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Performance Improvement of PMSM Using PID and GA-PID Controllers

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ABSTRACT- A permanent magnet synchronous motor (PMSM) is widely used in AC servo drives because of its high-power density and high torque for industrial applications, with a wide range of applications. The Permanent Magnet Synchronous Motor is modeled, and simulation is used in MATLAB's Simulink. After representing the motor mathematically with the transfer function according to characteristics suitable for applications similar to the proposed characteristics. This paper proposes using PID to improve the performance of PMSM. Then, the genetic algorithm, an optimization method, is used to adjust the P, I, and D parameters. Simulation tests are conducted for an open and closed system circuit without control and with control. The outcomes are contrasted with conventional PID controller tuning by genetic algorithm. This paper uniquely contributes by integrating GA-based PID tuning with PMSM control, offering improved performance over traditional methods. Unlike prior studies that rely on fixed or manually tuned PID controllers, this work optimizes parameters dynamically, leading to enhanced efficiency and accuracy. The simulation results demonstrate the effectiveness of the designed system in terms of reduced settling time, rise time and peak overshoot. The results are compared with traditional trial and error tuning of the PID controller, which gives the GA-PID controller maximum positive overshot =3.3062, undershoot = 0, Settling time 0.4096 sec and rise time =0.0375 sec.

Keywords: Permanent Magnet Synchronous Motor (PMSM), PID Controller, Genetic-PID controller.

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1. INTRODUCTION

During the previous years, Permanent magnet synchronous motors (PMSM) are synchronous motors that have received great attention in recent years, especially in industrial applications that require high precision, such as car air conditioners, wipers, robotics and personal computers, due to their many advantages, including high energy density, reliability, high efficiency, and ease of achieving high control of the motor performance, and high torque [1-5].

In (PMSM) motors, there is no energy consumption because these motors do not need to be excited and are characterized by their small size compared to conventional DC motors because they do not contain the requirements of the winding field and therefore, their cost is relatively low [6-7]. However, there are many doubts; for example (external load, noise, and friction force) affect the system in terms of performance quality [8-9]. The PID controller has a simple structure and good performance, so it is widely used in various control applications. However, there are problems with the PID controller in that it does not reach the high precision requirements when working in a non-linear system such as (PMSM) by operating the motor in extreme conditions. The performance of the PID controller is related to the parameters of the PID, so scientists have proposed the technique of adjusting and controlling PID parameters, one of the innovative ways to improve PID's ability to resist motor disturbance and improve the dynamic response [10-11]. The performance of the PMSM using PID and fractional order proportional, integral, and derivative (FOPID) by MATLAB/Simulink program. And to obtain effective results for the motor's performance with the FOPID controller, which reduces ripples in torque, current, and response speed [12-13]. Several studies have explored different tuning methods for PMSM controllers. Traditional methods such as Ziegler-Nichols are widely used for PI/PID tuning but often lead to suboptimal performance due to their reliance on fixed tuning rules. In contrast, intelligent optimisation techniques, including Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO), have been introduced to enhance controller tuning. However, these methods have limitations in convergence speed and computational complexity. Recent research has also investigated machine learning-based tuning approaches, such as Reinforcement Learning and Neural Networks. While these methods show promising results, they require extensive training data and computational resources. Conversely, GA provides a balance between optimization efficiency and computational feasibility, making it a suitable choice for PMSM controller tuning. In this research, we present a comparative analysis between GA-based tuning and conventional methods, highlighting its advantages in terms of precision, robustness, and computational efficiency [14-15].

In this work, a genetic algorithm (GA) methodology was used to adjust the outputs of the PID controller optimally. The structure GA-PID has benefits when operating, such as obtaining the desired point, settling time, and having a lower peak value of overshoot. This paper presents a study of a permanent magnet synchronous motor at constant and variable speed by using open and closed loops without a controller and by using two types of controllers, which are represented in the genetic-PID algorithm, the classic PID controller, and a comparison of all these scenarios in order to enhance PMSM performance by achieving the best simulation results. The novelty of this research lies in the application of Genetic Algorithm (GA) for controller tuning, offering a more efficient and optimized approach compared to traditional methods. Unlike classical tuning techniques, which often result in oscillatory responses, GA-based tuning provides a more stable dynamic response. This work explores the effectiveness of GA in improving the control accuracy and robustness of Permanent Magnet Synchronous Motors (PMSM), demonstrating its superiority over conventional methods. The remainder of this paper is organized as follows: *Section 2* illustrates the related modelling of PMSM, including the overall framework transfer function. *Section 3* presents a partial introduction to the PID controller and the proposed Genetic algorithm for tuning it. *Section 4* presents these simulation results compared with state-of-the-art methods and discusses them in *section 5*. *Section 6* concludes the paper.

2. PMSM MATHEMATICAL MODELING

A mathematical model of the PMSM is required to create permanent magnet synchronous motor control. The model typically includes stator flux, voltage, mechanical, and electromagnetic torque equations. The transfer function between the output and the command input, which was determined and is displayed in equations, is the goal of the PMSM mathematical model.

In order to convert the three-phase system to a controllable DC system, filed-oriented control is used, and Clarke/Park transformation is applied. After the transformation of coordinates, the system can be presented in the d-q coordinates. The motor's stator voltages in the d-q frame [16-18]:

$$V_q = R_S i_q + p\lambda_q + W_e \lambda_d$$

$$V_d = R_S i_d + p\lambda_d - W_e \lambda_q$$

$$\lambda_d = L_d i_d + \lambda_{af}$$

$$\lambda_q = L_q i_q$$

Substituting *equations (3)* and *(4)* into *eq. (1)* and *(2)*

$$V_q = R_S i_q + pL_q i_q + W_e(L_d i_d + \lambda_{af})$$

$$V_d = R_S i_d + p(L_d i_d + \lambda_{af}) - W_e L_q i_q$$

The electromagnetic torque for PMSM in the (d-q) axes may be calculated using the equation [15];

$$T_e = \left(\frac{3}{2}\right) P(\lambda_{af} i_q + (L_d - L_q) i_d i_q)$$

Torque equilibrium:

$$JPW_m = T_e - T_L + BW_m$$

The relationship between electrical and mechanical speed depends on the number of pole pairs;

$$W_e = PW_m$$

Where the d, q axis voltages are V_d, V_q; the d, q axis flux linkages are λ_q, λ_d ; and d, q axis currents are i_d, i_q; The number of pole pairs is P, the load torque and electric torque are T_L, T_e and the d,q axis inductance is L_q, L_d. The electric speed is W_e, the mechanical speed is W_m , the moment of inertia is J, and the damping coefficient is B. λ_{af} represents the air gap flux or mutual flux. The open loop model can be derived from *equations (5) - (8)* and, as illustrated in *figure 1*;

$$G_{open}(S) = \frac{W_m(S)}{V_q(S)} = \frac{\frac{3}{2} P \, \lambda_{af}}{(R_s + L_q s)(Js + B) + \frac{3}{2} P^2 \lambda_{af}^2}$$

which is a combination of the two transfer functions

$$G_{electrical}(S) = \frac{1}{L_q s + R_s}$$

$$G_{mechanical}(S) = \frac{\frac{3}{2} P \, \lambda_{af}}{Js + B}$$

Fig. (1) displays the block diagram of the permanent magnet synchronous motor. The electrical and mechanical time constants are $\tau_{elec} = \frac{L_q}{R_s} = 2.5ms$, $\tau_{mech} \approx \frac{J}{P} = 0.67s$. The parameters of PMSM: Kt=6.807 N-m/amp, λaf=1.513 V/rad/sec, Js=0.0337 kg-m2, R=0.12Ω, Lq=0.76 mH, B=0.086, and P=2 (pole pairs). The overall transfer function is shown as:

$$\frac{W_r(S)}{V_q(S)} = \frac{4.705S + 2.2190}{S^3 + 7.504S^2 + 3.36S + 2.702}$$

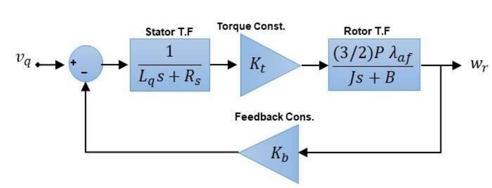

Figure 1. Block diagram of PMSM System

3. PROPOSED GA-PID CONTROLLER SETTING OPTIMAL PARAMETERS

Two different control strategies are investigated. One is a conventional Proportional Integral- Derivative controller (PID)

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that is widely used for all kinds of different control systems. The other strategy investigated uses a genetic algorithm to tune the PID controller. It is a more advanced strategy in terms of user-friendliness and tuning parameters, but it generates an optimized control signal.

3.1. PID Control of PMSM

One of the main features of the PID controller is its simplicity and ease of use, so it is considered the most widely used traditional controller in the industry. The PID control unit has a simple structure consisting of three signals: Kp stands for derivative gain, Ki is for integral gain, and Kd is for proportional gain. The PID controller's mathematical equation is found in *equation (14)* [19-21];

$$PID = K_P * err + K_i * \int err * dt + K_d * \frac{d_{err}}{dt}$$

Where PID is the control signal (input to the control system) and er is the control error defined as the difference between the reference signal and the output of the system, which is intended to be minimized.

$$err = reference\ signal - ouput$$

The proportional part of a PID controller controls the system's speed, where a greater Kp results in a faster response. A P-regulator cannot eliminate the control error by itself but often results in a static error. Therefore, adding an integral that aims to gain the input signal as long as the output is less than the reference is natural. Intuitively, the greater the values of Kp, the faster the rise to the desired output, but one has to bear in mind that the signal is getting more oscillate with a greater amplitude and eventually will lead to instability.

3.2. GA-Based PID Tuning Algorithm

In general, the operators' experimental experience manually adjusts the parameters of PID. However, artificial regulation exhibits randomness. Therefore, providing full play to the robust performance of the PID controller is difficult in practical operations. Genetic algorithms are introduced to adjust the parameters automatically to enhance the robustness of the PID controller further. Genetic algorithms are heuristic group evolution algorithms with few adjustment parameters and intense global search and optimization abilities [22-24]. One such optimization technique is genetic algorithms (GAs). The program starts when the three evolutionary factors—duplication, fusion, and mutation—arrive at the optimal solution. The general process diagram for GA is shown in Fig. (2) [25-26].

The tuning of the PID controllers was made using a genetic algorithm based on a process model and a desired closed-loop transfer function where the time constant of the closed-loop system is a design parameter. The output of the GA-tuned PID controller is significantly superior to that of a conventionally tuned PID regulator. The system's first PID configuration is achieved by varying the critical time and critical gain. This procedure sets the integral Ti time and derivative Td time to zero and infinity, respectively. This PID configuration will be optimized further. The Kp value is adjusted until it approaches the critical Ker when the device's performance fluctuations occur regularly. *Table 1* presents the values of the parameters used to execute the proposed genetic algorithm. The choice of these parameters is also based on many tests of AG performance and convergence.

Table 1. Genetic algorithm parameters

Parameters	Symbol	Value
Population size	np	50
Generation size	ng	100
Coefficient of selection	qs	0.08
Probability of crossover	pc	0.8
Probability of mutation	pm	0.02

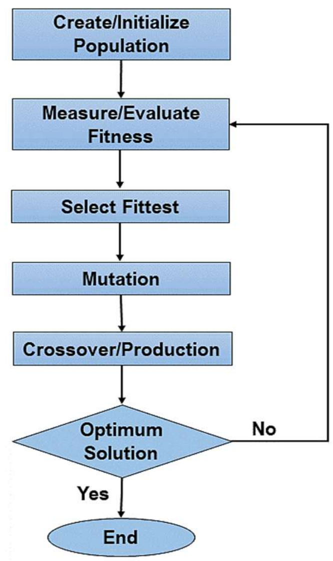


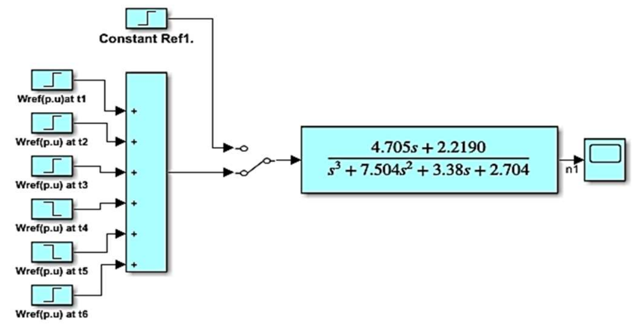
Figure 2. GA's general process diagram

4. SIMULATION RESULTS

This paper presents a study dealing with many cases, including working operations for PMSM with and without a controller for each open loop and closed loop, as well as comparing these results to obtain the best performance characteristics.

4.1. Simulation Models and Results Without Controller

First of all, the PMSM motor, whose transfer function is obtained, is operated with an open loop. The simulation model without a controller at constant and variable speed for open loop T.F of the PMSM system can be shown in *figure 3a*. The response results obtained are given in *figure 3b* and *figure 3c*, respectively. As can be seen from the graph, the PMSM motor cannot provide the speed output as desired. *Figure 4a* shows the simulation models without a controller at closed loop T.F of the PMSM system, and their response results obtained are given in *figure 4b* and *figure 4c*, respectively.



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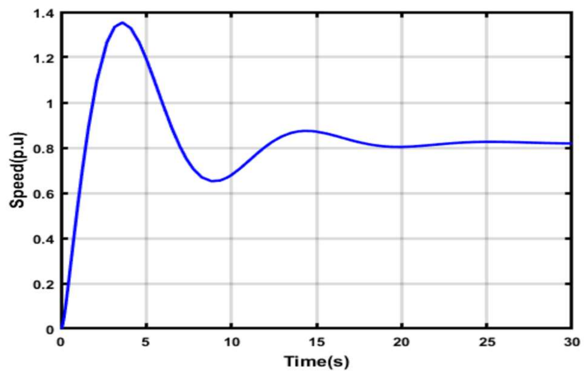

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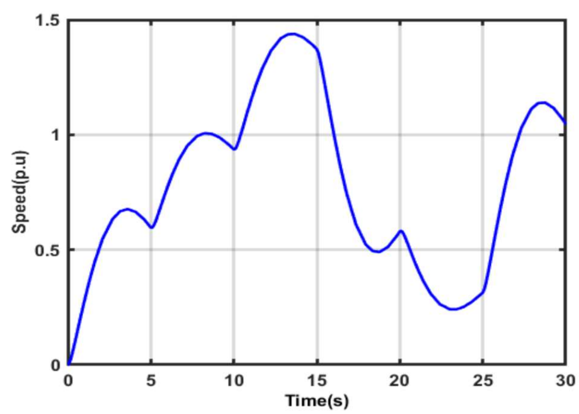
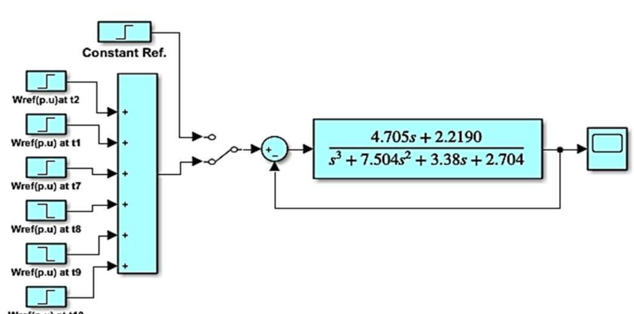


(c)

Figure 3. Open Loop PMSM system without a controller, (a) Simulation model, (b) response at a constant speed, (c) response at variable speed



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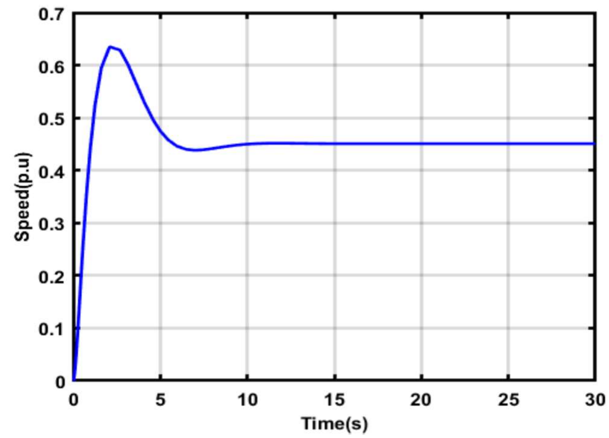

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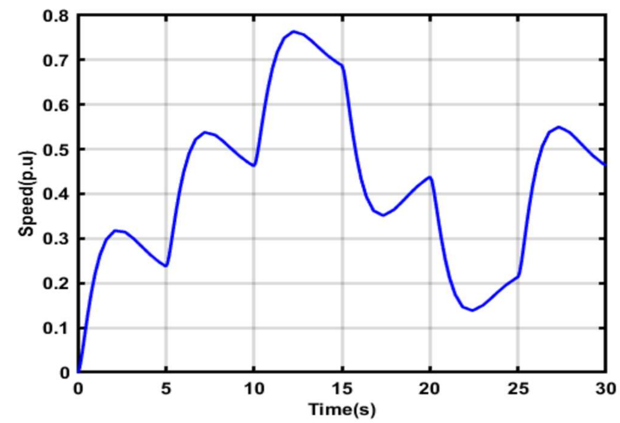
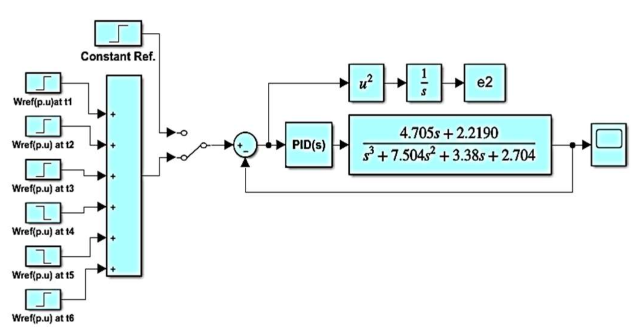


(c)

Figure 4. Closed Loop PMSM system without a controller, (a) Simulation model, (b) response at a constant speed, (c) response at variable speed.

4.2. Simulation Models and Results with Controller

This part deals with simulation models and results using two types of controllers (PID and GA-PID) to develop the workings of PMSM and obtain the best results. The PID's settings are Kp = 3.7516, Ki = 2.6357, and Kd = 0.91961. *Figure 5* shows the simulation model and results of the system for a close-loop at constant and variable speeds using the PID controller.



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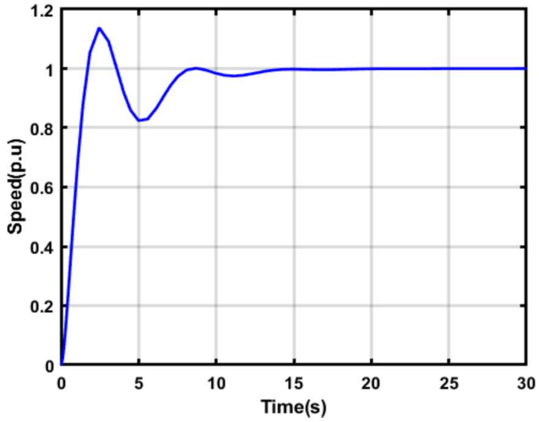

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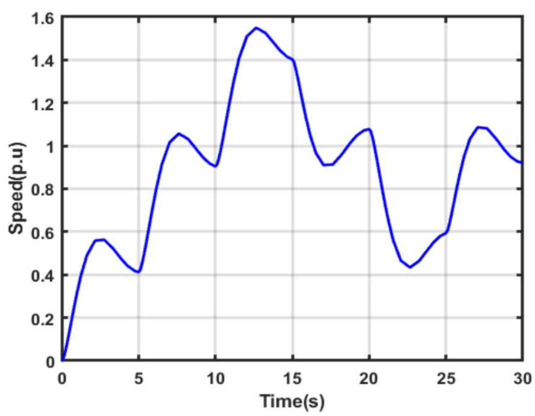
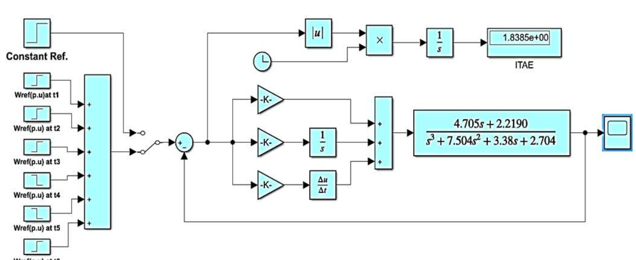


(c)

Figure 5. PMSM system with PID controller, (a) Simulation model, (b) response at a constant speed, (c) response at variable speed.

In order to enhance PMSM's performance and operational efficiency, this section suggests utilizing a Genetic-PID controller to generate the simulation model and results at both constant and variable speeds, as seen in *figure 6*. Step response and performance of Open loop, Closed loop without controller, PID and GA-PID controllers include max overshoot, rise time, settling time, and steady-state error can be shown in *table 2*, and the values of parameters (KP, Kd, Ki) for PID and GA- PID Controller that can be shown in *table 3*. By comparing the simulation results above, it becomes clear that in the closed loop case, the results were improved over the open loop case, and the results were also improved even more when using the PID controller.



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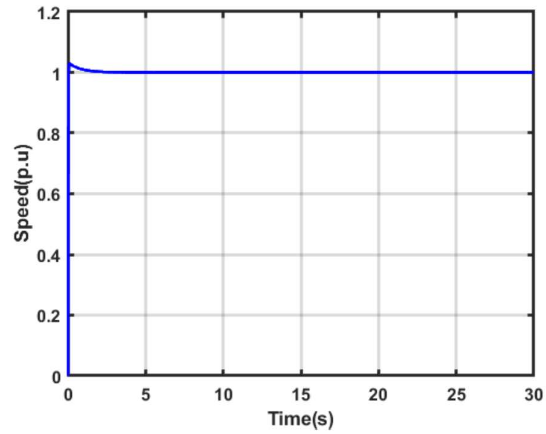

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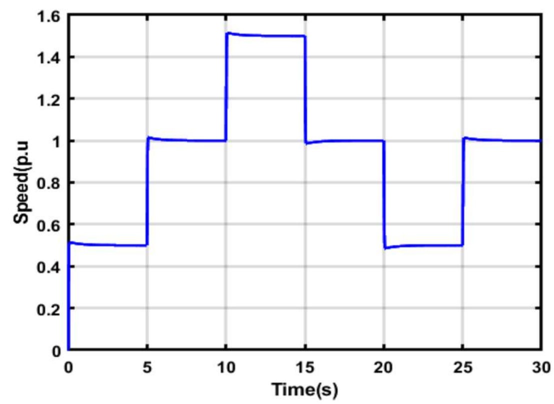

(c)

Figure 6. PMSM system with GA-PID controller, (a) Simulation model, (b) response at a constant speed, (c) response at variable speed.

Table 2. Simulation results of PMSM in different cases

Controls type	Rise Time (s)	Settling time (s)	max overshoot (%)	steady-state error
Without controller (Open-loop)	1.0821	20.2943	64.8653	0.821
Without controller (closed-loop)	0.7212	8.0589	41.6264	0.451
PID	0.6897	6.8107	5.3021	0
GA-PID	0.0375	0.4096	3.3062	0

Table 3. Parameters of PID and GA-PID Controllers

Parameters	PID Controller	GA-PID controller
Kp	3.7516	793.989
Ki	2.6357	959.733
Kd	0.91961	17.813

As for the last case, which is represented by using the GA-PID controller, which is better than all of the above solutions which led to obtaining the best simulation results by reducing overshoot to the lowest possible value and reaching PMSM to steady state in the least time and obtaining a smooth curve in order to improve the performance and operating characteristics of PMSM. The system performance comparison is shown in *table 4*. The statistical analysis confirms the effectiveness of the GA-PID controller, as shown in *table 5*.

Table 4. System Performance Comparison

Performance Metric	Open Loop	Closed Loop (PID)	Closed Loop (GA-PID)
Stability	Poor	Improved	Best
Over shoot	High	Moderate	Low
Response Time	Slow	Faster	Fastest
Steady State Error	Present	Reduced	Eliminated

Table 5. Statistical Analysis Values

Metric	Mean	Standard Deviation	Confidence Interval (CI)
Settling Time(s)	0.36	0.015	[0.34,0.38]
Rise Time(s)	0.12	0.012	[0.11,0.14]
Over Shoot (%)	5.2	0.15	[5.0,5.4]

5. DISCUSSION

By comparing the simulation results above, it becomes clear that in the closed loop case, the results were improved over the open loop case, and the results were also improved even more when using the PID controller. The results demonstrate that GA-PID tuning significantly enhances PMSM performance under both constant and variable speed conditions. The optimization process allowed for improved control accuracy, reducing overshoot, settling time, and steady-state error. By comparing different control approaches, it was evident that the GA-PID controller provided faster response times and improved system stability compared to conventional PID tuning. Under variable speed conditions, the controller effectively adapted to changes, maintaining a smooth response and minimizing fluctuations. The closed-loop system with GA-PID achieved better performance than both the open-loop and standard PID configurations, highlighting the advantages of using evolutionary optimization for controller tuning. The findings confirm that GA tuning enhances system adaptability across different operating speeds, ensuring reliable and stable operation.

6. CONCLUSION

To strengthen our conclusions, we conducted statistical analysis on the performance metrics of the PMSM system. We evaluated the mean, standard deviation, and confidence intervals for key parameters such as settling time, rise time, and overshoot. The statistical analysis confirms the effectiveness of the GA-PID controller, showing an average reduction in settling time, rise time and overshoot. Performance metrics such as steady-state error and peak overshoot were assessed, showing significant improvements compared to traditional PID controllers, as shown in *table 5*. The results confirm the robustness of the proposed approach with statistical significance. Future work could explore additional optimization techniques or real-time implementations to further validate the effectiveness of GA-based tuning in PMSM control.

A simulation of an electric motor (PMSM) was carried out with a mathematical model of the conversion function with four cases, and each of the two cases controls the speed of the motor and its operation as an open circuit. The other closed with and without the proposed control units to verify the operating preference. The possibility of improving performance and comparison proved through the results that tuning the traditional controller by adopting the genetic algorithm gave results. It is better in terms of the speed of reaching the steady state, as well as the time of ascent and the over and under excesses of the required average value, as detailed previously within the research paragraphs.

Author Contributions: Helen J. Jawad: Conceptualization, methodology, and software design. **Ekhlas M. Thajeel:** Data curation, written original draft preparation, interim review, and editing. **Hadeel N. Abdullah:** Visualisation, investigation, validation, written review, and finalisation. All authors have read and agreed to the submitted version of the manuscript.

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