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RESEARCH ARTICLE

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DESIGN OF PARTICLE SWARM OPTIMIZATION-BASED PID CONTROLLER FOR HIGH-PERFORMANCE PMSM SPEED CONTROL

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ABSTRACT

The present study shares an appropriate technique for regulating the speed of a Permanent Magnet Synchronous Motor (PMSM) drive system using a PID controller. This approach maintains the main architecture of the PID controller while significantly improving its performance compared to previous controllers. The resulting controller offers great resilience to changes in PMMS settings, fast and precise responses, and necessary noise rejection. Testing revealed that for accuracy, parametric variation, and load torque disturbances the suggested system performs best with proportional gain of 0.0029, integral gain of 0.65, and derivative gain of 0.0012.

Moreover, we utilized Particle Swarm Optimization (PSO) to improve the parameters of the PID controller, leading to significant performance improvements under various scenarios. The proposed method offers simplicity and ease of real-time implementation while providing stability and outstanding efficacy in achieving optimal performance.

I. INTRODUCTION

The remarkable progress in electric motor technology has increased the need for high-efficiency motor control systems. The Permanent Magnet Synchronous Motor (PMSM) is widely used among motor types due to its high power density, excellent efficiency, and precise torque control [1]. The PMSM is now widely regarded as a key drive technology in industrial applications such as robots, electric vehicles, and aircraft. Still, achieving perfect results in Permanent Magnet Synchronous Motor (PMSM) operation remains difficult, especially with relation to energy efficiency, torque ripple reduction, and speed control.

Permanent Magnet Synchronous Motors (PMSMs) are often regulated with traditional Proportional-Integral-Derivative (PID) controllers. They need to be enhanced, nevertheless, to function efficiently with load fluctuations, nonlinearities, and outside disturbances. [2].

However, it is still difficult to precisely and reliably manage PMSM speed, especially when there are external disturbances and parameter deviations. The growing need for dependable, high-performance motor drives in contemporary applications like robotics, industrial automation, and electric cars has led to a great deal of research into the management of PMSMs [3].

The simplicity, ease of implementation, and adequate performance of traditional control techniques—like proportional-integral-derivative (PID) controllers—make them popular in many real-world systems. That being said, the proper choice of a PID controller's gain parameters is crucial to its performance, with performance including overshoot, lengthy settling times, and steady-state error that can be caused by improper tuning. Particularly for nonlinear and time-varying systems like PMSMs, traditional PID tuning techniques like Ziegler-Nichols and trial-and-error procedures frequently fail to achieve optimal performance.

Advanced optimization methods have been investigated to improve and automate the PID tuning procedure in order to overcome this constraint. Particle Swarm Optimization (PSO) is a potential metaheuristic technique among these algorithms because of its fast convergence features, global search capabilities, and ease of use [4], [5].

For instance, Field-oriented control (FOC) [3] is a common approach of controlling AC motors. FOC separates torque and flux by changing stationary phase currents into a rotating d-q frame. The FOC approach simplifies the AC motor control challenge to a DC motor control problem. FOC is not without its potential failures, significant shortcomings, and restrictions such as relies on accurate motor parameters, variations due to temperature changes and magnetic saturation. Furthermore, FOC needs to know the rotor location. Incorrect commutation due to sensor damage or noise can result in instability and torque ripple [6].

Furthermore, DTC was originally introduced by I. Takahashi and T. Noguchi in (Takahashi and Noguchi (1986)) as a powerful systematic design solution for improving the dynamic torque and speed response without using Park transformation and PI controller. DTC achieves direct control of flux and torque, while it also enjoys design simplicity, and less dependence on parameter values. However, DTC may cause time varying switching frequency, and can also be prone to introduce relatively large torque and flux ripples, since the inverter keeps the same switching sequence as long as the flux and torque hysteresis controller outputs remains the same.[7], [8].

Moreover, many advanced control methods have been proposed to control PMSM including: Model Predictive Control [9], Sliding Mode Control [10], Sliding Mode Control and Artificial Neural Networks [11]. The combined use of predictive algorithms and intelligent control is anticipated to propel additional developments in PMSM control, while enhanced AI and optimization strategies are boosting performance and adaptability. Kumar and Palani (2020) achieved reliable performance under load variation by using a modified PSO method for adaptive PID tuning in electric car applications [12].

Furthermore, utilized a modified PSO technique for adaptive PID tuning in electric vehicle applications, resulting in dependable performance under load variation. For PID tuning in PMSM control, [13] suggested a hybrid GA-PSO algorithm, which produced better optimization accuracy and greater adaptability. In [14] combined fuzzy logic with PSO to produce a fuzzy-PID controller with optimized gains, which provided smoother and more dependable performance.

In this context, the present study proposes a PSO-based PID controller specifically tailored for PMSM speed control with the aim of optimizing both transient and steady-state responses. The controller is evaluated using standard performance indices (e.g., IAE, ITAE) and tested under varying load and disturbance conditions using MATLAB/Simulink, contributing to the growing body of research on intelligent motor control systems.

The rest of this paper is organized as follows: Section 2 presents the mathematical modeling of the PMSM and the control strategy. Section 3 describes the design and implementation of the PSO algorithm for PID tuning. Section 4 discusses the simulation results and performance evaluation. Finally, Section 5 concludes the paper with future directions.

II. THEORETICAL REFERENCE

II.1 Mathematical Modeling of the PMSM:

A mathematical model in the rotating dq-reference frame provides an accurate description of the dynamic behavior of a Permanent Magnet Synchronous Motor (PMSM). By transforming three-phase time-varying values into two steady-state quantities, this transformation streamlines the analysis and enables decoupled torque and flux control, much like in DC machines as shown in figure1[5][6].

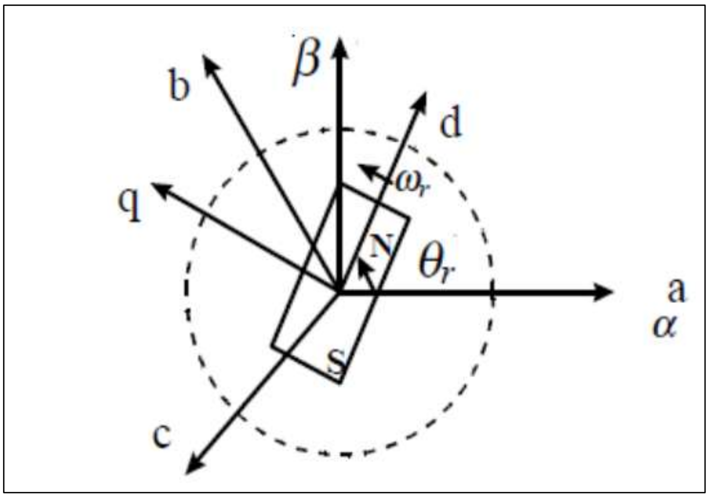

Figure 1: The stationary and synchronous frame.
Source: Authors, (2025).

In PMSM, the d-q axis reference frame (rotating frame of reference) is commonly used for modeling because it simplifies the dynamic equations. The following are the core equations [7]:

Voltage Equations in d-q Frame:

d-axis voltage: $\mathrm{vd} = \mathrm{Ri_d} + \mathrm{L}(\frac{\mathrm{di_d}}{\mathrm{dt}} - \mathrm{w.iq})$……..………… (1)

q-axis voltage: $\mathrm{vq} = \mathrm{Ri_q} + \mathrm{L}\left(\frac{\mathrm{di_q}}{\mathrm{dt}} + \mathrm{w.id}\right) + \mathrm{w}\lambda_m$ …….(2)

Where: v_d & v_q are the voltage components along the d-q axes, i_d & i_q are the current components along the d-q axes, L is the Inductance, R is the Resistance, w is the Angular Speed of the motor, λ_m is the permanent magnet flux linkage (Wb) and L_m is the Magnetizing Inductance.

The electromagnetic torque given by the PMSM is:

$$T = \frac{3}{2} P(\lambda_m i_q + (L - L_m) i_d i_q) \text{……… (3)}$$

Where: T is the torque, λ_m is the flux leakage of the permanent magnet and P is the number of poles in the motor. Also, The mechanical dynamic of the PMSM can be module as:

$$\frac{dw}{dt} = \frac{T_e - T_l}{j} \text{ ……………………………… (4)}$$

Where: w is the angular speed, T_e is the electro-magnetic torque, T_l is the load torque and j moment of inertia.

II.2 CONTROL STRATEGY USING PSO AND PID:

The presented work employs a Particle Swarm Optimization (PSO) in order to -tunning a PID controller to automatically optimize the PID settings for improved performance. Motor control systems have used a traditional PID tuning techniques, including as Ziegler-Nichols, Cohen-Coon, and trial-and-error methods. These techniques might not always provide the best results because they frequently rely on linear approximations. Additionally, they are usually unavailable and do not adjust to changes in parameters or outside interruptions. Researchers are increasingly using intelligence and optimization-based techniques to get beyond the drawbacks of conventional tuning methods. To adjust PID parameters for a variety of applications, metaheuristic algorithms including Genetic Algorithms (GA), Artificial Bee Colony (ABC), Differential Evolution (DE), and Particle Swarm Optimization (PSO) have been popular in recent years. PSO has become well-known among them because of its powerful worldwide search capabilities, simplicity of use, and computing economy.

The Proportional-Integral-Derivative (PID) controller is a common way to control things, but it needs to be fine-tuned to work well and stay stable, especially when loads change and the system isn't linear [8]. We use the Particle Swarm Optimization (PSO) algorithm to quickly optimize the PID's parameters for enhanced efficiency [15].

The standard PID control law is defined as:

$$u(t) = K_P e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \text{ ………. (5)}$$

Where $e(t)$ is the error (difference between the reference and actual values). K_p, K_i, K_d are the proportional, integral and derivative respectively. The proportional, integral, and derivative components of the PID controller then generate a control signal that modifies the PWM duty cycle. By adjusting the PWM inputs, the controller effectively controls the motor's torque and current, thereby matching the motor speed with the reference value. This direct control of the PWM signal allows precise and dynamic speed regulation, allowing quick responses to changes in load or desired

II.3 PSO - PID PARAMETER OPTIMIZING:

Particles Swarm Optimization (PSO) is an optimization method that was created in 1995 by Drs. Eberhart and Kennedy and was motivated by the social behavior of fish schools and flocks of birds. PSO, an optimization technique inspired by nature, enhances the controller's adaptability by minimizing overshoot, accelerating response time, and enhancing system stability. The social behavior of fish schools or flocks of birds, in which a population of particles searches the search space for the best answer, serves as the model for PSO. Based on both its own and its neighbors' experiences, each particle modifies its course.

The Integral of Absolute Error (IAE), Integral of Time-weighted Absolute Error (ITAE), or Integral of Squared Error (ISE) are examples of performance criteria that can be efficiently minimized by using PSO in PID tuning [17]-[16]. The PSO concept uses a swarm of agents, or particles, to move around the search space in pursuit of the optimal answer. Every particle in the search area modifies its "flying" based on both its own and other particles' flying experiences; the best are referred to as "pbest." Additionally, individual particles know the group's values the best (gbest). To adjust their location, each agent uses the data pertaining to their current position (x, y), current velocity (vx, vy), and the distance between their current position and the best group. Equations (18) and (19) below alter each agent's position and velocity.peed while maintaining system stability and performance [9].

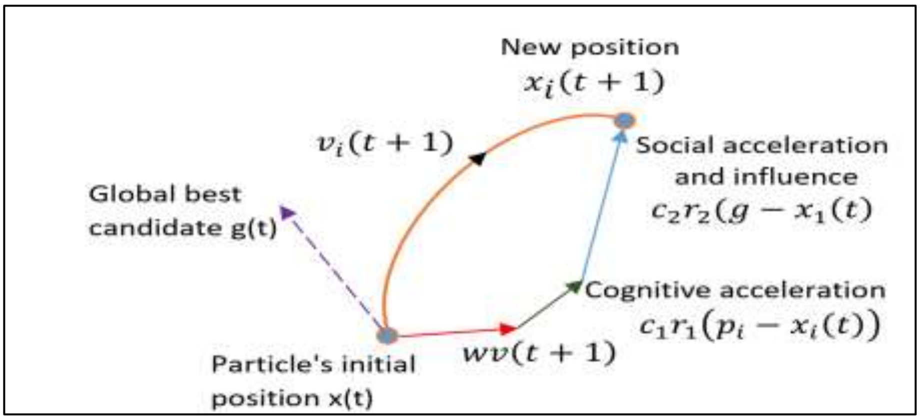

Figure 2: Primary Procedures of PSO.
Source: Authors, (2025).

The update method is as follows [17]:

Position Update:

$$x_i(t+1) = x_i(t) + v_i(t+1) \text{ …………….. (6)}$$

Velocity Update:

$$v_i(t+1) = wv_i(t) + c_1 r_1 \big(p_i - x_i(t)\big) + c_2 r_2 (g - x_1(t)) \quad (7)$$

Where:

- x_i is the position of the particle (representing the PID parameters).
- v_i is the velocity of the particle.
- w is the inertia weight.
- c_1 and c_2 are the cognitive and social coefficients, respectively.
- r_1 and r_2 are random numbers between the [0, 1] range.
- p_i is the particle's personal best position.
- g is the global best location the swarm discovered.

Usually the Integral of Time-weighted Absolute Error (ITAE) or Integral of Squared Error (ISE), the fitness function is defined as the error in the system evaluated using the current PID settings [16]-[17].

$$Fitness = \int_0^T |e(t)|^p dt \text{ ………………… (8)}$$

Where p is a constant typically chosen as 2 for ISE (Integral of Squared Error).

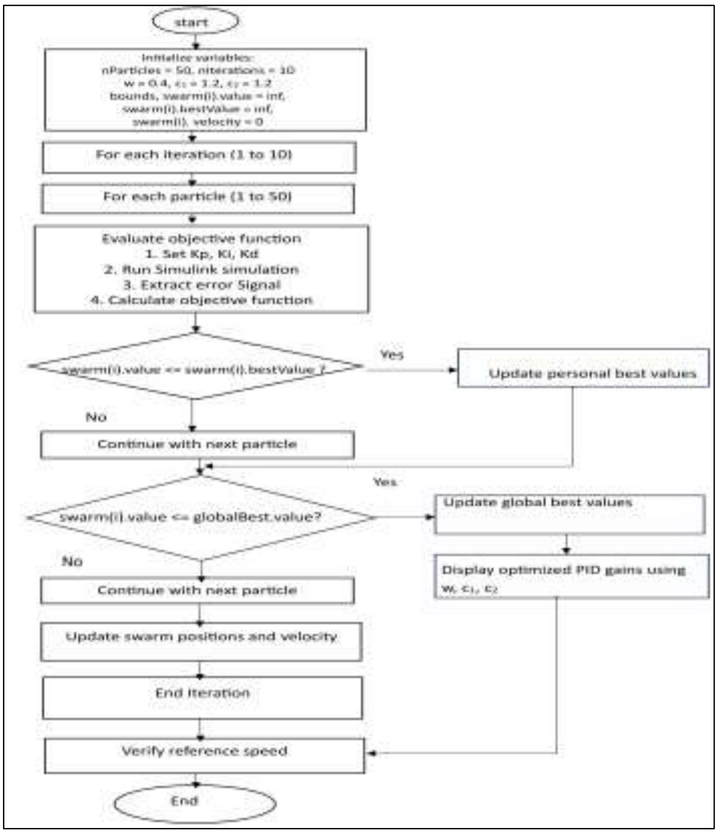

Figure 3: Particle Swarm Optimization (PSO) flowchar.
Source: Authors, (2025).

The flowchart represents the Particle Swarm Optimization (PSO) algorithm applied to optimize the PID parameters [18]. Initially, the necessary variables, including the number of particles (50), iterations (10), and constants w, c1, and c2, are defined. The swarm (population of particles) is initialized, with each particle having an initial value (swarm(i).value), best value (swarm(i).bestValue), and velocity (swarm(i).velocity). For each iteration, each particle evaluates the objective function by calculating its performance based on the PID values. The algorithm compares the particle's value with its personal best (swarm(i).bestValue) and the global best (globalBest.value). If a better value is found, the particle's personal best and the global best are updated. The particle's position and velocity are then updated using the PSO velocity update equation, which incorporates the inertia weight (w), personal attraction constant (c1), and global attraction constant (c2). The process repeats for all particles and iterations. Once the optimization completes, the best PID parameters are displayed, and the reference speed is verified

II.4 PULSE WIDTH MODULATION (PWM):

The PWM technique is applied to control the voltage and current fed to the PMSM. PWM ensures efficient motor performance and enables precise control of speed and torque by adjusting the duty cycle of the switching signals [19], [20]. Pulse Width Modulation (PWM) is also used to control the voltage and current data going to the motor, which gives precise control over how the PMSM works. Using PSO-optimized PID control along with PWM switching methods makes the system more efficient, cuts down on power losses, and boosts motor performance under a range of load conditions. [3] [4]. This study looks at how PSO-optimized PID controls and PWM signal handling affect the performance of PMSMs, focusing on important factors like controlling speed, lowering torque ripple, saving power, and making the system strong. The study's goal is to make it easier to make high-performance motor control systems that use less energy by combining smart optimization and advanced switching methods.

III. MATERIALS AND METHODS

Different load conditions were applied to the system. We operated the Permanent Magnet Synchronous Motor (PMSM) at a reference speed of 750 rpm under the specified circumstances: Case 1 features an open-loop state without a controller, Case 2 has a closed-loop condition with a proportional-integral-derivative controller, Case 3 uses a PSO-PID controller, and Case 4 features a PSO-PID controller with a two-step load.

Table 1: PMSM SPECIFICATION.

Stator Phase Resistance (Rs)	0.0485 ohm
Stator Phase Inductance (Ls)	0.000395 H
Voltage Constant	300[Vrms/krpm]
Moment of Inertia	0.02 J(kg.m^2)
Rated Speed	750 r.p.m

Source: Authors, (2025).

IV. RESULTS AND DISCUSSIONS

A block diagram of a PSO-tuned PID control system for PMSM speed regulation is displayed in Figure (3) . By modifying the PID gains in response to feedback on system performance, the PSO algorithm minimizes a specified objective function.

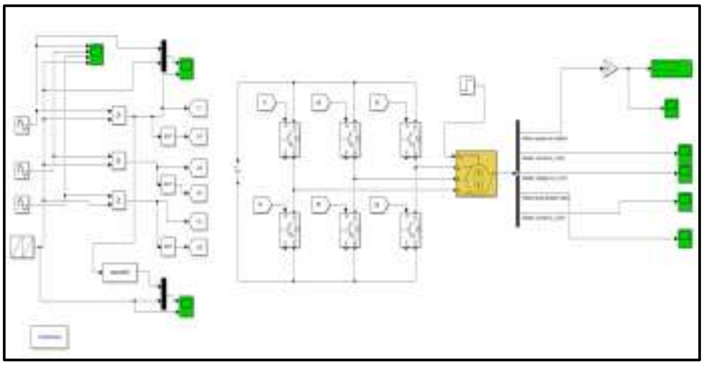

Figure 4: PMSM drive system without controller (open loop)
Source: Authors, (2025).

The diagram represents a Simulink model of a Permanent Magnet Synchronous Motor (PMSM), designed to control and monitor the motor's performance. The system receives control signals such as voltage and current, which are processed through logical gates to regulate the motor's speed and torque. The motor model simulates the behavior of the PMSM, producing outputs like torque, rotor speed, and current in both the stator and rotor. Key parameters such as rotor speed, stator current, stator voltage, rotor angle, and rotor current are measured to evaluate the motor's efficiency and performance. This model helps in simulating and analyzing motor operation, ensuring optimal control and monitoring of the system in applications like electric vehicles and industrial machinery.

The following figures represent the speed and torque profiles of the PMSM under open-loop control, where no feedback control is applied to adjust the motor's performance. In an open-loop system, the motor operates based on predefined input signals without any real-time adjustments. As a result, the speed and torque may exhibit fluctuations and may not maintain optimal performance, especially under varying load conditions. These profiles highlight the behavior of the motor when it is running in an uncontrolled open-loop configuration, providing a basis for comparison with closed-loop controlled systems, where feedback mechanisms are used to stabilize and optimize

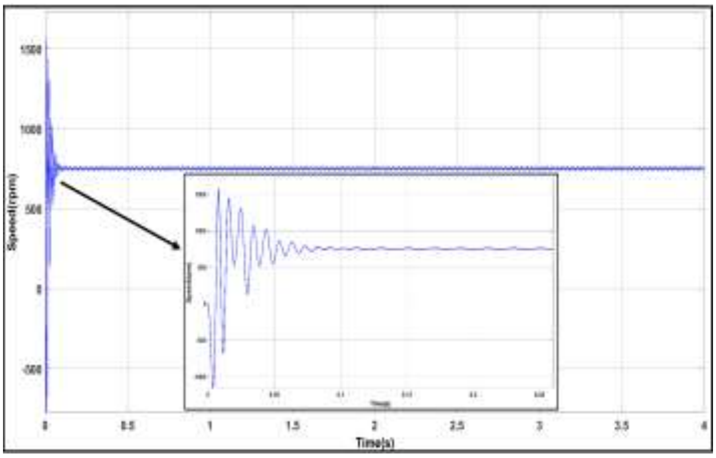

Figure 5: Speed response at open-loop condition.
Source: Authors, (2025).

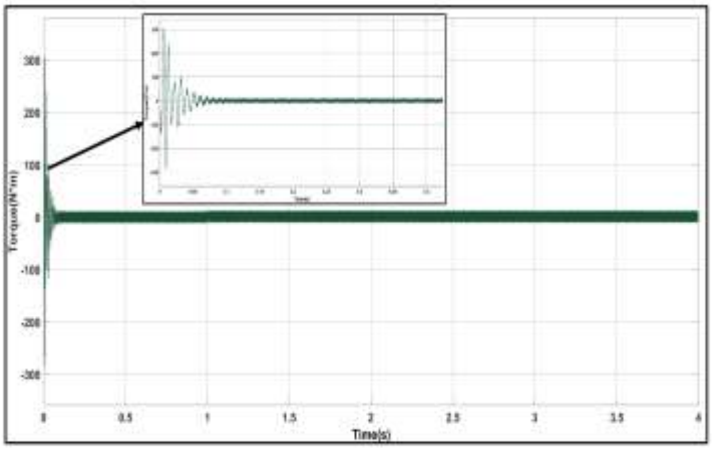

Figure 6: Torque response at open-loop condition.
Source: Authors, (2025).

Figure (7) represents a closed-loop control system for a Permanent Magnet Synchronous Motor (PMSM), where PID control is applied to regulate the motor's performance. The system consists of a PID controller that takes feedback from the motor's performance parameters, such as speed and torque, to adjust the input signals accordingly. The feedback loop ensures that any deviations from the desired motor speed or torque are corrected in real time.

The motor operates under this closed-loop configuration, where the PID controller adjusts the control signals to maintain stable and optimal motor operation, improving performance and reducing the effects of external disturbances or load variations. This system provides enhanced control compared to open-loop configurations, ensuring the motor's speed and torque remain at desired levels throughout operation.

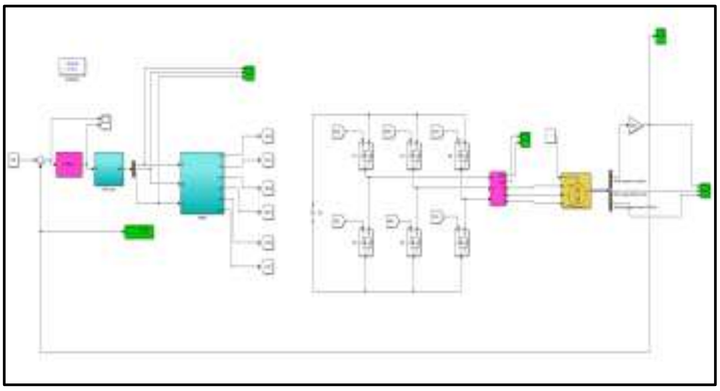

Figure 7: PMSM drive system with PID Controller.
Source: Authors, (2025).

In Fig(7)and Fig(8) respectivly, the speed and torque waveforms of the PMSM are shown under closed-loop PID control. Compared to the open-loop system, where the motor operates without feedback, the closed-loop control significantly improves performance. The speed waveform becomes much more stable and smooth as the PID controller adjusts the input signals to maintain a consistent motor speed, minimizing any fluctuations caused by load variations.

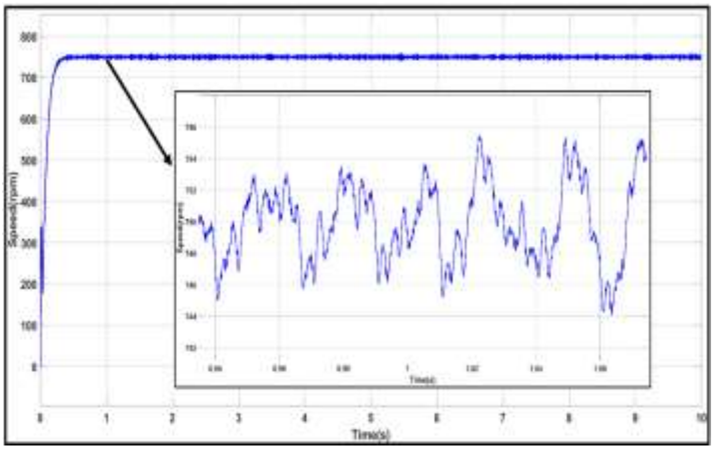

Figure 8: Speed response with PID controller.
Source: Authors, (2025).

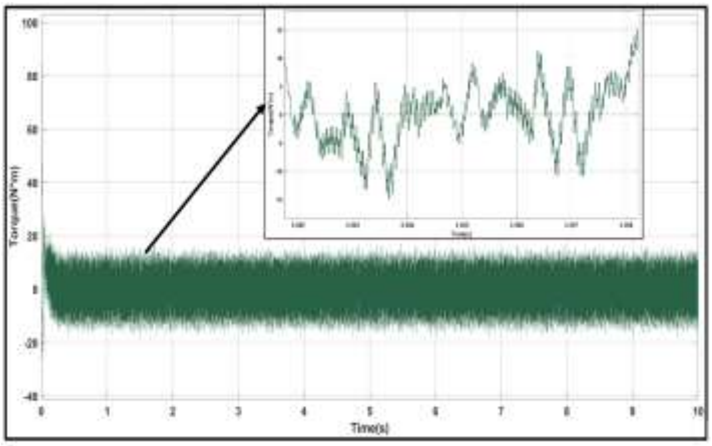

Figure 9: Torque response with PID controller.
Source: Authors, (2025).

PID controller-driven speed control of a Permanent Magnet Synchronous Motor (PMSM) is investigated in this work. Simulated performance of the PMSM drive system in open-loop, that is, without control, and with the PID controller operating to regulate the motor's speed is achieved.

Figure (7) illustrates that the input voltage significantly affects the motor speed in an open-loop condition, as depicted in Figure (4), leading to substantial oscillations and prolonged settling times. The PID controller significantly enhances speed control by minimizing steady-state error, enabling the motor's speed to attain the goal setpoint more swiftly, with less overshoot and expedited settling time. As depicted in Figure (8). The PID controller facilitates the system's transition from a critically damped state to an underdamped state in open-loop settings, thereby optimizing the balance between swift response and minimal overshoot.

The PID controller enhances overall system performance through more precise speed regulation and smoother operation, which are essential for PMSM applications. Adjusting the PID parameters according to motor specifications and control requirements will enhance the system's maximum performance. This study emphasizes the significance of feedback control in motor systems by illustrating the real-time response of the PID controller to variations in motor speed. The PID controller continuously monitors the motor's speed and adjusts the control signal accordingly, thereby stabilizing the system and enhancing its responsiveness.

The comparison of open-loop and closed-loop performance underscores the necessity of employing a controller for accurate and consistent speed regulation in PMSM applications, thereby ensuring the motor operates within its specified range. Particle Swarm Optimization (PSO) was employed to optimize the gains of the PID controller. Inspired by the social behavior of birds flocking and fish schooling, Particle Swarm Optimization (PSO) is an evolutionary algorithm.

The optimal configuration of proportional gain (Kp), integral gain (Ki), and derivative gain (Kd) that minimizes the discrepancy between the reference speed and the actual speed of the PMSM, resulting in an effective control response, was established. A block diagram of a PSO-tuned PID control system for PMSM speed regulation is displayed in Figure(10) By modifying the PID gains in response to feedback on system performance, the PSO algorithm minimizes a specified objective function.

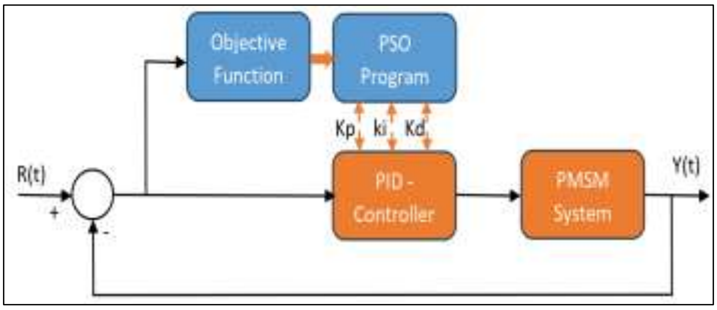

Figure 10: block diagram of PSO-tuned PID control system for PMSM.
Source: Authors, (2025).

In the PSO process, particles (potential solutions) move through the search space, adjusting their positions based on their own experiences and the experiences of neighboring particles. The optimization objective was to minimize the integral of time-weighted absolute error (ITAE) or another similar error metric that quantifies the control system's performance.

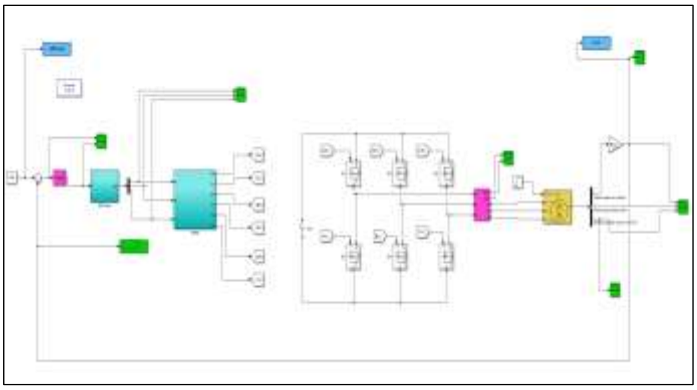

Figure 11: PMSM drive system with PSO-PID Controller.
Source: Authors, (2025).

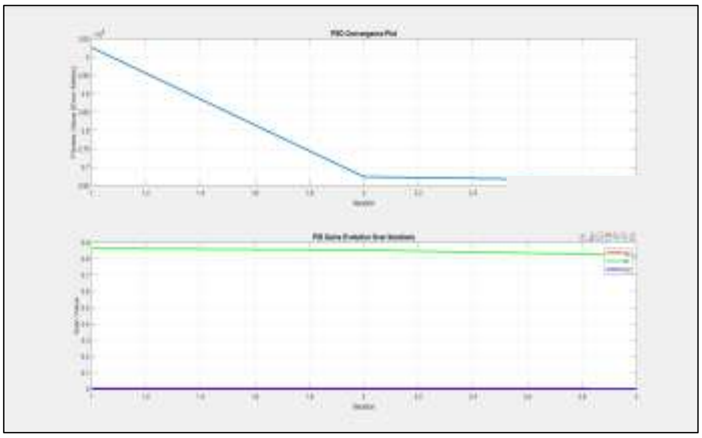

Figure 12: PSO Optimization Results for PID Gains Tuning.
Source: Authors, (2025).

The Particle Swarm Optimization (PSO) results for tuning the PID controller to control the Permanent Magnet Synchronous Motor (PMSM) speed show that the PSO algorithm essentially optimized the PID gains (Kp, Ki, Kd) to minimize the error between the reference speed and the motor's output speed (yout) as shown in Figure (11). The PSO Convergence Plot Figure(12) shows a consistent declining fitness value, therefore validating the effective optimization process.

The PID Gains Evolution Plot shows that while Kp stayed constant after the first adjustments, Ki settled around 0.8 and Kd about 0.0002, and the PID gains stabilized rapidly. Reference speed and motor speed are compared to find that, with some slight oscillations typical of an underdamped system, the motor speed closely after a transitory period follows the reference speed. With minimum steady-state error and regulated transient behavior, the optimized PID controller—tuned by PSO—produced good performance by closely tracking the motor speed from the reference speed.

After applying the PID-PSO (PID controller optimized by Particle Swarm Optimization), the speed response has significantly improved. The waveform now shows a smoother and faster transition to the desired speed, with minimal overshoot and oscillations. The motor reaches the target speed more quickly, with reduced overshoot and less fluctuation around the steady-state value. This indicates better system control, resulting in a faster settling time, smoother operation, and overall more stable performance. The PID-PSO optimization has thus enhanced both the efficiency and stability of the motor control system.

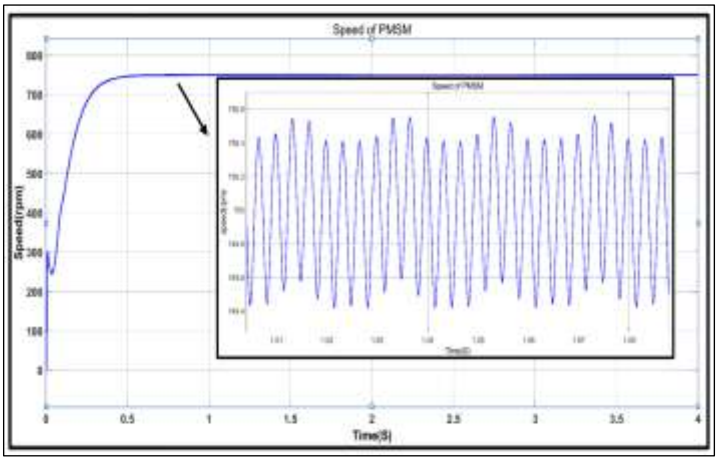

Figure 13: Speed response with PSO-PID Controller.
Source: Authors, (2025).

With a total speed over-shoot of 0.0263%. A low overshoot value indicates that the system responds quickly to changes without excessively exceeding the desired target, which is a sign of a well-tuned system. It ensures stability and minimizes the risk of oscillations, making the system more reliable and efficient in its operation as shown in Figure (13). After applying the PID-PSO optimization, the electromagnetic torque response has significantly improved as well.

The Open-loop waveform shows large fluctuations and oscillations in the torque, indicating instability and poor control. However, in figure(14) after optimization, reveals a much smoother and more stable torque signal. The torque reaches a steady value quickly, with minimal oscillations and fluctuations around the target. This indicates that the PID-PSO optimization has enhanced the torque control by reducing instability, leading to a more efficient and reliable system. The improvements include a faster settling time, reduced overshoot, and a more stable performance overall.

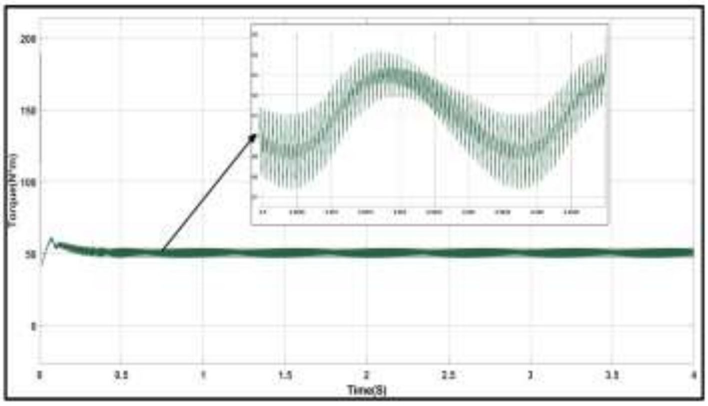

Figure 14: torque response with PSO-PID controller.
Source: Authors, (2025).

The presence of some oscillations in the torque waveform Figure(14) is due to several factors inherent to the system. Firstly, the physical limitations of the motor, such as friction and mechanical imperfections, can introduce small, unavoidable oscillations that cannot be entirely eliminated, even with optimal tuning. Additionally, electrical noise or interference, often generated by the motor or surrounding equipment, can cause minor fluctuations in the torque signal. The non-linear dynamics of the system, where the motor's behavior may change under varying conditions, can also lead to subtle oscillations despite careful optimization. Furthermore, the use of a PWM (Pulse Width Modulation) circuit for motor control can contribute to these oscillations. The switching nature of PWM can introduce high-frequency ripples and voltage variations, which may manifest as slight oscillations in the torque waveform. These factors combined contribute to the persistence of minor oscillations in the system.

ESS Calculation:

The ESS (Steady-State Error) was calculated using the initial PID values and the final values after applying the PSO-PID optimization, based on the equation outlined below. The results obtained from this calculation are as follows:

$$ESS = |\,{}_{\text{otimizepd}}Kp - {}_{\text{initial}}Kp\,| + |\,{}_{\text{optimized}}Ki - {}_{\text{initial}}Ki\,| + |\,{}_{\text{otimized}}Kd - {}_{\text{initial}}Kd\,| \quad ....(9)$$

The initial values of Kp, Ki , and Kd were, respectively, as follows (0.0015 , 0.8 , 0.0006) And the final values of the same parameters after using PSO-PID controller were (0.0029 ,0.65 , 0.0012) so ESS = 0.152 .An ESS value of 0.152 for the PMSM indicates a relatively small steady-state error, which is generally considered acceptable in many applications

Stator Current Response at Constant Load:

In addition to the speed and torque responses, the stator current waveforms for phases a, b, and c at constant load are shown in figure(15)(16) . The currents in each phase exhibit smooth, sinusoidal waveforms, characteristic of steady-state operation in a PMSM. These waveforms indicate that the system has stabilized after initial transients and is now operating under a constant load without significant fluctuations

The currents remain around 200 A for all three phases, reflecting a balanced load distribution across the motor's stator. Figure(15) shows the current waveforms over a longer time span, with consistent oscillations around the steady-state value. This steady current profile is expected in PMSM motors operating at constant load, confirming the system's efficiency and balance figure(16) zooms in to provide a closer view of the current oscillations within one cycle, showing minimal variation and smooth transitions, indicating the motor's stable operating condition. This behavior further confirms that the PSO-PID controller is effectively managing the motor's electrical characteristics to maintain stability and performance, even under constant load conditions

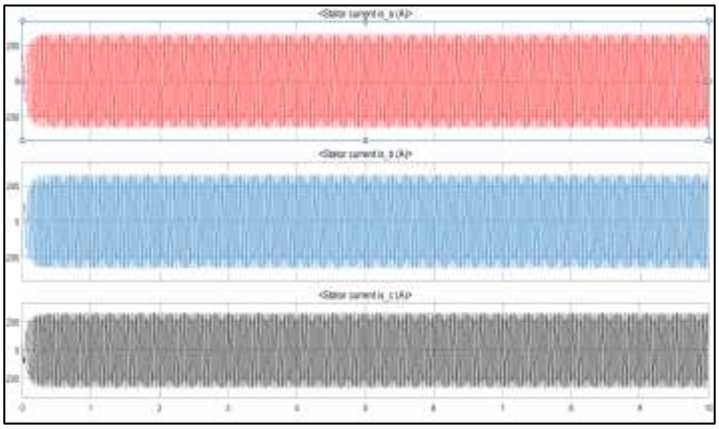

Figure 15: current waveforms.
Source: Authors, (2025).

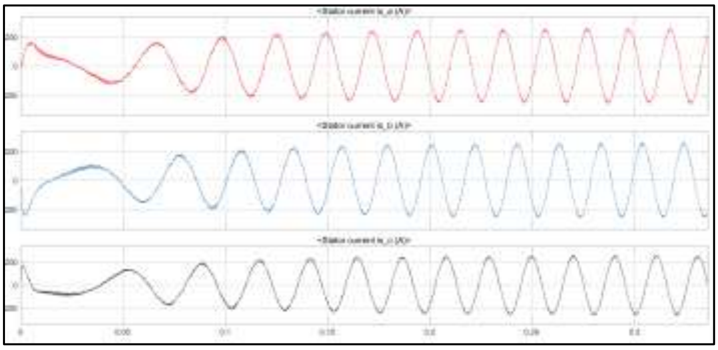

Figure 16: a closer view of the current oscillations within 0.3sec.
Source: Authors, (2025).

PSO-PID Controller and Two step load

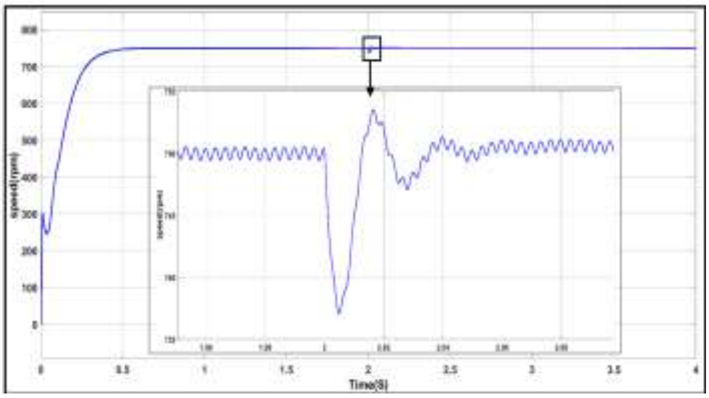

Figure 17: Speed response with PSO-PID Controller and Two step load.
Source: Authors, (2025).

The speed response in Figure (17) shows the behavior of the system with a PSO-PID controller when subjected to a two-step load change. Upon the first load change around 2 seconds, a brief oscillation in the speed is observed as the system reacts to the disturbance. This oscillation can be attributed to the sudden load variation, causing a temporary deviation in the speed. However, the system quickly stabilizes, and the speed returns to its target value.

The settling time after the load change, where the system regains stability, is observed to be approximately 0.06 seconds. Specifically, the speed begins stabilizing around 2 seconds and fully settles by 2.06 seconds, demonstrating a fast and effective recovery of the system from the disturbance with minimal oscillation. This behavior indicates the controller's strong performance in maintaining the desired setpoint even in the presence of sudden load changes

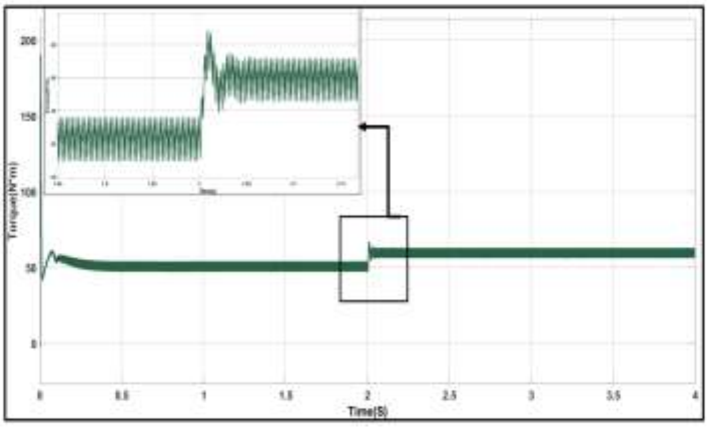

Figure 18: Torque response with PSO-PID Controller and Two step load.
Source: Authors, (2025).

Similarly, in the torque response shown in Figure (18), the system exhibits a sharp spike in torque at exactly 2 seconds due to the load change, followed by oscillations. However, the torque quickly stabilizes and settles back to its target value within about 0.15 seconds by 2.15 seconds. This demonstrates that the PSO-PID controller effectively handles both speed and torque disturbances, ensuring that the system returns to a steady state with minimal fluctuation in both parameters following the load change.

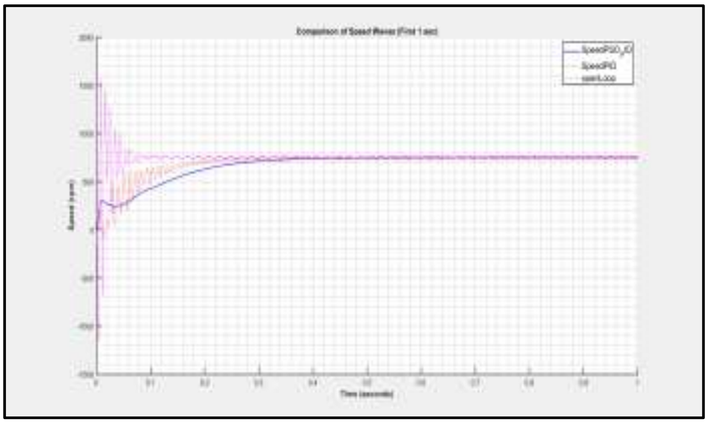

Figure 19: Compression of Speed Waves.
Source: Authors, (2025).

Figure (19) shows three responses from different control systems, with the comparison happening only in the first second. Speed PSO_PID (blue) shows a rapid response and good stability after an initial fluctuation, thanks to the combination of the PSO algorithm with PID control. Speed PID (red) responds more slowly but with excellent stability, showing small oscillations after reaching the desired speed.

In contrast, open Loop (purple) shows an uncontrolled response with large oscillations, as it lacks any form of control, leading to instability. Since the time range was limited to 1 second (X_{lim} [0 1]), the comparison focuses solely on the initial behavior of the systems within this short time frame, highlighting their different response characteristics during the first second after startup.

V. AUTHOR’S CONTRIBUTION

Conceptualization: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.
Methodology: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.
Investigation: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.
Discussion of results: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.
Writing – Original Draft: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.
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Supervision: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.
Approval of the final text: Ghufran Saad Mohammed and Mohammed Obaid Mustafa.

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