	6.4065	9.9909	3.646	1.309	1.592	8
	ITAE	0.000327	9.9764	9.9968	6.250	1.449	0.932	5

Figures 8 and 9 show the standard deviation and standard error of the objective function values obtained from the simulation. Based on the statistical results, the suitable performance index used in the optimization of speed control for PMSM using the ABC algorithm is ITAE. This proves again that the selection in Figure 7 is correct. This is because it can generate a lower objective function value and has the lowest standard deviation and standard error when compared with the performance indices ISE and IAE. It is also proven that the results obtained from optimization of the speed controller based on ITAE in PMSM are more accurate or closer to the expected solution. This is because a lower standard deviation indicates that the value obtained is closer to the mean value of the objective function. Therefore, the output speed of the PMSM drive that is tuned based on ITAE criteria can achieve the reference speed of the PMSM or have very little steady-state error.

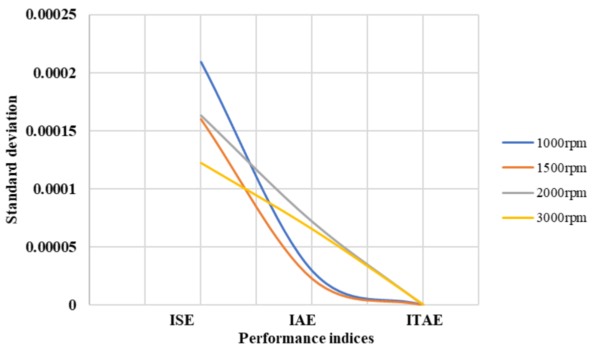

Figure 8. Standard deviation of objective function

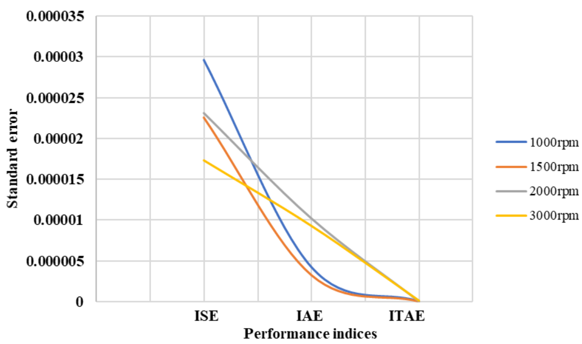

Figure 9. Standard error of objective function values

3.3. Performance index using PSO algorithm

The speed control of PMSM is then optimized by using the PSO algorithm. The PI controller in the PMSM drive is tuned by the PSO algorithm in 50 iterations. As mentioned in the results section, which uses ABC optimization, the results are focused on the output speed of the PMSM with zero or very small steady-state error. The performance of the control system is also tested based on 3 types of error criteria, such as ISE, integral absolute error (IAE), and integral time-weighted absolute error (ITAE), in order to compare the quality of the controlled response and determine which measure is suitable for speed control of the PMSM. The final values of PI gains, average fitness value, overshoot, settling time, rise time, and steady-state error obtained from the speed response of the PMSM drive are tabulated in Table 4.

Based on the data obtained, the PMSM drive based on the ITAE criterion can generate the output speed with zero or small steady-state error when compared to ISE and IAE performance measures. Although it is unable to produce the best transient response when compared to the responses obtained based on ISE and IAE error criteria, it can achieve the reference speed of the PMSM drive with an error not more than 6rpm. In summary, the PMSM drive based on the ITAE performance index that is optimized by the PSO algorithm can give the best response on the output speed of the PMSM drive with very low steady-state error when compared to the other two performance measures.

Figure 10 shows the average global best fitness value where the PMSM drive is optimized by the PSO algorithm based on ISE, IAE, and ITAE error criteria. As the rated speed increases, the global best fitness value also increases. Based on the outcomes from Figure 10, it can be summarized that the control measures ITAE are better for the parameter tuning of the PMSM drive to achieve low steady-state error. This is because it can give very small fitness values in every iteration compared with the control measures of ISE and IAE. Therefore, it can better control the output speed of the PMSM drive, following its rated speed with zero or very small steady-state error compared to ISE and IAE performance measures.

Figures 11 and 12 show the standard deviation and standard error of the fitness values obtained from the PSO optimization of the PMSM drive based on different performance indices. Based on the results, the suitable performance index used in the optimization of speed control for PMSM using the PSO algorithm is ITAE. This is because it can generate a lower fitness value and has the lowest standard deviation and standard error when compared with the performance indices ISE and IAE. The lower standard deviation indicates that the value obtained is close to the mean value of the objective function. Therefore, the output speed of the PMSM drive that is tuned based on ITAE criteria can achieve the rated speed of the PMSM or have very little steady-state error.

Based on the analysis in Table 5, it can be concluded that the performance of the PMSM drive based on ITAE error criteria is more suitable for both ABC and PSO optimization of the speed controller. This is because the overall results show that the steady-state error generated from the optimization of the speed controller of the PMSM drive based on the ITAE criterion is lower than that based on the ISE and IAE error criteria.

Table 4. Transient responses for the PSO algorithm

Rated speed (rpm)	Performance measure	Ave. fitness value	Kp	Ki	%OS (%)	Ts (ms)	Tr (ms)	e_{ss} (rpm)
1000	ISE	1610.852	2.7407	18.5163	8.152	3.483	0.571	16
	IAE	2.41068	6.2548	19.3331	13.068	1.185	0.574	10
	ITAE	0.00325	23.6004	15.1056	25.510	3.812	0.300	3
1500	ISE	2304.276	2.4030	28.4037	4.737	0.763	0.824	9
	IAE	2.21340	5.0089	2.0915	6.989	1.055	0.822	17
	ITAE	0.00349	15.4688	40.3313	9.341	3.508	0.826	3
2000	ISE	2103.194	2.2651	17.2265	2.577	0.892	1.071	14
	IAE	1.97302	3.6419	27.2067	4.737	0.975	1.073	7
	ITAE	0.00829	20.0215	8.9732	6.989	1.732	1.075	6
3000	ISE	3428.273	3.2063	18.7192	4.386	0.895	0.937	5
	IAE	2.61682	4.1484	25.6095	4.098	0.914	1.009	0
	ITAE	0.02140	3.9036	25.8387	3.012	1.115	1.370	0

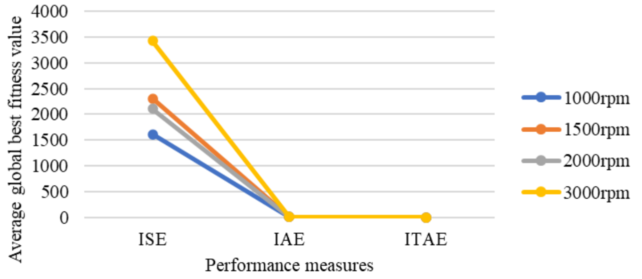

Figure 10. Average fitness values obtained from PSO optimization

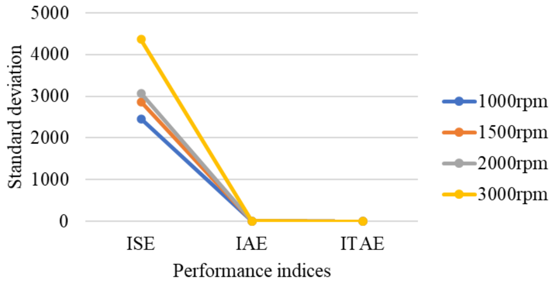

Figure 11. Standard deviation of fitness values

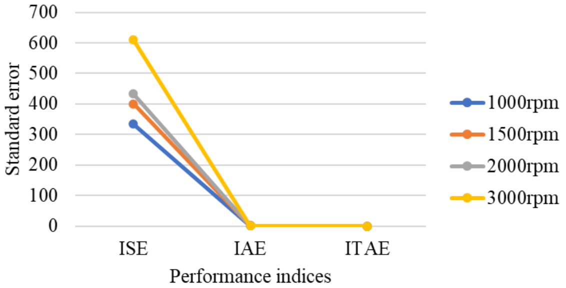

Figure 12. Standard error of fitness values

Table 5. Effectiveness in achieving steady-state error, tuned by the ABC and PSO algorithms

Rated speed	Performance indices	ABC	PSO	Rated speed	Performance indices	ABC	PSO
1000 rpm	ISE			2000 rpm	ISE		
	IAE				IAE		
	ITAE	✓	✓		ITAE	✓	✓
1500 rpm	ISE			3000 rpm	ISE		
	IAE				IAE		
	ITAE	✓	✓		ITAE	✓	✓

4. CONCLUSION

In conclusion, the speed controller of the PMSM drive can be tuned by the ABC algorithm based on the ITAE error criterion to optimize the output response. The ABC optimization technique can produce the overall output performance of the speed with a lower percentage of overshoot, shorter settling time, and rise time when compared to that of using PSO optimization and the trial-and-error method. In addition, the system that is based on the ITAE performance index also helps to produce a smaller percentage of overshoot or oscillation. Therefore, the speed of the PMSM drive can be optimized by tuning the K_p and K_i values of the controller to cope with different conditions, such as no-load operation and forward and reverse operation. The PMSM drive was also tested with forward and reverse operation. The simulation results showed that the speed response of the PMSM drive optimized by three different tuning methods is able to cope with the suddenly instruction given or changed. However, this section proved that the PSO algorithm is more effective in optimizing the speed controller and generating a better transient response of the speed. As overall results from no-load operation to forward and reverse operation, it can be concluded that ABC is more suitable for tuning the controller in the PMSM drive. The simulation results showed that the PMSM drive based on the ITAE criterion is better than ISE and IAE performance measures for ABC and PSO optimization. It can generate the output speed of a PMSM drive with a very small steady-state error or fully achieve the reference speed. At the end of this report, the conclusion that can be made is that ABC optimization is suitable used to optimized the speed controller in a PMSM drive based on the ITAE criteria.

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C : **C**onceptualization
M : **M**ethodology
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D : **D**ata Curation
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E : Writing - Review & **E**diting
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P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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