An optimized FOC method for three-phase induction motor drives using PSO algorithm

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Abstract – The Three-Phase Induction Motor (TPIM) is a cornerstone of modern industrial systems, valued for its robustness, cost-effectiveness, and low maintenance. Achieving high performance control of TPIM drives necessitates sophisticated strategies that minimize steady-state ripple, provide rapid dynamic response, and maintain robustness under parameter variations. Field-Oriented Control (FOC) is a widely adopted method for decoupling torque and flux control, akin to a DC motor, but its conventional implementation using single Proportional-Integral (PI) controllers often suffers from limitations in accuracy, susceptibility to parameter changes, and significant torque and current ripple. This paper presents a novel and optimized indirect Field-Oriented Control strategy specifically designed to enhance the performance of Three-Phase Induction Motor Drives (TPIMDs). The core innovation lies in the structural modification of the control loop, where conventional single PI regulators are replaced with optimized double PI regulators. In this architecture, two PI controllers are employed in parallel, effectively increasing the degrees of freedom for error correction and improving the system's ability to handle both transient and steady-state demands. This modification retains the inherent simplicity and ease of implementation of the classic FOC while targeting its primary weaknesses. To fully harness the potential of the double PI structure, the critical challenge of parameter tuning is addressed through an intelligent optimization approach. The Particle Swarm Optimization (PSO) algorithm is employed to systematically and optimally tune the parameters (proportional and integral gains) of the parallel PI controllers. PSO, inspired by the social behavior of birds or fish, efficiently searches the parameter space to minimize a defined cost function, which in this context relates to performance metrics like settling time, overshoot, and steady-state error. This automated tuning method surpasses traditional trial-and-error techniques in both efficiency and result quality. The proposed FOC scheme integrating double PI regulators with PSO-based optimization was rigorously evaluated through comprehensive simulations in MATLAB/Simulink for a 1.5 kW induction motor drive.The simulation results conclusively demonstrate the superiority of the proposed method. Compared to the conventional FOC, the optimized double PI-based FOC exhibited a significantly faster dynamic response and a drastic reduction in speed ripple during steady-state operation. When compared to the non-optimized double PI FOC, the PSO-tuned version showed further improved transient performance and lower steady-state error, validating the critical role of systematic parameter optimization.

Keywords: Double PI regulators, field-oriented control, optimized controllers, particle swarm optimization, three-phase induction motor drive

Nomenclature

$[v^s_{dqs}]$, $[v^s_{dqr}]$	Stator and rotor voltages
$[i^s_{dqs}]$, $[i^s_{dqr}]$	Stator and rotor currents
$[\varphi^s_{dqs}]$, $[\varphi^s_{dqr}]$	Stator and rotor fluxes
p	Differential operator
r_s, r_r	Stator and rotor resistances
l_s, l_r	Stator and rotor self-inductances
l_m	Magnetizing inductance
l_{ls}, l_{lr}	Stator and rotor leakage inductances
ω_r	Rotor speed
τ_e	Electromagnetic torque
n_p	Number of pole pairs
$\lvert\varphi_r\rvert$, θ_e	Rotor flux amplitude and position

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1. Introduction

The use of electric Alternating Current (AC) machines is continually growing in industrial sectors, for example turbines, electric vehicles, aerospace, traction, etc. [1-3]. Squirrel-cage Induction Motors (IMs) are the most extensively used machines in different fields due to their robustness, low price, high reliability, and low maintenance. Furthermore, IMs are considered by simple and easy control compared to other electric machines [4-6].

The high-tech development in the field of electronics and control systems made it possible to utilize IMs in the field of drive systems. To achieve a high performance of Three-Phase IM Drives (TPIMDs), control techniques with high efficiency should be chosen. They should be able to decrease the steady-state ripple error and improve the dynamic response [7]. These standards are among the circumstances for choosing control approaches for TPIMDs to attain high performance in industries [8].

In literature, numerous control methods have been suggested to control TPIMDs, where these methods are different in terms of simplicity, robustness, efficiency, accuracy, cost, ease of implementation, etc. Among the most well-known of these approaches can be stated backstepping control methods [9,10], passivity-based control strategies [11,12], Field-Oriented Control (FOC) methods [13,14], Sliding Mode Controllers (SMCs) [15,16], Direct Torque Control (DTC) techniques [17,18], Model Predictive Control (MPC) systems [19,20], etc.

Different research works have also combined methods for improvement of the features of TPIMDs. These strategies have confirmed their usefulness in improving the superiority of the currents, decreasing the torque ripple, etc. For example in [21], a modified DTC of a dual IM based on neural algorithms have been proposed. This method has many advantages such as accuracy, simple structure, high reliability, robustness, low cost, and high dynamic performance. In [22], the authors have proposed a robust adaptive super twisting SMC for high performance TPIMDs. In this paper to optimize the control system performance, a robust adaptive neural-network controller based on adaptive Particle Swarm Optimization (PSO) algorithm has been developed. In [23], an effective DTC based on the neuro-fuzzy controller method and a five-level inverter has been suggested to control TPIMDs. By using the output of the neuro-fuzzy controller, the space vector modulation has developed the suitable pulses to the inverter. The suggested technique in [23] has been simulated in the Matlab/Simulink.

A novel sensorless DTC method based on the space vector modulation was introduced for TPIMDs [24], whereby two non-identical Extended Kalman Filters (EKFs) were designed and used for the speed estimation. This estimator can provide simultaneous estimation of both rotor and stator resistances. The use of this method leads to an important enhancement in the results. But it increases the system complexity and difficulty of implementation. Furthermore, the use of two EKFs to improve the usefulness of the FOC method leads to an increase in the response time and makes the TPIMD much slower, which is not desirable. Another control method is a combined algorithm based on the FOC and DTC for improving the performance of TPIMDs [25]. The main goal of this control strategy is to start the TPIMD by selecting DTC during the transient mode while FOC is substituted smoothly to the steady-state.

To improve the performance and efficiency of TPIMDs, an adaptable steady-state detection system has been introduced and integrated into a phase-locked loop-based FOC in [26]. A reinforcement learning-based controller has been used to control the speed of TPIMDs using the FOC strategy and the space vector modulation in [27]. Several simulations in this paper were performed to assess the controller performance under different operating circumstances. To improve the performance of a TPIMD using FOC and DTC approaches, a Darwinian PSO method in the fuzzy procedure has been used in [28]. In [29], a novel MPC strategy has been presented to improve the performance and efficiency of the TPIMD. Based on the results in [29], the use of the suggested MPC method leads to decreasing the torque ripple. Furthermore, it increases the dynamic response compared to the traditional control technique.

Compared to the DTC and MPC methods, FOC techniques provide satisfactory results, as there are low ripples in the torque and current responses of TPIMDs. In other words, while FOC methods are control schemes recognized by slow dynamics compared to DTC and MPC techniques, they are more accurate. FOCs are two types, where the first form is direct FOCs [30,31] and the second type is indirect FOCs [32,33]. The differences between these two types are the difficulty, dynamic response, cost, etc. In general, indirect FOC is preferred due to low cost, low size, and high reliability.

In the conventional FOC system, the reference d-q voltages are calculated according to the speed and rotor flux through the Proportional-Integral (PI) controllers. Using PI controllers in FOC systems makes them less robust, particularly in the situation of changing the motor parameters [31]. On the other hand, the values of PI parameters utilized in FOC systems affect the operating circumstance of the TPIMD expressively, which leads to the reduction of the motor performance with a high torque ripple.

In this paper, a developed and optimized indirect FOC scheme is proposed to control the speed of TPIMDs. The suggested control structure is based on the use of double PI controllers, where two traditional PI controllers are employed in parallel. In this work also a method for tuning the parameters of double PI controllers is used, namely the PSO technique. Parameter optimization using this technique has stable results compared to other strategies [34,35]. The proposed controller keeps the simplicity of the conventional FOC and the ease of implementation while significantly improving the steady-state ripple error, dynamic response, and etc. Matlab/Simulink is utilized to confirm the suggested control structure compared to the performance of different FOC strategies.

The use of PI controller in the conventional FOC method makes it less robust, especially when the motor parameters change [36]. In this paper, to solve this problem a simple controller is presented. This controller is used to improve the performance of PI-based TPIMDs.

The controller designed in this paper is a combination of two common PI controllers in a parallel manner. The double PI controller was used for direct FOC of TPIMDs in [36] as well. Nevertheless, this controller is modified in this research for indirect FOC of TPIMDs. In general, indirect FOC method is better than direct FOC strategy in terms of steady-state ripples and response time. In addition, the FOC technique in [36] uses additional voltage sensors, which increases the cost and complexity of the system. Furthermore, in this paper the PSO algorithm is utilized to optimize the parameters of double PI controllers.

This paper is divided into six Sections. After an introduction in Section 1, Section 2 shows the mathematical model and FOC of TPIMDs. In Section 3, the designed controller is presented. The PSO algorithm and the proposed FOC scheme are presented in Section 4. In Section 5, different simulations are presented to assess the motor performance under the introduced FOC method. Section 6 presents the conclusion.

2. Mathematical model and FOC of TPIMDs

In many control systems for example FOC strategies, to realize more precise results a suitable mathematical model of the machine should be chosen. A well-known mathematical model of an IM in the d-q stationary reference coordinate is given in (1)-(5) [35]:

$$[v^s_{dqs}] = \begin{bmatrix} r_s + l_s p & 0 \\ 0 & r_s + l_s p \end{bmatrix} [i^s_{dqs}] + \begin{bmatrix} l_m p & 0 \\ 0 & l_m p \end{bmatrix} [i^s_{dqr}] \quad (1)$$

$$[v^s_{dqr}] = \begin{bmatrix} l_m p & \omega_r l_m \\ -\omega_r l_m & l_m p \end{bmatrix} [i^s_{dqs}] + \begin{bmatrix} r_r + l_r p & \omega_r l_r \\ -\omega_r l_r & r_r + l_r p \end{bmatrix} [i^s_{dqr}] \quad (2)$$

$$[\varphi^s_{dqs}] = \begin{bmatrix} l_{ls} + l_m & 0 \\ 0 & l_{ls} + l_m \end{bmatrix} [i^s_{dqs}] + \begin{bmatrix} l_m & 0 \\ 0 & l_m \end{bmatrix} [i^s_{dqr}] \quad (3)$$

$$[\varphi^s_{dqr}] = \begin{bmatrix} l_m & 0 \\ 0 & l_m \end{bmatrix} [i^s_{dqs}] + \begin{bmatrix} l_{lr} + l_m & 0 \\ 0 & l_{lr} + l_m \end{bmatrix} [i^s_{dqr}] \quad (4)$$

$$\tau_e = n_p l_m \left(i^s_{qs}\, i^s_{dr} - i^s_{ds} i^s_{qr} \right) \quad (5)$$

To obtain these equations, the 3 to 2 transformation has been used [35].

In this section, the conventional structure of the indirect FOC technique based on the rotor flux is discussed briefly. Rotor flux-based FOC system is one of the power control procedures for TPIMDs. This method has been used to control different electric machines for example synchronous motors, synchronous generators, doubly-fed induction generators, brushless DC motors, etc. It is based on the orientation of the rotor flux. In this method the rotor flux is aligned to the d-axis which means that the q-axis component of rotor flux is equal to zero ($\varphi^e_{dr} = |\varphi_r|^*$ and $\varphi^e_{qr} = 0$).

In this case, the IM operates as a DC motor. The structure of the conventional indirect rotor flux-based FOC using PI controllers is represented in Figure 1 [35].

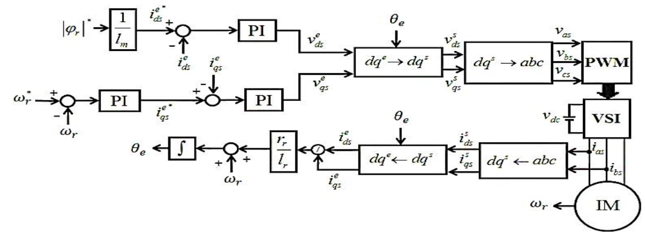

Fig 1. Structure of the conventional indirect rotor flux-based FOC using PI controllers

In Figure 1, three PI regulators are used to control speed and d-q currents. In addition, the Pulse Width Modulation (PWM) is utilized for the Voltage Source Inverter (VSI). In Figure 1 [35]:

$$\begin{bmatrix} i^e_{ds} \\ i^e_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i^s_{ds} \\ i^s_{qs} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} v^s_{ds} \\ v^s_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v^e_{ds} \\ v^e_{qs} \end{bmatrix} \quad (7)$$

3. Double PI controller

The FOC of TPIMDs can be designed by different kinds of controllers such as integral, derivative, and proportional regulators. These regulators aim to improve the system performance such as transient response and steady-state error. PI and Proportional-Integral-Derivative (PID) are among the most prevalent and simple regulators for FOC of TPIMDs due to their convenient adjustment, trouble-free software design, and simple implementation. In this case, the PI controller is preferred because of its easy implementation and simple structure. The block diagram of the traditional PI controller is as Figure 2.

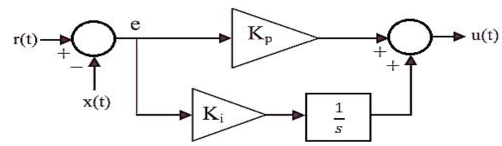

Fig.2. Block diagram of the traditional PI controller

where, K_i and K_p are integral and proportional parameters, respectively. It is relevant to mention that while the conventional controllers like PI are extensively used in the FOC of TPIMDs, they face some problems for example low robustness. PI controllers require adjustment because of the approximations of the model, changes of the parameters during the process, and external uncertain disturbances.

In this section, a controller is introduced based on the combination of two PI regulators to find a controller that is considered by simple of implementation and low cost compared to other controllers for example SMC, backstepping, etc. In [36], two PI regulators were combined in parallel to improve the FOC strategy. The presented double PI regulator in [36] has been used to reduce the torque and current ripples as well as robustness of the FOC approach. This regulator structure is shown in Figure 3.

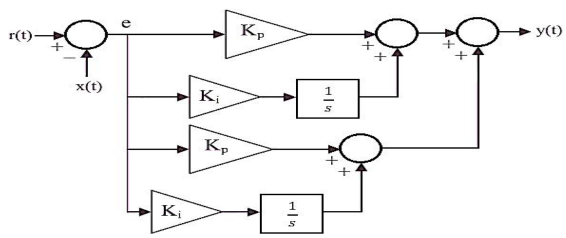

Fig.3. Structure of the double PI controller

4. PSO algorithm and the proposed FOC scheme

The parameters of double PI regulators in Figure 2 can affect the efficiency of the proposed FOC strategy, which leads to restrictions in TPIMD performing. In this paper, the PSO algorithm is employed to calculate the parameters of the proposed double PI controllers to improve the responses. The use of PSO can improve the responses of the control system [34].

PSO algorithm is an optimization method developed by Eberhart and Kennedy in 1995 which was inspired by the social behavior of a flock of birds or fish. In the PSO, the swarm is supposed to have an undoubted size with each particle beginning location at an accidental position in multidimensional space. Each particle is supposed to have two features, i.e. position and velocity.

To sum up, the suggested FOC scheme is a modification of the conventional technique, where the traditional PI regulators are substituted by the optimized double PI regulators. Figure 4 presents the proposed FOC strategy for the IM control.

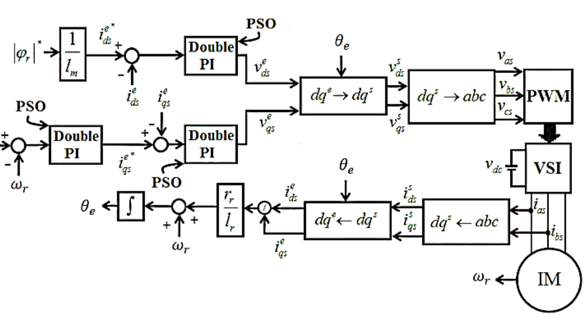

Fig. 4. Proposed FOC strategy for the IM control

As mentioned before, the proposed FOC based on the optimized double PI regulators remains better than the FOC based on the traditional PI regulators in terms of results, particularly steady-state ripple and dynamic response.

5. Simulations

The proposed indirect FOC model based on Figure 4 is tested for a 1.5kW IM in a simulated environment by Matlab/Simulink. Moreover, the result of the conventional FOC model based on the traditional PI regulators and the result of the proposed double PI-based FOC model without PSO are given. The comparison is made in terms of the steady-state ripple error, dynamic response, and etc. of the speed signal.

In simulations, the rotor flux reference is set to 1Wb. The switching frequency is 10kHz and the sampling time is set to 100μs. The IM parameters are given in Table 1.

Table 1. IM parameters

r_s	r_r	l_s, l_r	l_{ls}, l_{lr}	$pole$	j
5.5	4.5	0.3	0.006	4	0.056k
Ω	1Ω	H	H		g.m^2

In testing the optimization technique using the PSO algorithm, there are some steps of testing including testing the cognitive acceleration constant, testing the social acceleration constant, and testing the number of generation values. In this paper, the values of cognitive acceleration constant, social acceleration constant, and number of generation values are 0.8, 0.8, and 40, respectively.

5.1. Comparison of the conventional FOC model based on the traditional PI regulators and the proposed strategy

The result of the conventional FOC model without optimization based on the traditional PI regulators as shown in Figure 1 is presented in Figure 5(a). In addition, the result of the proposed FOC model based on optimized double PI regulators as illustrated in Figure 4 is shown in Figure 5(b). In this figure, the reference speed is set to 35rad/s.

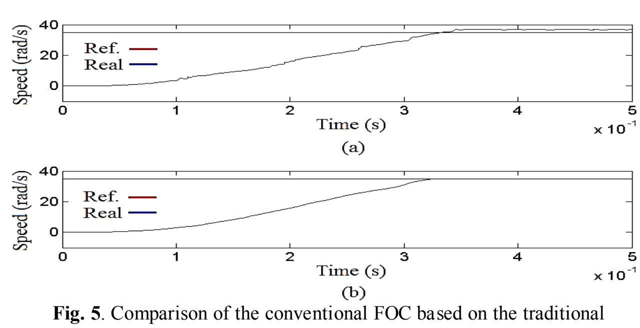

Fig. 5. Comparison of the conventional FOC based on the traditional PI regulators (a) and the proposed strategy (b)

The result of Figure 5(a) shows the conventional FOC is unable to control the IM correctly, while the result of Figure 5(b) displays the superiority of the suggested controller. Based on the result of Figure 5, the proposed FOC strategy in this paper has a faster dynamic response and a lower ripple compared to the conventional FOC based on the traditional PI regulators. In other words, the proposed control method enjoys an accurate response when compared to the conventional control method.

5.2. Comparison of the not-optimized FOC model based on the double PI regulators and the proposed strategy

The result of the not-optimized FOC model based on the double PI regulators (Figure 4 without PSO) is shown in Figure 6(a). Furthermore, the result of the proposed FOC based on Figure 4 is illustrated in Figure 6(b). In this figure, the reference speed is set to 25rad/s.

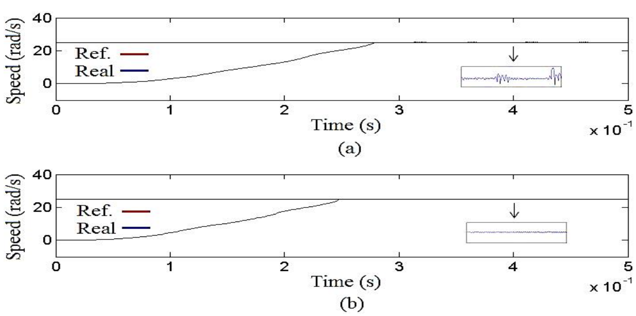

Fig. 6. Comparison of the not-optimized FOC model based on the double PI regulators (a) and the proposed strategy (b)

This figure specifies that the speed response under the introduced FOC system is faster compared to the not-optimized double PI-based FOC model. Also, the steady-state speed ripple of the proposed FOC method is lower compared to the not-optimized double PI-based FOC. It can be observed that the result of the proposed method using the tuning technique with the PSO show a better performance than the not-optimized double PI-based FOC model.

6. Conclusion

This paper presents the simulations of a modified FOC technique for the speed control of a TPIMD using optimized double PI regulators. In this technique, two PI regulators in parallel instead of the conventional PI regulators are used. Furthermore, the PSO approach is presented to tune the parameters of double PI regulators. Matlab simulation results are analyzed during transient and steady-state circumstances. Simulation results show a high performance of the FOC system based on optimized double PI regulators. According to the results gained from simulations, it is obvious that the double PI regulators give a better performance compared to the traditional PI controllers. Moreover, the tuning technique based on the PSO algorithm shows a better performance compared to the trial and error process. The proposed control method in this paper used for TPIMDs. However, it can be extended for two-phase IMs or multi-phase IMs.

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