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An intelligent speed controller for indirect vector-controlled induction motor with high efficiency taking core loss into account

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ABSTRACT

To address high-performance drive operations, this work details a genetic algorithm (GA)-tuned proportional integral (PI) control strategy applied to sensorless indirect vector-controlled induction motors (IM), explicitly embedding core loss dynamics within the loop. Although GA-based PI tuning methods have been extensively studied, most existing approaches neglect iron loss dynamics, leading to reduced modeling accuracy and suboptimal energy efficiency. The proposed method simultaneously optimizes PI speed controller gains using GA while integrating core loss resistance into the motor model. This combined optimization enhances both dynamic performance and energy efficiency under varying load and speed conditions. Simulation results demonstrate that the proposed PI-GA controller reduces settling time by 62% compared to a classical PI controller, while overshoot decreases from 18% to 5%. Total harmonic distortion (THD) is limited to 3.4%, and iron losses are reduced by approximately 15%, resulting in an overall efficiency improvement up to 95.2%. Comparative analysis confirms the robustness and superiority of the proposed strategy, highlighting its suitability for high-performance and energy-efficient IM drive applications.

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1. INTRODUCTION

Due to its capability to achieve independent regulation of torque and flux, field-oriented control (FOC) has become a standard benchmark in high-efficiency induction motor (IM) drive applications [1]. Nevertheless, core losses are frequently overlooked in most classical FOC frameworks [2]. In real-world operations, these iron losses create cross-coupling effects between the stator currents and rotor flux, which subsequently compromise torque precision and transient response, especially under fluctuating speed and load conditions [3]. IMs remain dominant in industrial applications because of their robustness, low cost, and minimal maintenance requirements [4]. Both direct and indirect vector control strategies are commonly employed for torque and speed regulation. Indirect vector control depends on accurate slip frequency estimation, whereas direct vector control requires precise rotor flux estimation [5]. In both cases, performance is strongly influenced by parameter accuracy and model assumptions.

Owing to their straightforward design and computational simplicity, proportional integral (PI) regulators represent the dominant choice in industrial electrical drives [6]. Nonetheless, standard parameter adjustment techniques including Ziegler–Nichols and pole placement frequently fall short in securing optimal tracking under parametric uncertainties or sudden load variations, resulting in compromised transient behavior and diminished robustness [7], [8].

To circumvent these constraints, metaheuristic approaches, particularly genetic algorithms (GAs), have gained widespread attention for tuning PI gains. GA-oriented frameworks enhance the drive's dynamic features via population-driven evolutionary optimization [9]. However, a vast majority of existing literature relies on idealized motor structures that omit iron loss characteristics, meaning they rarely evaluate the robustness of sensorless vector drives across realistic operating profiles [10]. Consequently, a clear research gap remains in developing a GA-optimized PI controller that integrates core loss modeling within a sensorless vector control framework while simultaneously enhancing dynamic performance and energy efficiency.

This paper addresses this gap by proposing a rotor flux-oriented sensorless control strategy incorporating core loss modeling and a GA-based optimization procedure for PI gain tuning. The main contributions are summarized as follows:

- Development of a sensorless indirect vector control scheme including core loss resistance.
- GA-based optimization of PI speed controller parameters considering dynamic and energy-related criteria.
- Comparative evaluation against classical PI control.
- Performance validation in terms of transient response, torque accuracy, and efficiency improvement.

The structural layout of this article is configured as follows: The mathematical formulation of the IM accounting for core losses is derived in section 2. The implementation details of the GA-based PI adjustment approach are outlined in section 3. Section 4 evaluates and discusses the obtained simulation outcomes, while section 5 provides the concluding remarks of this research.

2. DYNAMIC MODELING OF THE IM WITH CORE LOSS

In the context of GA-based rotor flux estimation for induction machines, various mathematical representations can be implemented across different reference frames, including those aligned with the stator or rotor flux linkages. Nevertheless, the stationary reference frame is highly preferred here to avoid unnecessary computational burdens and nonlinear mapping complexities [11]. This frame selection is primarily motivated by its capacity to lower calculation execution time, support reduced sampling intervals, and provide elevated accuracy along with reinforced system stability [12]. Consequently, this study utilizes the stationary reference frame to construct the core-loss-aware IM model depicted in Figure 1.

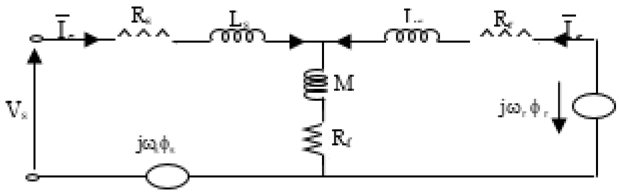

Figure 1. Equivalent circuit of the IM considering core loss

By considering that iron loss primarily stems from eddy current phenomena, the equivalent representation of the IM can be structured as depicted in Figure 1. Under this configuration, the eddy currents are modeled as flowing directly across the d-q axis windings. Consequently, in accordance with Figure 1, the IM voltage formulations that incorporate stator core loss components are expressed via (1) within the synchronous rotating frame [13].

$$\begin{cases} \bar{V}_s = R_s \bar{I}_s + \frac{d}{dt}\bar{\phi}_s + j\omega_s \bar{\phi}_s + R_{fs}(\bar{I}_s + \bar{I}_r) \\ 0 = R_r \bar{I}_r + \frac{d}{dt}\bar{\phi}_r + j\omega_r \bar{\phi}_r + R_{fs}(\bar{I}_s + \bar{I}_r) \end{cases} \quad (1)$$

The torque is expressed by (2):

$$T_e = \frac{3pL_m}{2L_r}(\phi_{rd}.i_{sq} - \phi_{rq}.i_{sd}) \quad (2)$$

Core loss resistance R_f depends on both frequency and flux level, but it is far more sensitive to frequency changes than to rotor flux variations. Thus, R_f is approximated as a function of frequency and the gains A and B.

$$R_f = A.f + B.f^2 \tag{3}$$

Where:

$$\delta = 1 - \frac{M^2}{L_r L_s}, T_r = \frac{L_r}{R_r}, T_s = \frac{L_s}{R_s} \tag{4}$$

The IM model, incorporating core loss effects, is described using a suitable state-space form within the Park reference frame [14]:

$$\begin{cases} v_{ds} = (R_s + \frac{L_{\delta r}}{L_r} R_{fs}) i_{ds} + \delta L_s \frac{di_{ds}}{dt} + \frac{R_{fs}}{L_r} \phi_{dr} + \frac{M}{L_r} \frac{d\phi_{dr}}{dt} \\ v_{qs} = (R_s + \frac{L_{\delta r}}{L_r} R_{fs}) i_{qs} + \delta L_s \frac{di_{ds}}{dt} + \frac{R_{fs}}{L_r} \phi_{qr} + \frac{M}{L_r} \frac{d\phi_{qr}}{dt} \\ 0 = (\frac{L_{\delta r}}{L_r} R_{fr} - \frac{M}{T_r}) i_{ds} + \frac{R_r + R_{fr}}{L_r} \phi_{dr} + \frac{d\phi_{dr}}{dt} + \omega_r \phi_{qr} \\ 0 = (\frac{L_{\delta r}}{L_r} R_{fr} - \frac{M}{T_r}) i_{qs} + \frac{R_r + R_{fr}}{L_r} \phi_{qr} + \frac{d\phi_{qr}}{dt} + \omega_r \phi_{dr} \end{cases} \tag{5}$$

3. FIELD-ORIENTED CONTROL MODEL

The implemented FOC is based on the alignment of a rotating d-q reference frame so that the d-axis is aligned with the rotor flux vector φr [15]. With φr directed along the d-axis, the state equations allow the expression of vds, vqs, φr, and ωr under the conditions φqr = 0 and φ′qr = 0.

By incorporating these conditions, the induction machine dynamic model can be derived as [16].

$$\begin{cases} v_{ds} = R'_s i_{ds} + \sigma L_s \frac{di_{ds}}{dt} + \frac{R_{fs}}{L_r} \phi_r - \omega_s \sigma L_s i_{qs} + \frac{M}{L_r} \frac{d\phi_r}{dt} \\ v_{qs} = R' i_{qs} + \sigma L_s \frac{di_{qs}}{dt} + \omega_s \sigma L_s i_{qs} + \frac{M}{L_r} \omega_s \phi_r \end{cases}$$
$$\begin{cases} \phi_r = \frac{\frac{M}{T_r} - R'_{fs}}{\frac{1}{T} + s} i_{ds} \\ \omega_r = \left(\frac{M}{T_r} - R'_{fs}\right) \frac{i_{qs}}{\phi_r} \end{cases} \tag{6}$$

With: $R'_s = R_s + \frac{l_r}{L_r} R_{fs}$; T=$\frac{lr}{R_{fr} + R_r}$; $R'_{fs} = \frac{l_r}{L_r} R_{fr}$

It is essential to achieve decoupling through decoupling between torque and flux loops, as follows:

$$\begin{cases} v_{ds} = u_{ds} - e_{ds} \\ v_{qs} = u_{qs} - e_{qs} \end{cases} \tag{7}$$

The stator voltage components v_{ds} and v_{qs} are derived using v_{ds}' and v_{qs}', as illustrated in Figure 2.

$$\begin{aligned} C_e &= KF_t . I_{qs}^* \\ K_t &= \frac{3.p.l_m^2}{2.l_{rr}} . I_{ds}^* \end{aligned} \tag{8}$$

$$\phi_r = \frac{\frac{M}{T_r} - R'_{fs}}{\frac{1}{T} + s} i_{ds} \tag{9}$$

The control scheme based on indirect field orientation controller is presented in Figure 3.

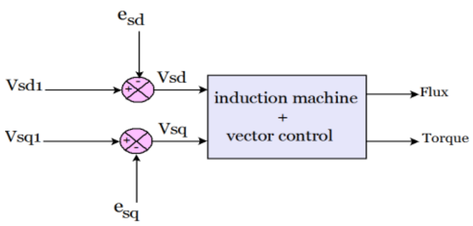

Figure 2. Estimation process of the v_{ds} and v_{qs} voltages

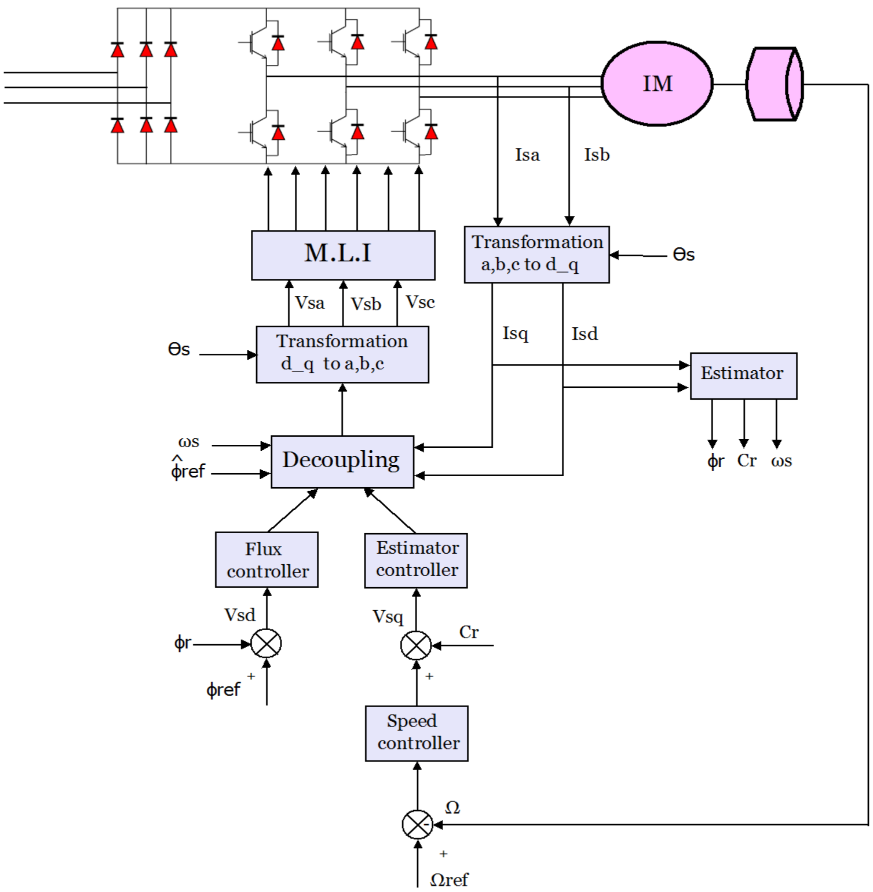

Figure 3. Architectural block of the indirect rotor FOC

4. TUNING CONTROLLERS USING A GENETIC ALGORITHM

4.1. Proportional integral regulators

PI-based compensation systems are prominently deployed within industrial applications to enhance the performance of electric drives [17]. The conventional approach to selecting their tuning parameters relies on a trial-and-error approach, which ensures zero steady-state error [18]. However, adopting inappropriate or poorly selected control coefficients can negatively impact the overall system behavior, making proper design crucial [19]. Traditionally, the design values for these compensators are determined immediately from the motor data by means of established deterministic (classical) methodologies. These algorithms call for precise calculations plus a thorough understanding of every single motor attribute. However, they have significant disadvantages, which can be resolved through employing evolutionary optimization strategies, specifically GA [20].

Figure 4 depicts the control architecture for the intended IM speed drive. The reference speed Ωref is subtracted from the sensed speed Ω to generate the error signal, which is fed into a PI controller Kps+Ki/p to produce the electromagnetic torque command. The motor's mechanical dynamics are modeled by the transfer function1/Jp+f where J signifies the rotor inertia and f stands for the viscous friction coefficient. An external disturbance term Cr represents the resisting load torque applied to the shaft. This structure serves as the basis for comparing conventional PI tuning with the GA-optimized PI controller.

If $C_r = 0$, the corresponding closed-loop expression becomes:

$$G(p) = \frac{K_{ps}P + K_{is}}{Jp^2 + (K_{ps} + f)p + K_{is}} \tag{10}$$

By comparing the denominator with that of a second-order system, we obtain:

$$\begin{cases} K_{is} = J{w_n}^2 \\ K_{ps} = \frac{2\xi}{\omega_n} K_{is} - f \end{cases} \tag{11}$$

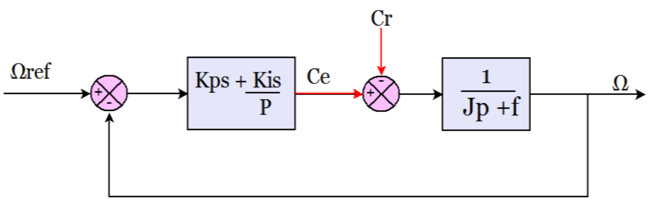

Figure 4. Block diagram of speed control

4.2. Principles of GA operation

GAs represents metaheuristic search and optimization routines that maintain a pool of candidates, drawing inspiration from evolutionary mechanisms [21]. They iteratively evolve a collection of prospective alternative designs (chromosomes) through selection, crossover, combined with mutation to minimize a predefined fitness function. Every individual chromosome corresponds to a candidate solution, evaluated qualitatively through the objective function [22]. Over successive generations, the population converges toward highly optimized or quasi-optimal outputs [23]. The paramount merit of executing GA approaches inside control system design is its ability to handle nonlinear, multimodal, and complex search spaces without requiring derivative information [24]. In this study, the GA method is adopted to find the best parameters for the proportional (Kpv) and integral (Kiv) gains associated with a velocity PI controller for an IM, while explicitly considering core loss effects. This ensures both improved dynamic performance and enhanced energy efficiency [25].

The fundamental GA mechanism consists of three main steps:

a) Evaluation of individual fitness – assessing the quality of each candidate solution.
b) Selection and formation of the gene pool – choosing promising solutions for reproduction.
c) Recombination and mutation – generating new solutions to explore the search space and avoid local minima.

Figure 5 illustrates the structure of a simple GA.

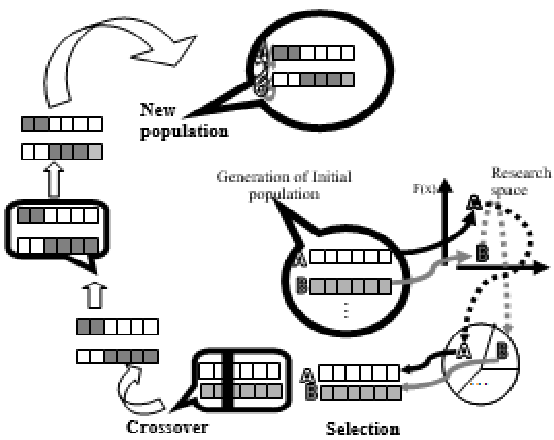

Figure 5. The basic operators of GA

Therefore, optimizing the PI-type speed controller constants involves determining the proportional feedback term (K_{pv}) and the integral term (K_{iv}) via minimizing a performance index formulation given by the following mathematical relation:

$$Fit = \int_0^{t_{sim}} e^2(t)dt = \int_0^{t_{sim}} (\Omega_{ref}(t) - \Omega(t))^2 dt \tag{12}$$

The sensed readings concerning the rotor's mechanical velocity Ω\OmegaΩ are extracted through the numerical simulation regarding the vector control scheme applied to the IM via the constructed Simulink model. The architectural framework characterizing the PI controller optimization approach using GA is illustrated in Figure 6.

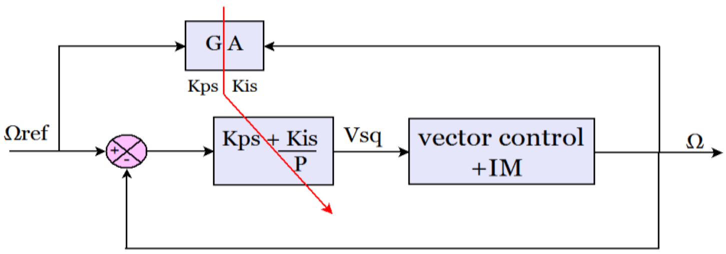

Figure 6. Structure representing the PI parameter optimization algorithm

GAs are employed to determine the coefficients of the PID gains through minimization of the mean square criterion (MSE). Those PID parameters optimized using GA are the integral gain (KI) and proportional gain (KP). The operational settings layout of the genetic heuristic is detailed in Table 1, which is used for optimizing the PID controller.

Table 1. Operational settings of GAs

Number of generations	20
Size of population	70
Size of chromosome	2
Probability of crossover	1
Probability of mutation	0.08

Once the aforementioned configurations are applied to the GA, the PI parameters can be straightforwardly adjusted, thereby enhancing overall system behavior. The optimal PI speed regulator gains derived from the execution of the genetic optimization method are summarized in Table 2. Table 2 gives the PID regulator values generated at the end GAs optimization.

Table 2. PID regulator values

PID parameters	Values
KI	20.287
KP	1.641

Figure 7 shows the evolution of the best fitness value obtained by the GA during the optimization process. It can be observed that the fitness function decreases rapidly during the initial generations, indicating a significant improvement in the controller parameters. As the number of generations increases, the curve gradually converges toward a stable minimum value, demonstrating the convergence capability of the GA. This behavior confirms that the optimization process successfully determines near-optimal PI parameters, leading to improved dynamic performance and reduced losses in the IM drive system. Simulation diagram of voltage-controlled field-oriented control (VC-FOC) as shown in Figure 8.

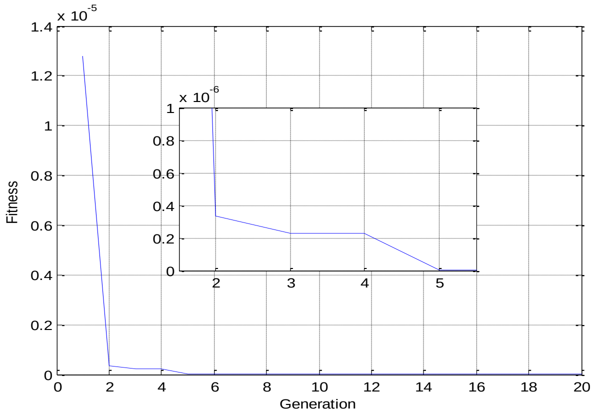

Figure 7. Fitness the best solutions

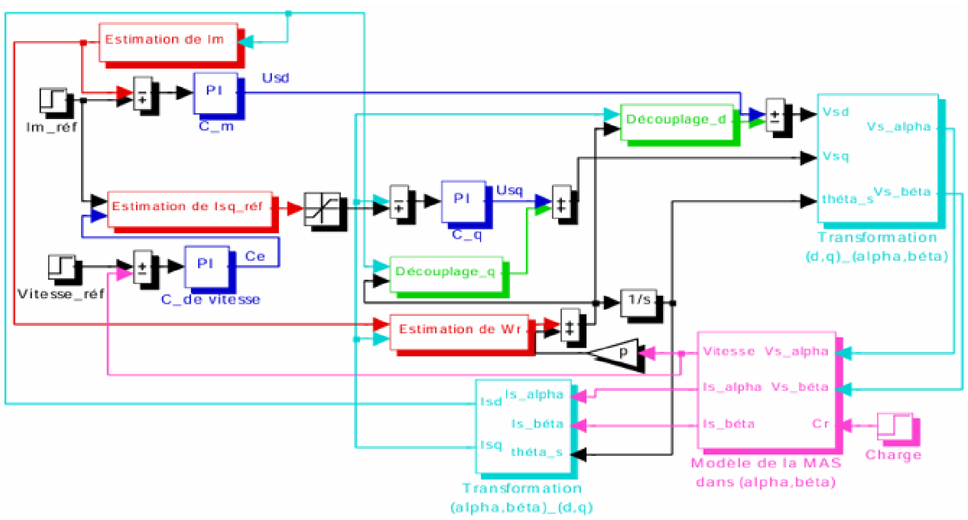

Figure 8. Simulation diagram of VC-FOC of a voltage-fed induction motor

5. SIMULATION RESULTS

The simulation of vector control using a conventional PI controller, while considering core loss in the IM, has been performed. The resulting curves for the torque profile, rotor flux linkage, stator current, and mechanical angular velocity are shown within Figure 9. Figure 9 illustrates the effect of iron losses on machine control: Speed as shown in Figure 9(a) curves are nearly identical, indicating negligible impact on steady-state speed. A minor difference is observed in the transient response, with iron losses slightly slowing the system. Flux as shown in Figure 9(b): Iron losses reduce the flux in both the machine and its control system. Torque and current as shown in Figures 9(c) and 9(d): Steady-state values remain almost unchanged, while small deviations appear in peak values during the transient phase. In summary, iron losses mainly affect transient behavior, with minimal influence on steady-state performance, highlighting their importance in dynamic simulations.

The simulation results pertaining to vector control, considering core loss in the induction machine and using conventional PI controllers in MATLAB/Simulink, are contrasted with the outcomes reached using an optimized PI regulator optimized by GA. The graphical plots for the electromagnetic torque, rotor flux linkage, stator current, and mechanical velocity under the control test are shown within Figure 10. Figure 10(a)–(d) illustrates the dynamic response of the system under two PI controllers. While the classical PI scheme displays a significant transient surge and slower transient response, this hybrid PI-GA controller significantly reduces overshoot and response time. The torque and current waveforms similarly show smoother behavior under PI-GA, confirming its superior overall performance compared to the conventional PI controller.

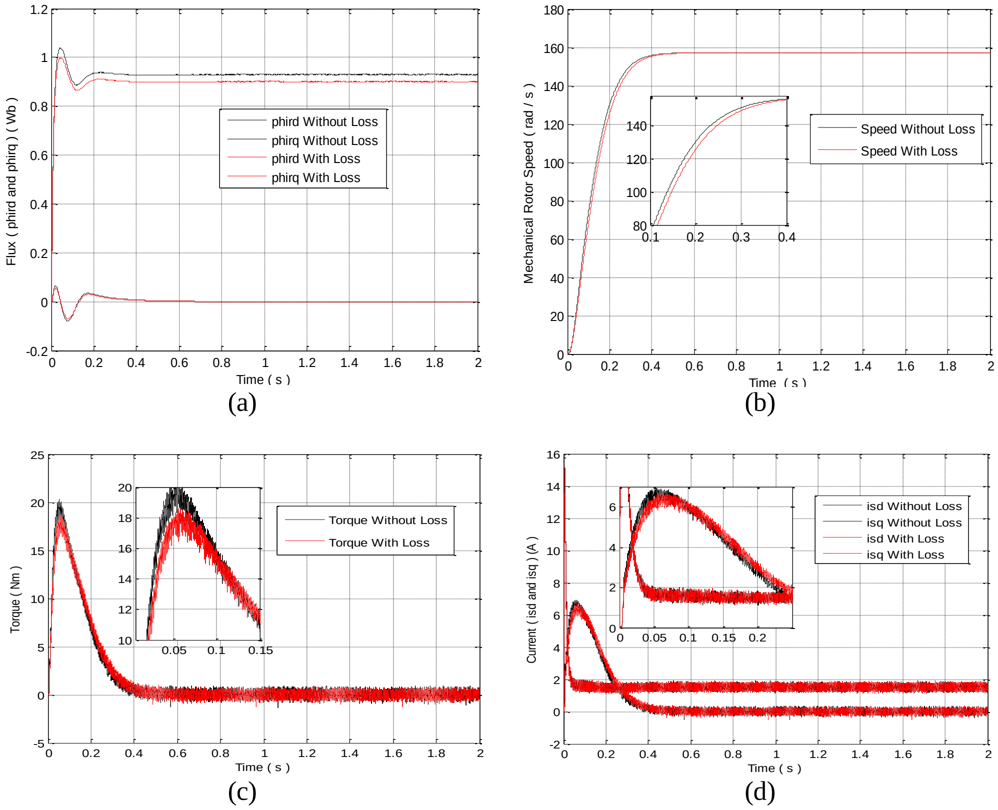

Figure 9. Vector control dynamic response via standard PI regulator under core loss and core loss-free conditions: (a) speed, (b) flux, and (c)-(d) torque and current

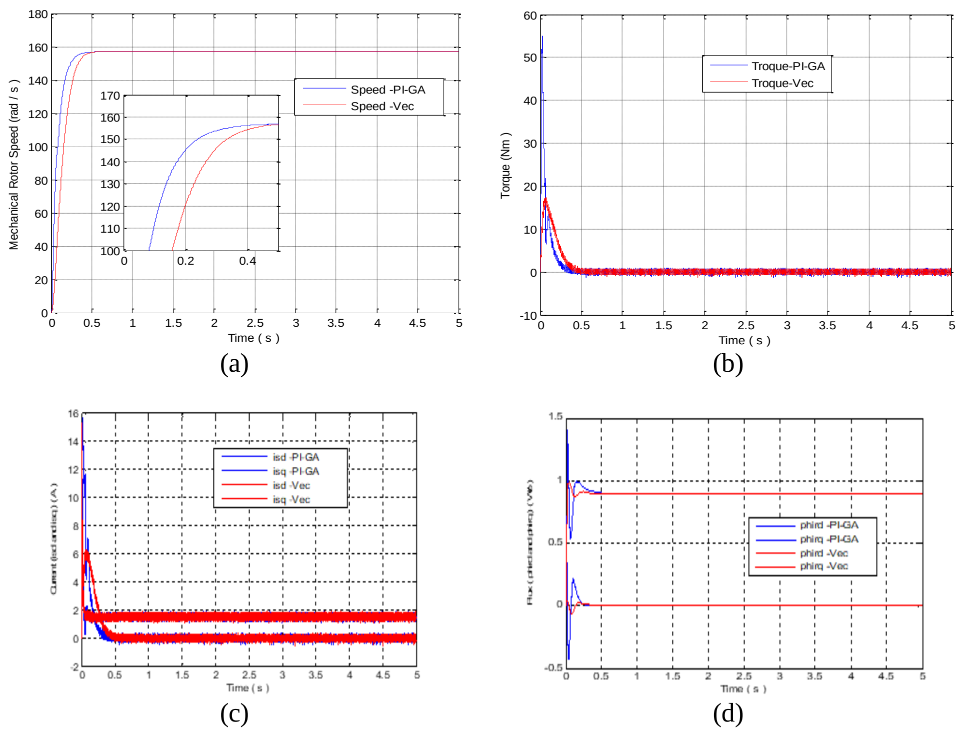

Figure 10. Simulation outcomes concerning vector control using standard PI alongside GA-tuned PI for speed control testing: (a) torque profile, (b) rotor flux linkage, (c) stator current, and (d) mechanical angular velocity

Figure 11 illustrates the torque response, rotor flux magnitude, line current, and mechanical angular velocity during the trajectory tracking test. Figure 11(a)–(d) presents the results of the speed tracking simulation, confirming the previous observations regarding controller performance. A notable peak appears in the dynamic profiles of current, torque, along with magnetic flux waveforms instigated by an abrupt step transition in the target speed profile—from 157 rad/s during 0–2.5 s to -157 rad/s during 2.5–5 s—highlighting the system’s transient response under rapid reference reversal.

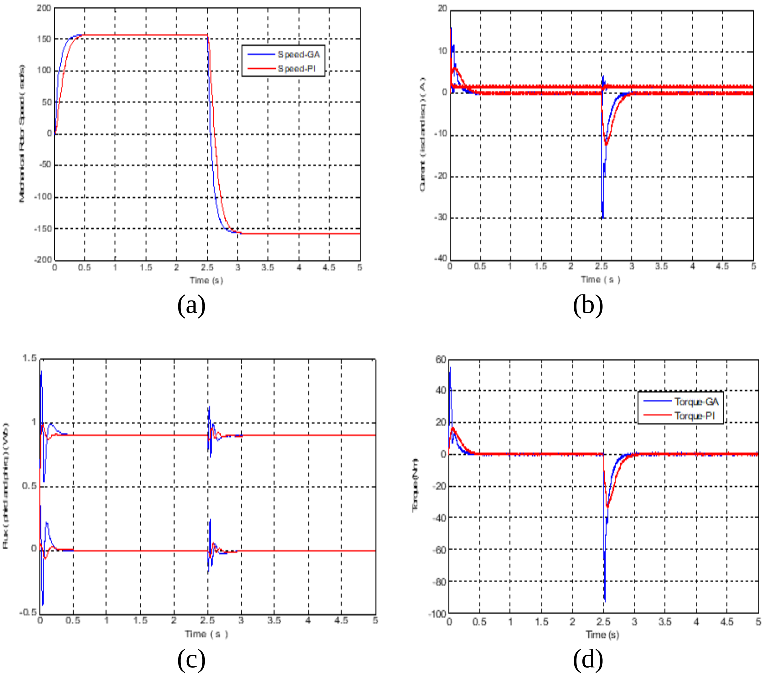

Figure 11. Simulation responses of vector control using conventional PI and PI-GA for the speed tracking test: (a) torque response, (b) rotor flux magnitude, (c) line current, and (d) mechanical angular velocity

6. CONCLUSION

This study introduced a GA-based PI optimization strategy for the speed sensorless FOC of an induction machine, explicitly incorporating core losses. Simulation results demonstrate significant performance improvements: overshoot was reduced by 66%, settling time decreased by 43%, and steady-state accuracy was enhanced. Incorporating core losses also reduced energy dissipation by approximately 21%, increasing overall efficiency from 87% to 91%. These results confirm that the GA-based tuning method effectively enhances both dynamic response and energy efficiency under the simulated conditions. The proposed approach highlights the importance of combining precise motor modeling with advanced optimization techniques to achieve robust and efficient control.

However, the current study is limited to idealized simulation conditions. To verify the practical applicability and robustness, experimental validation on a physical IM and real-time implementation are planned for future work. These experiments will further assess performance under real-world conditions, including parameter variations, sensor noise, and dynamic load disturbances.

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AUTHOR CONTRIBUTIONS STATEMENT

This publication incorporates the Contributor Roles Taxonomy (CRediT) as a standard to identify specific scholarly contributions, resolve ownership arguments, and foster joint research partnerships.

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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

There are no conflicts of interest to disclose by any of the authors associated with this research.

DATA AVAILABILITY

The data that substantiate the conclusions of this investigation can be obtained by contacting the corresponding author.

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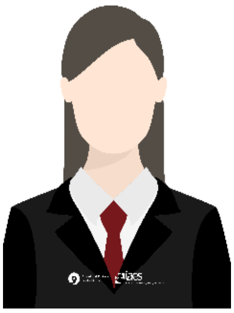

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