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IMPROVED INDIRECT FIELD-ORIENTED CONTROL OF INDUCTION MOTOR DRIVE BASED PSO ALGORITHM

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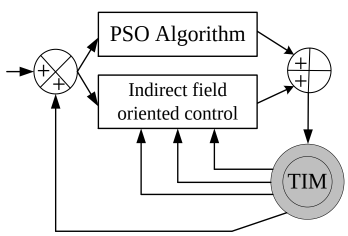
Graphical abstract



Abstract

Optimization techniques are increasingly used in research to improve the control of three-phase induction motor (TIM). Indirect field-oriented control (IFOC) scheme is employed to improve the efficiency and enhance the performance of variable speed control of TIM drives. The space vector pulse width modulation (SVPWM) technique is used for switching signals in a three-phase bridge inverter to minimize harmonics in the output signals of the inverter. In this paper, a novel scheme based on particle swarm optimization (PSO) algorithm is proposed to improve the variable speed control of IFOC in TIM. The PSO algorithm is used to search the best values of parameters of proportional-integral (PI) controller (proportional gain (kp) and integral gain (ki)) for each speed controller and voltage controller to improve the speed response for TIM. An optimal PI controller-based objective function is also used to tune and minimize the mean square error (MSE). Results of all tests verified the robustness of the PSO-PI controller for speed response in terms of damping capability, fast settling time, steady state error, and transient responses under different conditions of mechanical load and speed.

Keywords: Particle swarm optimization, indirect field oriented control, SVPWM, Inverter, induction motor.

1.0 INTRODUCTION

Squirrel-cage three-phase induction motors (TIMs) are commonly used in considerable research because they are considered industrial workhorses for various applications, as well as because of their ease of maintenance, ruggedness, simple structure, affordability, high degree of reliability, and robustness [1]. The vector control scheme for TIM drives has been widely used in high-performance control systems because of its robustness, high efficiency, good power factor, and extreme ruggedness [2,3]. Indirect field-oriented control (IFOC) scheme has been designed to enhance the controller robustness of TIM drives and realize the torque-flux decoupling technique. This scheme realizes the characteristics of separately excited DC motor TIM drives [2,4]. Considerable studies have employed IFOC as a control for various applications, such as double-star induction machine [5], TIM [2–4], and system to monitor wind energy conversion [6].

TIMs supplied by three-phase bridge inverter is generated through the control techniques on the switching. These control techniques are called pulse width modulation (PWM) approaches, such as sinusoidal PWM, space vector PWM (SVPWM), carrier-based PWM, selective harmonic elimination PWM, and harmonic band PWM [7,8]. The SVPWM is the best approach for switching control of the inverter because this technique can minimize switching losses and harmonic output signals [3,8,9].

Various conventional controllers are available such as proportional-integral (PI) controller. This controller has been widely used in many devices because of its simple control structure, ease of design, and affordability [4]. This controller scheme is also used to control the speed, flux, currents, and voltages in the TIM to minimize high overshoot, high steady state error, and oscillation of speed response. However, the disadvantage of the PI controller is the difficulty of finding the best values for its parameters. These parameters are closely dependent on the performance of the controller in TIM. Thus, several methods, such as the Ziegler–Nichols method and Cohen–Coon method, have been employed to search the parameters of the PI controller. These methods require a mathematical model, trial and error, and process upset, which lead to a time-consuming tedious process and unsatisfactory results [4,10]. Particle swarm optimization (PSO) algorithm is one of the commonly used optimization techniques, and has the advantages of strong robustness, global convergence capability, and ease of implementation [11]. In this study, the PSO algorithm is developed to improve the performance of the TIM employing IFOC by tuning the parameters of the PI controller for torque and voltage controller. The results obtained from the developed torque and voltage controller showed that the performance of the PI controller was robust in terms of minimizing overshoot, settling time, steady state error, and mean square error (MSE) under the condition of sudden change in speed and mechanical load.

2.0 INDIRECT FIELD-ORIENTED CONTROL

The principal idea of vector control is to separately and independently control the flux and torque in the TIM, which is a method similar to controlling a separately excited DC motor [12]. IFOC is a type of vector control used by several researchers because it can improve or develop the performance of a TIM drive [2]. Figure 1 shows the phasor diagram of the fundamental principle of indirect vector control [6]. The $d^s - q^s$ axes are settled on the stator, the $d^r - q^r$ axes are settled on the rotor, and $d^e - q^e$ are settled on the synchronous rotor [13].

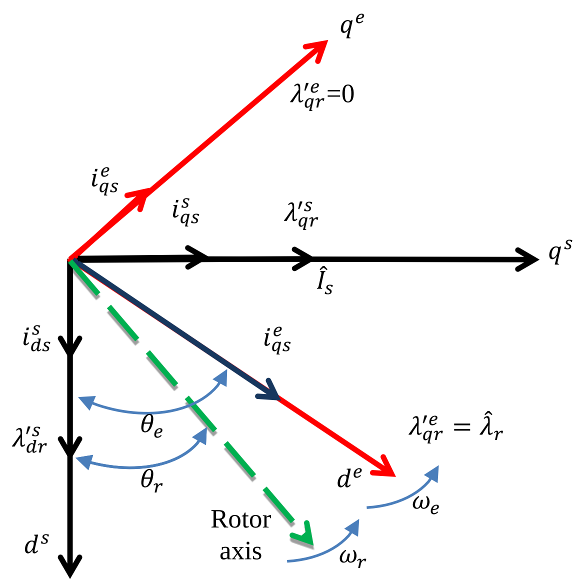


Figure 1 Phasor diagram of indirect vector control

The d-axis is aligned with the rotor field and q-axis of the rotor field based on the assumption that the reference frame is zero ($\lambda'^e_{qr} = 0$). The rotor current can be obtained using the following equation [5]:

$$\lambda'^e_{qr} = L_m i^e_{qs} + L'_r i'^e_{qr} = 0, \qquad i'^e_{qr} = -\frac{L_m}{L'_r} i^e_{qs} (1)$$

where λ'^e_{qr} is q of rotor flux, L_m, L'_r is magnetic inductance, i^e_{qs}, i'^e_{qr} is q-axis current for stator and rotor, and P is number of pair poles. IFOC cannot directly measure air gap flux, but it uses the conduction in Equation 1. The electromagnetic torque (T_{em}) can be controlled by calculating slip angular frequency (ω_{sl}) and q-axis for the stator current (i^e_{qs}). The d-axis of the rotor flux (λ'^e_{dr}) can be calculated through the d-axis of the stator current (i^e_{ds}), as shown in the following equations [6,13]:

$$\lambda'^e_{dr} = \frac{r'_r L_m}{r'_r + \frac{dL'_r}{dt}} i^e_{ds} (2)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L'_r}\lambda'^e_{dr} i^e_{qs} (3)$$

$$\omega_{sl} = \omega_e - \omega_r = \int (\theta_e - \theta_r) dt = \frac{r'_r}{L'_r}\frac{i^e_{qs}}{i^e_{ds}} (4)$$

where ω_e, ω_r are electrical and rotor angular frequencies, θ_e, θ_r are synchronous and rotor angle speed, r_r is rotor resistance, L_r is rotor inductance, and i^e_{qs}, i^e_{ds} are d-q axes for stator currents.

3.0 DESIGN OF PSO-PI CONTROLLER

Primary PSO is an evolutionary computation technique developed by Eberhart and Kennedy in 1995, which is inspired by the social behavior of bird flocking. This optimization algorithm is considered by numerous researchers because of its verified robustness, ease of implementation, and global exploration ability in various applications [11,14]. The particles in the PSO algorithm search the space in two locations. The first location is the best point where the swarm has found the current iteration (local best). The second location is the best point found through all previous iterations (global best) [15]. The principle of the PSO algorithm depends on two factors, namely, velocity and position of particles. These factors can be updated by using the following equations [11,14,16]:

$$V_i^d(t+1) = wV_i^d(t) + c_1 r_1 \left(P_i^d(t) - X_i^d(t)\right) + c_2 r_2 \left(P_t^d(t) - X_i^d(t)\right) \quad (5)$$

$$X_i^d(t+1) = X_i^d(t) + V_i^d(t+1) \quad (6)$$

where c_1 is social rate and c_2 is cognitive rate. r_1, r_2 are the random in the interval (0,1). V is the velocity factor of agent i at iteration d, t is the present iteration, w is the inertia factor, and X is the position factor.

The PI controller or conventional controller is one of best ways to control TIM because this control scheme has the advantages of simple structure, ease of design, and inexpensive hardware implementation. However, this scheme has difficulty finding suitable values for coefficients of the PI controller (*kp*, *ki*). Thus, the PSO algorithm is used to find the best values for parameters of PI in TIM. The objective function used the MSE to obtain a minimized error in speed response of TIM. The MSE is expressed as follows [15]:

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{error}^2 \quad (7)$$

where $\mathrm{error} = \omega_{ref.} - \omega_r$, the error and n is number of sample. Figure 2 shows the flow chart of the improved speed, q-axis voltage, and d-axis voltage of the PI controller by using the PSO algorithm for the performance development of TIM [11,14,16].

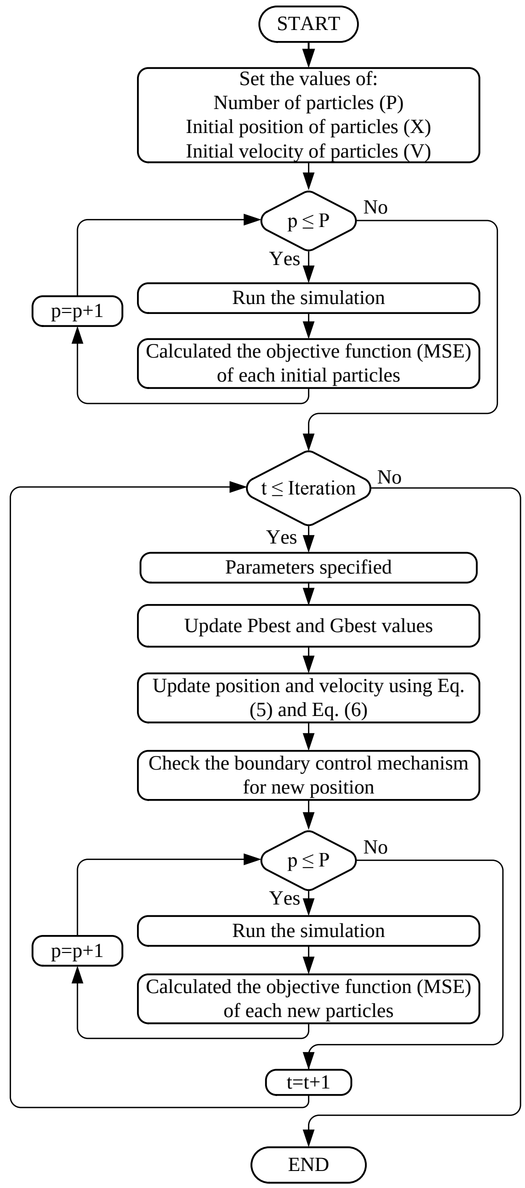


Figure 2 Flow diagram of PSO-based optimal PI controller

4.0 MODELING AND DESCRIPTION OF THE PROPOSED SYSTEM

Figure 3 shows the developed PSO-PI controller simulation model for the three controllers (torque, q-axis voltage, and d-axis voltage) in the TIM drive model. The SVPWM switching technique is utilized to control the TIM drive to improve the signals that are supplied to the TIM. The TIM model is a stationary reference frame, where rotor speed and stator currents are measured depending on the feedback signal. Therefore, the speed sensor and current sensor have to be measured.

The IFOC strategy generates the three voltages to the SVPWM, which are needed for the four-signal feedback. The first signal is rotor speed (ω_r) coming from the speed sensor to the PSO-PI torque controller to produce the torque reference (T_{em}) and the field weakening to generate the d-axis of the rotor flux. These control signals are inputted to field-oriented control (FOC) to create the d-q axes of stator current reference (i_{qs}^{*e}, i_{ds}^{*e}) and slip speed (ω_{sl}). The three signals of feedback are stator currents coming from the current sensor and converted to the d-q axes of stator currents by using Clark's and Park's transformation techniques. The error of the stator currents is inputted to two PSO-PI controllers. The first controller is the control on the q-axis stator current to produce the q-axis voltage stator. The second controller is the control on the d-axis stator current to produce the d-axis voltage stator. Thus, the d-q voltages convert to three voltages and proceed to SVPWM to be supplied to the TIM.

5.0 RESULTS AND DISCUSSION

Figure 3 shows the Simulink model for IFOC, which represents the total structure of VSI fed to TIM. The modeling includes the three controllers called the PSO-PI controllers, which are used to improve the IFOC method to obtain robustness of controller in TIM. Moreover, the modeling includes the SVPWM technique that receives three voltages to control switching derives (IGBT) in the inverter to obtain regularity of voltage and frequency supplied to the

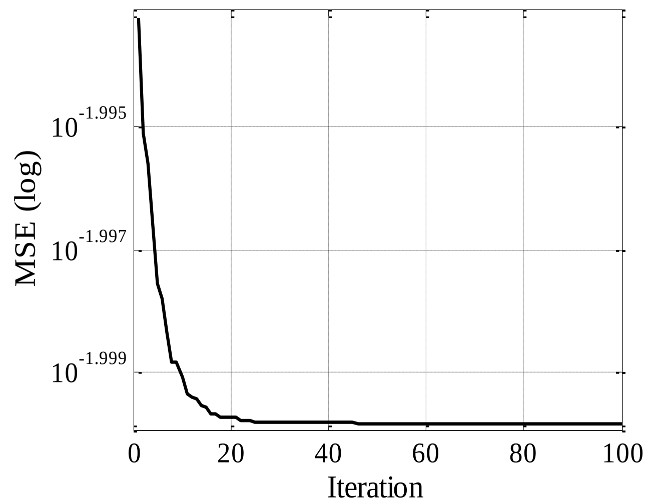


Figure 4 Relationship curve between MSE and iterations

The simulation results are presented in two test cases to calculate the robustness and enhance effectiveness of the proposed PSO-PI controllers with IFOC. The two cases are (1) fixed speed with varying mechanical load and (2) constant mechanical load with varying speed.

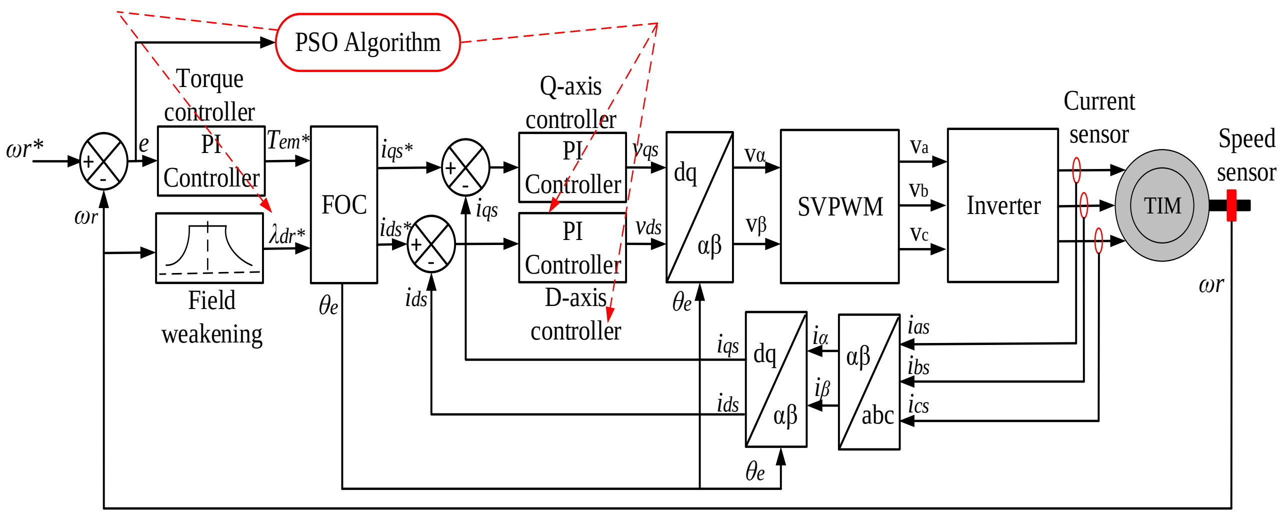


Figure 3 Block diagram of the proposed PSO controller for IFOC

TIM. The performance of the proposed PSO-PI controllers on the TIM is found to be a strong controller under sudden changes in the reference speed andmechanical load at different intervals. The proposed controller has used 100 iterations to find the best results and minimize MSE on speed response (Figure 4). The proposed controller is applied on the TIM of 1HP by using Matlab/Simulink software.

5.1 Sudden Changes In Mechanical Load

The first test on the TIM assumes constant reference speed and varying mechanical load. The test is conducted to illustrate the possibility of controlling the sudden changes in mechanical load. The mechanical load is gradually changed starting from the TIM working on full speed (157 rad/s) but without load until 0.2 s. The load is then changed to a quarter of the mechanical load until 0.3 s, half of the mechanical load until 0.4 s, three quarters of the mechanical load until 0.5 s, and finally full mechanical load until 0.6 s. The process is repeated but inversely conducted, starting from full load to no load. Figure 5a shows that the speed response controller for TIM is good under the change of mechanical load by removing overshoot and settling time and minimizing steady-state error between the reference and actual speed. The stator currents showed fixed frequency and variable in peak value because of the dependence on fixed speed and varying mechanical load (Figure 5b).

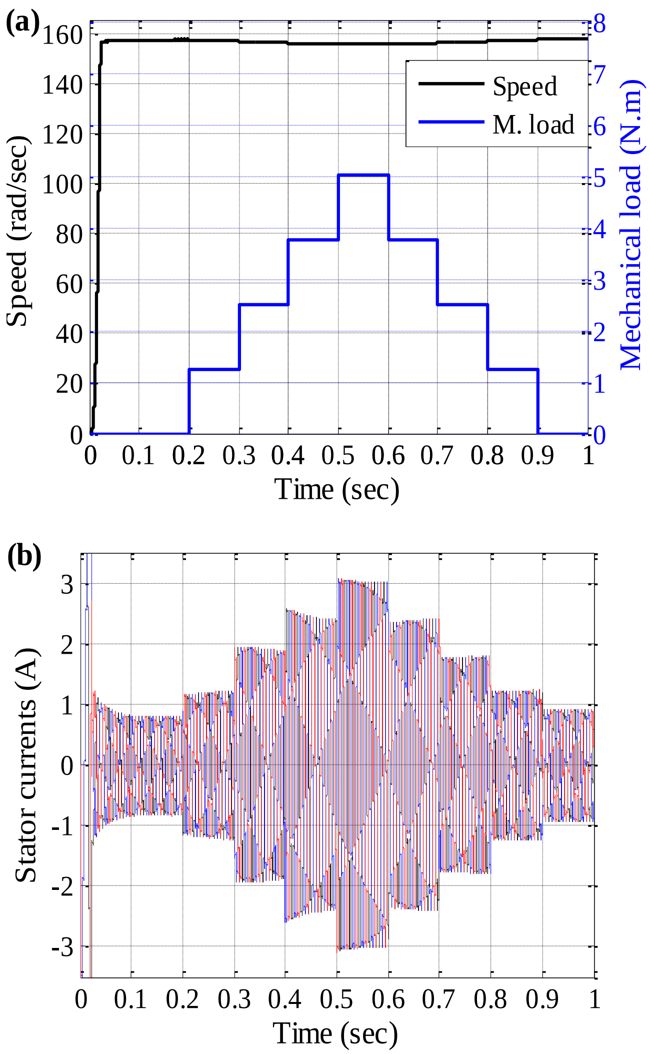


Figure 5 Speed with torque variations: (a) speed response and (b) stator currents

5.2 Sudden Changes In Reference Speed

The second test is conducted to verify the performance of the proposed controller under the sudden change in reference speed with constant load. The change of speed has considered two statuses. The first case is rotating the TIM direction counterclockwise by changing the ramp from initial to full speed at 0.1 s. The full speed is then fixed to 0.4 s and the direction is changed to clockwise (Figure 6). The second status is a difficult case, which is step changing of speed in the initial full speed (157 rad/s) at 0.2 s, and then changing to 118 rad/s at 0.3 s, 78.5 rad/s at 0.4 s, 59 rad/s at 0.6 s, 118 rad/s at 0.7 s, 78.5 rad/sec at 0.8 s, and finally to full speed at 1 s (Figure 7a). The stator currents showed the variable in frequency value because of the dependence on variable speed (Figure 7b).

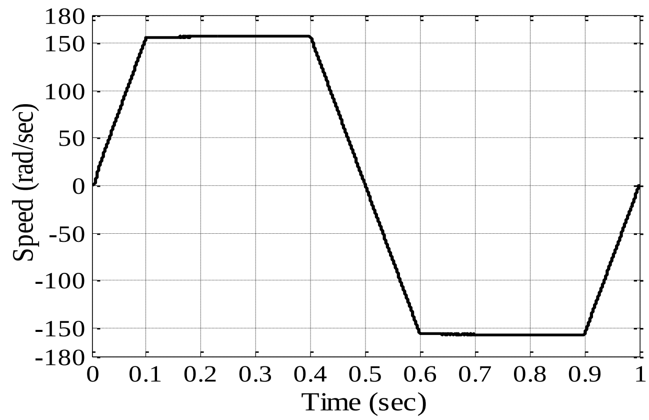


Figure 6 Ramp speed response

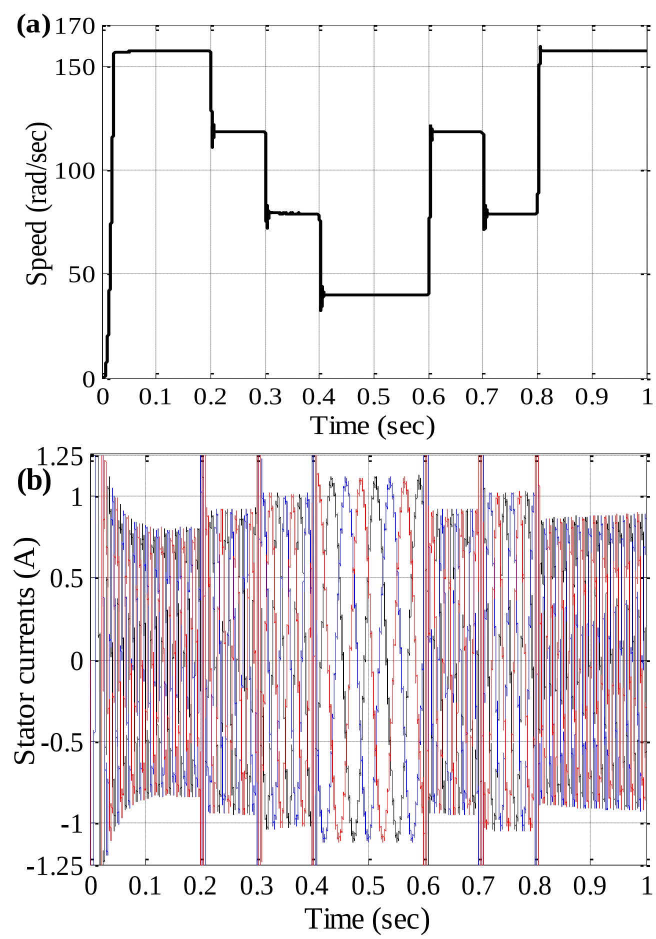


Figure 7 The speed variations with fixed load (a) speed response and (b) stator currents

6.0 CONCLUSION

This paper presented a PSO-PI controller to improve the IFOC in TIM. The proposed controller scheme is formulated to automatically change the parameters of the PI used in the three controllers (torque and d-q axis voltages). A suitable objective function is developed to minimize the MSE of the speed response and to enhance the effectiveness of IFOC by tuning the parameters of the proposed PI controller used in the TIM applications. The TIM drive is modeled with IFOC control and SVPWM technique under varying conditions of speed and mechanical load. The results confirmed that the PSO-PI controller scheme increased the robustness and performance of the controller as well as the speed responses under the conditions of sudden changes in mechanical load and speed by removing the overshoot, settling time, and steady state error.

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