DOI: 10.22146/jnteti.v414.22693

Adaptive PID Auto-Tuning Algorithm on Omron PLC for Speed Control and Stability

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[Received: 8 July 2025, Revised: 7 October 2025, Accepted: 29 November 2025]
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ABSTRACT — Speed regulation of three-phase induction motors under varying load conditions presents a major challenge in industrial automation due to their nonlinear dynamic behavior. This paper proposes an adaptive speed control system using a proportional-integral-derivative auto-tuning (PIDAT) algorithm implemented on the Omron CP1H-XA40DT-D programmable logic controller (PLC). The initial PID parameters were derived using the Ziegler–Nichols method, and the system continuously monitored the steady-state error during operation. When the error exceeded a predefined 5% threshold, the auto-tuning sequence was triggered. This sequence included a relay feedback test (RFT), system identification using a first order plus dead time (FOPDT) model, and real-time PID parameter recalculation. The system hardware integrated an Omron 3G3MX2 inverter, rotary encoder, and NB7W-TW01B human–machine interface (HMI) to form a closed-loop control structure. Experimental validation was performed under both spontaneous and constant load conditions. The PIDAT method consistently demonstrated superior performance compared to classical Ziegler–Nichols tuning, achieving steady-state errors in no-load tests below 1.70 % and under 0.8% in loaded conditions. Furthermore, the system achieved settling times below 9 s and recovered from load disturbances in less than 4 s. These results validate the proposed PIDAT system as an accurate, fast, and adaptive control solution, reducing the need for manual tuning and enhancing robustness in dynamic industrial environments.

KEYWORDS — Three-Phase Induction Motor, PID Auto-Tuning, Omron PLC, Speed Control; Adaptive Control, Industrial Automation.

I. INTRODUCTION

Three-phase induction motors represent a vital component in a wide range of modern industrial applications due to their reliability, simple construction, and cost-effective operational characteristics [1]–[3]. These motors operate based on the principle of electromagnetic induction, wherein a rotating magnetic field generated by the stator induces current in the rotor to produce torque [4]. Despite their advantages, induction motors exhibit an inherent limitation, which is their inability to maintain a constant speed under load variation [5], [6]. This instability can significantly affect product quality and process efficiency, particularly in systems that demand high-precision speed control.

In response to increasing demands for system stability within dynamic production environments, various speed control strategies have been developed. One widely adopted conventional method is the proportional–integral–derivative (PID) control technique [7]. While effective in many applications, the performance of PID controllers is highly dependent on the accuracy of their tuning parameters. In practice, tuning is often performed manually, requiring both time and expert knowledge, which reduces efficiency—especially in systems experiencing dynamically changing operating conditions.

Prior research has explored alternative control methods involving artificial intelligence, such as fuzzy-PID controllers, fuzzy logic–based multilevel inverter control systems, and machine learning–based adaptive controllers [8]. Although these approaches offer improved performance, they often require complex configurations and do not always respond effectively to sudden load disturbances. Hence, there remains a practical need for a control strategy that is both adaptive and straightforward to implement in industrial contexts.

This study proposes an implementation of a PID auto-tuning (PIDAT) method using the Omron CP1H-XA40DT-D programmable logic controller (PLC) as an efficient and adaptive solution to load variations. The proposed system integrates the Omron 3G3MX2-AB007-V1 inverter as the speed actuator, a rotary encoder as the feedback sensor, and the NB7W-TW01B human–machine interface (HMI) for operator interaction. These components form a closed-loop control system based on adaptive PID logic. A key feature of the system is its ability to automatically retune PID parameters when the steady-state error exceeds a defined threshold. The overall structure and interaction of these components are illustrated in Figure 1, which depicts the control system block diagram. This diagram depicts the signal flow from the HMI input through the PLC-based PID controller, to the inverter and motor, and back to the PLC via the encoder, thereby highlighting the feedback mechanism and the auto-tuning loop.

The primary objective of this research is to design and implement a three-phase induction motor speed control system that is not only stable and efficient but also capable of self-adapting to load disturbances. The proposed method aims to enhance the reliability and effectiveness of motor control in industrial automation environments. Furthermore, the results of this study may serve as a technical reference for the development of more adaptive and practical PLC-based control systems.

II. PID AUTO-TUNING ON OMRON PLC

Speed control of three-phase induction motors poses a major challenge in industrial automation, particularly under

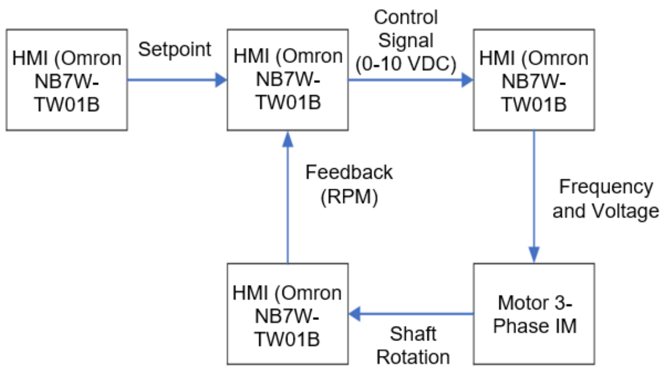

Figure 1. Schematic block diagram of the PID auto-tuning control system implemented on Omron PLC.

conditions of dynamic load variations. The inherent nonlinear characteristics of induction motors result in high sensitivity to load changes, leading to speed fluctuations that can degrade process efficiency and product quality [5], [9].

The PID controller remains one of the most widely adopted control strategies due to its simplicity and effectiveness in maintaining system stability [10]. Nevertheless, the controller's performance is highly dependent on the accurate tuning of its parameters—namely the proportional gain K_p , the integral time constant T_i , and the derivative time constant T_d . In practice, manual tuning is still commonly used, which is not only time-consuming but also lacks adaptability to real-time system dynamics and often requires specialized expertise [10], [11].

To address these limitations, a PIDAT approach was employed. This method allows for the automatic adjustment of control parameters based on system response, eliminating the need for manual intervention. In this study, the PIDAT technique was implemented using the Omron CP1H-XA40DT-D PLC [12], supported by the Omron 3G3MX2 inverter [13] and a rotary encoder for feedback.

The auto-tuning feature embedded in the PLC is capable of monitoring the system's steady-state error. When this error exceeds a predefined threshold (e.g., 5%), the PLC automatically initiates a retuning process to optimize the PID parameters and ensure consistent control performance. This adaptive mechanism enhances the system's robustness and responsiveness, particularly in environments characterized by frequent or abrupt load variations [14]. Recent studies have also demonstrated the effectiveness of adaptive PID tuning in PLC-based control systems using real-time modelling and closed-loop autotuning logic [15].

A. PID AUTO-TUNING MECHANISM IN OMRON PLC

The PIDAT process implemented in Omron PLCs is designed to simplify the parameter tuning procedure by enabling automatic adjustment of control parameters without requiring manual operator intervention. This mechanism consists of three primary stages: the relay feedback test (RFT), system modeling, and adaptive PID parameter computation [16]. Each stage is detailed as follows.

1) RELAY FEEDBACK TEST (RFT)

In this initial phase, the PID control loop is temporarily disabled, and a switching signal is applied to the system to induce sustained oscillations. The objective is to capture the closed-loop oscillatory response, specifically the amplitude and oscillation period. These time-domain characteristics provide essential data for identifying the system's dynamic behavior and for constructing a representative model.

2) SYSTEM MODELING (FIRST ORDER PLUS DEAD TIME-FOPDT)

The oscillatory response data acquired from the RFT serve as a foundational input for constructing an accurate mathematical representation of the system's dynamic behavior. In the context of closed-loop speed regulation for three-phase induction motors, the system is suitably modelled as a first order plus dead time (FOPDT) process. This modelling framework is widely adopted in industrial control applications due to its simplicity and effectiveness in approximating the dynamics of systems that exhibit lag and inertia, such as induction motors. The selection of the FOPDT structure is not arbitrary; it reflects the inherent characteristics of induction motors, which typically respond to input variations in a delayed and gradually stabilizing manner, consistent with first-order system dynamics that include a time delay component.

Mathematically, the FOPDT model is expressed as [17]:

$$G(s) = \frac{Ke^{-\theta s}}{Ts+1}. \quad (1)$$

where $G(s)$ denotes the process transfer function in the Laplace domain, K represents the steady-state gain, T is the time constant indicating the speed of the system's response, and θ denotes the dead time or transport delay, which accounts for the inherent latency before the output begins to react to changes in the input signal. This delay can arise from physical constraints, signal processing times, or actuator response lags, all of which are relevant in the control of electrical drives.

By fitting the oscillatory data from the RFT to this model, the control system gains a concise yet descriptive representation of motor behavior that can be utilized for adaptive control strategies, including automatic PID parameter tuning. The accuracy of the FOPDT approximation is crucial, as it directly influences the effectiveness of the PID controller in maintaining stability and achieving desired dynamic performance, particularly under load variations. The identification of the FOPDT parameters from real-time oscillatory data ensures that the controller remains responsive and well-tuned to the true dynamics of the motor system, thereby improving both the transient response and steady-state accuracy in industrial automation environments [15].

Through the RFT method, these parameters are identified directly from the system's time response without the need for a complex mathematical model. The oscillation period and amplitude observed during the test are used to approximate the dynamic behavior, which in turn supports the tuning of PID controller parameters.

The adoption of the FOPDT model significantly simplifies the control system design and allows for the implementation of adaptive control algorithms such as PIDAT within PLC environments. This modeling strategy ensures robustness and scalability in practical industrial applications, especially where real-time adaptation to load changes is required.

3) PID PARAMETER CALCULATION BASED ON FOPDT MODEL

The automatic computation of PID control parameters is fundamentally guided by FOPDT model identified during the system modelling phase. This model-based tuning approach enables a systematic and adaptive adjustment of control parameters in accordance with the actual dynamic characteristics of the three-phase induction motor. Rather than relying on trial-and-error or fixed empirical rules, the PID parameters are derived using a mathematical formulation that captures the essential process dynamics—specifically the gain, time constant, and time delay of the system. This strategy enhances the precision, responsiveness, and robustness of the control system, especially under conditions involving dynamic load changes or nonlinear behaviors.

The formulation employed for parameter computation is expressed as [18]:

$$K_p = \left(\frac{1}{K}\right)\left(\frac{T}{\theta}\right) f_1, \quad T_i = T \cdot f_2, \quad T_d = \theta \cdot f_3 . \qquad (2)$$

In this expression, K_p denotes the proportional gain, which determines the immediate response strength of the controller to deviations in speed; T_i is the integral time constant, responsible for eliminating steady-state error by integrating past error values; and T_d is the derivative time constant, which anticipates future error trends based on the rate of change of the error signal. The variables f_1, f_2, f_3 represent tunable correction coefficients or scaling factors that are selected according to the specific performance criteria of the system—such as prioritizing fast response, minimal overshoot, or high stability.

These tuning factors introduce a degree of flexibility, allowing the control strategy to be adapted to different operational requirements or disturbance profiles. For instance, a higher value of f_1 can increase the controller's aggressiveness, while larger values of f_2 or f_3 can be used to fine-tune the integral and derivative actions, respectively, to enhance stability or responsiveness. By embedding this adaptive computation into the PLC, the system achieves real-time self-tuning capability, ensuring optimal performance without manual intervention. This method not only reduces the complexity of controller deployment in industrial settings but also improves the reliability and repeatability of control performance across varying process conditions.

This adaptive approach enables precise tuning of the PID parameters— $K_p, K_i = K_p/T_i$, and $K_d = K_p \cdot T_d$ —in accordance with the actual dynamic behavior of the system. By leveraging real-time model parameters, the controller can continuously update its gains to maintain optimal performance, even in the presence of changing operating conditions or load disturbances.

The use of correction factors f_1, f_2, f_3 provides flexibility in controller design, allowing system integrators to prioritize stability, speed, or robustness depending on the application requirements. These correction factors are directly applied in the PID parameter calculation based on the FOPDT model, using (2). The selection of f_1, f_2, f_3 values depend on the desired tuning mode—fast, normal, or robust—each offering a different trade-off between responsiveness and control stability. Table I shows the predefined tuning factor values for each mode, which are utilized in real time during the auto-tuning process to adapt the PID controller gains. The numerical values listed in the table are specifically calibrated to produce distinct controller behaviors aligned with different operational goals.

In the fast mode, the correction factors are set to $f_1 = 0.9$, $f_2 = 0.9$, and $f_3 = 0.3$, resulting in a controller that reacts rapidly to setpoint changes and disturbance. This configuration is beneficial for system that demand quick responses, although it may lead to higher overshoot and reduced stability. Normal mode, with values $f_1 = 1.2$, $f_2 = 2.0$, and $f_3 = 0.5$, provides a balanced trade-off between speed and damping, making it suitable for general industrial applications where consistent performance is needed without extreme tuning. Meanwhile, the robust mode utilizes the highest values —$f_1 = 1.5$, $f_2 = 2.5$, and $f_3 = 0.6$ — to prioritize control stability and minimize the effects of noise and disturbances, although this comes at the expense of slower system response. Each of these modes offers a different dynamic profile, allowing the controller to be tailored according to specific operational requirements.

TABLE I
NO-LOAD TEST RESULTS

Mode Tuning	f_1	f_2	f_3
Fast	0.9	0.9	0.3
Normal	1.2	2.0	0.5
Robust	1.5	2.5	0.6

The ability to switch between these modes allows the control system to adapt to different needs without manual retuning. During the auto-tuning process, the PLC uses the selected correction factors in real time to update the PID parameters according to the system's behavior. Thus, Table I is not only a guide for selecting control modes, but also a key part of the system's ability to adjust itself and maintain optimal performance automatically. This model-based PID tuning framework significantly improves the adaptability and reliability of control systems implemented in industrial automation environments [18], [19].

B. IMPLEMENTATION OF PID AUTO-TUNING ON OMRON PLC

The implementation of the PIDAT algorithm was carried out on the Omron CP1H-XA40DT-D PLC using ladder diagram programming developed via the CX-Programmer software platform [20]. The control system was designed to accept speed setpoints entered by the operator through a HMI, specifically the NB7W-TW01B panel. These setpoints were read by the PLC and compared in real time with the actual motor speed obtained from a rotary encoder, serving as a feedback sensor.

The difference between the setpoint and the measured speed produces an error signal. When the steady-state error exceeded a predefined threshold—set at 5%—the PLC's auto-tuning function was triggered automatically. This auto-tuning process involved three core stages: acquisition of the system's oscillatory response, modeling based on the FOPDT approach, and recalculation of PID parameters according to the updated dynamic characteristics of the system. The sequence of these stages is depicted in Figure 2, which depicts the flowchart of the PIDAT algorithm implemented within the Omron PLC. This diagram outlines the decision-making logic and iterative steps taken by the system to evaluate performance, initiate tuning, and update control parameters in real-time.

Once the new PID parameters were computed, they were immediately applied to update the running PID control algorithm within the PLC [14]. The control output was generated in the form of a 0–10 VDC analog voltage signal, which was sent to an Omron 3G3MX2 inverter. The inverter then adjusted the frequency and voltage supplied to the three-phase induction motor, enabling precise speed regulation in accordance with the desired setpoint.

This implementation demonstrates a closed-loop, adaptive control framework capable of maintaining high accuracy and

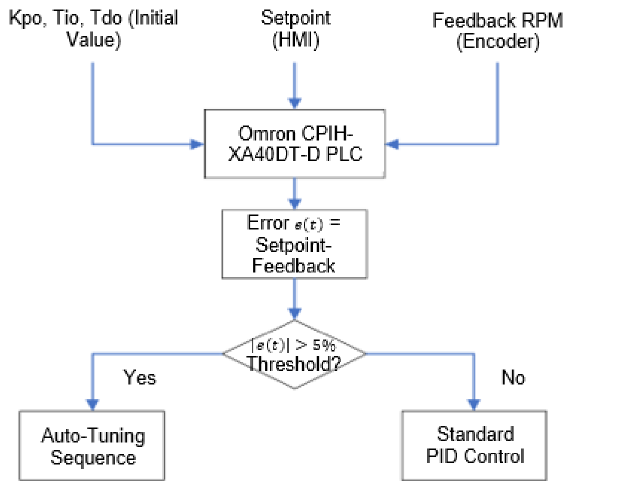

Figure 2. Flowchart of PID auto-tuning algorithm implemented on the Omron PLC.

stability under varying load conditions, thus fulfilling the demands of modern industrial automation systems.

III. METHODOLOGY

This research methodology was designed to develop and evaluate a speed control system for three-phase induction motors based on a PIDAT algorithm implemented on the Omron CP1H-XA40DT-D PLC. An experimental approach was employed to verify the system's ability to adaptively tune control parameters in response to load variations and dynamic process conditions. The methodology was divided into five primary stages: control system design, ladder diagram software development, hardware configuration, physical system implementation, and testing and evaluation procedures.

A. CONTROL SYSTEM DESIGN

The control system was architected as a closed-loop feedback structure to enable adaptive and precise speed regulation of a three-phase induction motor under varying load conditions. This design ensures continuous monitoring and correction of the motor's operating state by comparing real-time speed feedback with the desired setpoint, allowing the system to maintain stability, accuracy, and responsiveness. At the heart of this architecture was the Omron CP1H-XA40DT-D PLC, functioning as the central logic processor and controller. It executed the PIDAT algorithm, processes sensor inputs, and generates control signals for motor actuation.

To adjust the motor speed, the system employed the Omron 3G3MX2-AB007-V1 inverter, serving as the frequency actuator by converting the PLC's analog output signal (0–10 VDC) into a corresponding frequency input for the induction motor. The actual speed of the motor was measured using an Omron E6B2-C rotary encoder, which provides high-resolution feedback to the PLC through a high-speed counter input, enabling accurate calculation of rotational speed in revolutions per minute (RPM). This feedback is essential for detecting any deviations from the setpoint and triggering the PID control logic.

For user interaction and system configuration, the architecture incorporated the Omron NB7W-TW01B HMI. The HMI allows operators to input speed setpoints, monitor system status, and observe real-time performance metrics such as actual motor speed, steady-state error, and tuning status. It also facilitates manual overrides or triggering of the auto-tuning function if required.

This integrated configuration formed a robust and adaptive control loop that continuously aligned motor output with user-defined targets, compensating for internal and external disturbances. By combining reliable hardware components with a real-time control strategy, the system was optimized for industrial automation scenarios where speed stability, minimal manual intervention, and adaptability were critical.

The speed setpoint was entered via the HMI and transmitted to the PLC, which continuously compared it with the actual speed feedback from the encoder. The real-time error signal $e(t)$ was used as the input to the control process. When the steady-state error exceeded a predefined threshold (5% of the setpoint), the PIDAT mechanism was activated automatically.

The autotuning process employed a RFT to induce controlled oscillations in the system. The resulting data—oscillation amplitude and period—were extracted and used in the Ziegler–Nichols tuning rule, which calculated the PID parameters based on a simplified FOPDT model of the system. This model is particularly suitable for the motor's dynamics and enables accurate, model-based control.

The Ziegler–Nichols method computed the PID gains according to the selected tuning mode—fast, normal, or robust—to balance responsiveness, stability, and overshoot. Once computed, the new PID parameters were applied directly to the PLC's PID control block. The output control signal was converted to a 0–10 VDC analog voltage, which was sent to the inverter to adjust the motor frequency linearly across a 0–50 Hz range, corresponding to motor speeds between 0 and 1500 RPM.

This control design enables the system to maintain performance that is stable, efficient, and adaptive to load changes, making it suitable for industrial applications demanding high reliability and minimal manual tuning. The implementation of the Ziegler–Nichols table with FOPDT-based autotuning provided a mathematical and practical foundation for optimal PID controller design. Correction factors f_1, f_2, and f_3 were determined based on the selected tuning mode. Table I shows the tuning factor values used for fast, normal, and robust modes based on the modified Ziegler–Nichols method.

B. LADDER LOGIC DEVELOPMENT FOR PID AUTO-TUNING

The software implementation was carried out using CX-Programmer to realize the PIDAT algorithm on the Omron CP1H-XA40DT-D PLC. The ladder logic was designed to read process data, detect steady-state error conditions, trigger the autotuning sequence, and regulate motor speed via analog control outputs to the inverter. Figure 3 depicts the ladder logic implementation, highlighting the conditional structure that activates the auto-tuning routine when the steady-state error (SSE) exceeds 5%. The diagram provides a visual representation of how the PLC program dynamically transitions between normal operation and auto-tuning mode based on real-time error evaluation.

The process began by acquiring the speed setpoint from the HMI and the actual speed from the rotary encoder. These values were stored in memory registers (e.g., D100 and D101). The error was calculated using the SUB instruction, converted to percentage error using ABS, DIV, and MUL functions. If the

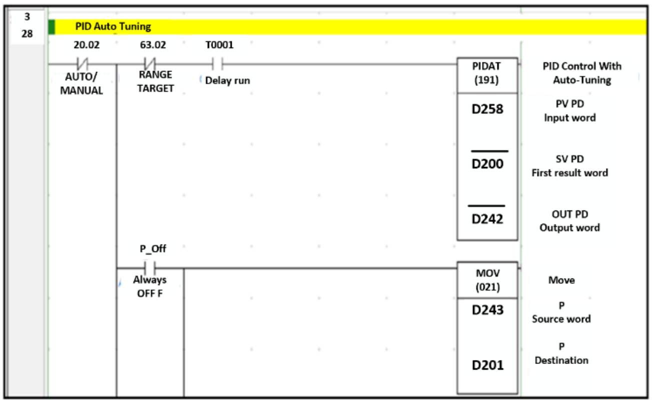

Figure 3. Ladder Diagram for PID Auto-Tuning activation logic on Omron PLC.

error exceeded 5%, the CMP instruction activated a logic bit (e.g., M0.00), triggering the autotuning sequence.

The PIDAT function executed a relay feedback operation, identified the FOPDT model parameters, and computed the PID values using Ziegler–Nichols formulas. These gains were applied in real time by writing values to designated PID memory registers (e.g., D300–D302), allowing continuous adaptive tuning during motor operation.

C. PHYSICAL SYSTEM IMPLEMENTATION

The physical platform was designed to precisely control the speed of a three-phase induction motor using the PIDAT method implemented on the Omron CP1H-XA40DT-D PLC. The system followed a closed-loop control structure where actual motor speed was automatically corrected based on real-time feedback.

The PLC outputted a 0–10 VDC analog signal to the Omron 3G3MX2-AB007-V1 inverter, which modulated motor frequency in the 0–50 Hz range. The motor's actual speed was measured using an incremental rotary encoder (E6B2-C) and processed by the PLC's high-speed counter to derive the RPM.

The measured speed was compared with the HMI-entered setpoint. The HMI also served as a user interface for monitoring system status and initiating automatic tuning. When the error surpassed the 5% threshold, the PLC activated the PIDAT function to retune control parameters dynamically.

System integration was achieved using standard analog and digital industrial signals. The closed-loop system ensures that PID parameter changes via autotuning are applied automatically, without interrupting operation.

D. TESTING AND EVALUATION

Testing and evaluation were conducted to assess the performance of the PIDAT speed control system implemented on the Omron CP1H PLC. The key evaluation criteria included control signal accuracy, response to setpoint variations, and adaptive capability under load disturbances.

Initial tests validated the PLC's analog output (0–10 VDC) against the RPM setpoint, confirming the linear conversion to motor speed. Subsequent evaluations verified the inverter's response to the control signal, ensuring frequency output corresponds to the motor's operational range (300–1,500 RPM).

The motor was tested under both no-load and load conditions. Speed feedback was captured via the encoder and converted to RPM by the PLC. Performance metrics analyzed include steady-state error (SSE) and settling time, both during setpoint changes and in the presence of sudden load disturbances.

To validate the PIDAT function, a load disturbance was introduced after steady operation. If deviation exceeded 5%, the PLC automatically retuned the PID parameters. The evaluation focused on the recovery time and post-tuning system stability. Results confirmed that the system adapted efficiently, maintaining speed stability within acceptable limits across varying operational conditions.

IV. RESULTS AND DISCUSSION

A. EXPERIMENTAL RESULTS

This study investigated the effectiveness of the PIDAT mechanism implemented on an Omron PLC for speed control of a three-phase induction motor under both spontaneous and constant loading conditions. Two tuning strategies were evaluated: the classical Ziegler–Nichols method and the automatic tuning function provided by the PLC.

In the spontaneous load experiments, tests were conducted at reference speeds of 500 RPM, 600 RPM, and 700 RPM. Initial PID parameters were computed using the Ziegler–Nichols method (P = 120, I = 2, D = 1) and later optimized using the auto-tuning feature, which yielded refined parameters (P = 29, I = 4). The system's response to abrupt braking was analyzed, demonstrating that auto-tuning outperformed the initial tuning in terms of reduced steady-state error and improved transient response. Specifically, auto-tuning achieved a rise time of 2.83 s, peak time of 4.15 s, settling time of 8.49 s, and a steady-state error of 1.4%, while Ziegler–Nichols produced a higher steady-state error of 4.821% with slower dynamics.

In the constant load experiments, eight trials were performed using load masses of 2 kg and 4 kg at reference speeds of 500 RPM and 700 RPM. Without any control, the motor speed failed to reach the reference setpoint (e.g., 476 RPM under a 500 RPM setpoint). When PID control was activated, auto- tuning successfully restored the motor speed to the desired setpoint despite the load disturbance. Under a 2 kg load at 500 RPM, the auto-tuning method achieved a rise time of 0.52 s, settling time of 2.1 s, maximum overshoot of 15 RPM, and a steady-state error of 0.4%. In comparison, Ziegler–Nichols tuning resulted in a slower rise time of 1.46 s, settling time of 4.17 s, and a higher error of 2%.

These results demonstrate that the PIDAT mechanism offers significant improvements in tracking performance and robustness against both abrupt and continuous load variations. Figure 4 and Figure 5 depict the system's dynamic response to external load disturbances, illustrating the transient behavior and recovery characteristics of the PIDAT control strategy implemented on the Omron PLC. These figures demonstrate how the system reacts to abrupt changes in load torque while maintaining a fixed reference speed, thereby providing empirical insights into the controller's ability to sustain stability and regulate output under non-ideal conditions. The response profiles shown include critical dynamic performance metrics such as rise time, overshoot, settling time, and steady-state error—each of which is essential for evaluating the robustness and responsiveness of the control algorithm.

The data depicted in the figures indicate that the PIDAT mechanism successfully identifies deviations caused by load perturbations and promptly initiates real-time retuning of control parameters to mitigate performance degradation. The resulting speed response curves revealed minimal overshoot, short settling times, and negligible steady-state error, which

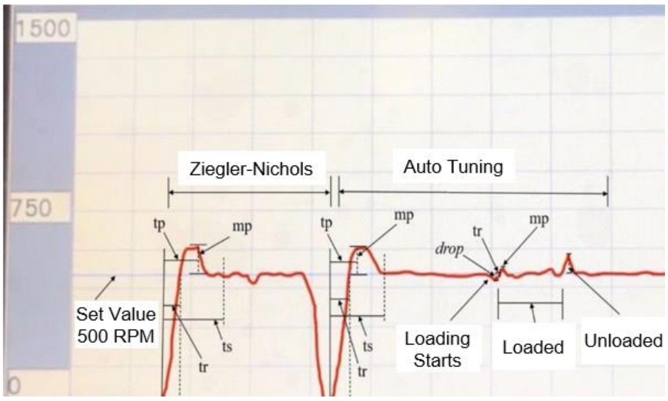

Figure 4. System response to spontaneous load disturbance at 500.

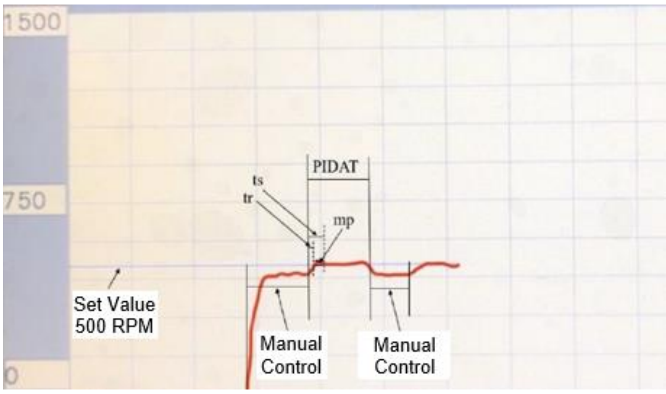

Figure 5. Experimental speed response at 500 RPM and 2 kg load using PIDAT.

collectively signified a high level of control accuracy and adaptability. This is particularly advantageous in dynamic industrial environments where speed regulation must remain reliable despite continuous operational variability.

By visually capturing the control system's behavior during transient events, these figures serve as a critical reference point for assessing the practical effectiveness of the proposed adaptive control method. Moreover, they validate the performance advantages of the PIDAT approach over conventional fixed parameter tuning methods, confirming its suitability for real-time applications that demand both precision and self-adjusting capabilities in motor speed regulation.

B. PERFORMANCE EVALUATION

A performance comparison between the auto-tuning and Ziegler–Nichols methods was conducted based on the key performance indices, including rise time, settling time, overshoot, and steady-state error, under both test conditions.

Under spontaneous load conditions, the PIDAT system yielded an average rise time of 3.57 s, settling time of 8.97 s, maximum overshoot of 110 RPM, and steady-state error of 1.66%. Compared to Ziegler–Nichols, which exhibited an average error of 4.6% and slower transient characteristics, the auto-tuning method demonstrated superior regulation and dynamic adaptability.

For constant load conditions, the auto-tuning method achieved better precision with an average steady-state error of 0.754%, settling time of 2.32 s, rise time of 0.72 s, and overshoot of 11.7 RPM. In contrast, Ziegler–Nichols showed a higher steady-state error of 1.465%, rise time of 1.44 s, and lower overshoot of 6.5 RPM. Although auto-tuning resulted in a slightly higher overshoot, its faster rise time and lower steady-state error are advantageous for applications requiring rapid and accurate speed regulation.

The closed-loop control system effectively compensated for both external disturbances and internal perturbations, such as motor slip, highlighting the practical reliability of the auto-tuning implementation. These results confirm that the PIDAT controller provides an efficient, adaptive, and less labor-intensive solution for maintaining speed stability in three-phase induction motors operating under varying industrial conditions.

C. DISCUSSION: PERFORMANCE ADVANTAGE OF PID AUTO-TUNING

The experimental results provide comprehensive insights into the dynamic behavior and steady-state performance of the PIDAT system in comparison to the classical Ziegler–Nichols tuning method. The experiments, conducted under both spontaneous and constant loading conditions, consistently demonstrate the superiority of the auto-tuning approach in terms of responsiveness, adaptability, and control precision.

One of the key findings from the spontaneous load experiments was the system's ability to recover rapidly from sudden disturbances. The auto-tuning method not only reduced steady-state error significantly (from 4.821% to 1.4%) but also exhibited a smoother transient response. This indicated that the adaptive mechanism embedded in the auto-tuning function effectively captured system dynamics and adjusted the PID parameters in real time to maintain control performance, which is particularly critical in environments where sudden load changes, such as braking or sudden torque variations, are common.

In the constant load scenario, the system under PIDAT consistently maintained the setpoint speed more accurately than with Ziegler–Nichols. Despite the presence of static friction and load inertia introduced by 2 kg and 4 kg weights, the controller was able to reduce the error margin to as low as 0.4%, significantly outperforming the classical tuning method. The results also revealed a trade-off: auto-tuning tended to introduce slightly higher overshoot compared to Ziegler–Nichols but compensated with a shorter rise time and quicker convergence to the steady-state condition.

From a control engineering perspective, this behavior is acceptable, especially in applications where response speed is prioritized over minimal overshoot. Moreover, the closed-loop structure of the auto-tuning system ensures that both internal perturbations—such as rotor slip—and external disturbances—such as electrical noise or mechanical friction—can be mitigated effectively. The ability of the controller to maintain stability and performance across varying operational conditions confirms its robustness and reliability.

Overall, these findings support the implementation of PIDAT in industrial automation systems, particularly those involving variable-speed drives for induction motors. The system reduced reliance on manual tuning, minimized commissioning time, and enhanced system resilience—making it a practical and scalable solution for real-world industrial control applications.

The comprehensive performance data obtained from both spontaneous and constant load test scenarios are systematically tabulated in Table II and Table III, respectively. These tables serve as a quantitative foundation for evaluating the dynamic and steady-state behavior of the PIDAT control system compared to the classical Ziegler–Nichols method across a variety of load conditions and setpoint references.

TABLE II
EXPERIMENTAL RESULTS OF PIDAT WITH SPONTANEOUS LOAD

ω_{set} RPM	M_P RPM	t_r (s)	t_s (s)	E_{ss} (%)
500	105	2.64	9.46	4.6
500	100	2.83	8.49	1.4
600	104	4.03	9.47	2.0
700	128	3.85	8.94	1.6

TABLE III
EXPERIMENTAL RESULTS OF PIDAT WITH CONSTANT LOAD

ω_{set} RPM	Method	Load (kg)	M_P RPM	t_r (s)	t_s (s)	E_{ss} (%)
500	AT	2	15	0.52	2.10	0.4
500	ZN	2	5.5	1.46	4.17	2.0
700	AT	2	5	0.94	1.32	0.29
700	ZN	2	6.8	1.28	5.95	1.43
500	AT	4	9	0.86	2.24	1.2
500	ZN	4	5.5	1.02	4.08	1.3
700	AT	4	18	0.58	3.65	1.13
700	ZN	4	8.3	2.00	6.28	1.13

Table II shows the experimental results obtained under spontaneous load disturbances, where abrupt variations in load torque were introduced while maintaining constant reference speeds of 500 RPM, 600 RPM , and 700 RPM. The key performance indicators recorded included maximum overshoot (MP), rise time (t_r), settling time (t_s), and steady-state error (E_{ss}). These metrics allow a direct comparison between the classical Ziegler–Nichols tuning method and the proposed PIDAT algorithm. At 500 RPM, the Ziegler–Nichols method resulted in an overshoot of 105 RPM, rise time of 2.64 s, settling time of 9.46 s, and steady-state error of 4.6%. In contrast, the PIDAT approach demonstrated a lower overshoot of 100 RPM, slightly faster rise time of 2.83 s, shorter settling time of 8.49 s, and a significantly reduced steady-state error of 1.4%. These trends were consistently observed across higher setpoints at 600 RPM and 700 RPM, PIDAT maintained steady-state errors of 2.0% and 1.571%, respectively, compared to the higher and more variable errors under Ziegler–Nichols. Figure 4 depicts the system's speed response at 500 RPM under PIDAT control. The graph shows a smooth rise with limited overshoot and quick stabilization, confirming the values reported in Table II. Together, the data and figure demonstrate that PIDAT adapts more effectively to sudden disturbances, resulting in improved accuracy and faster recovery compared to conventional tuning.

Table III shows the system's performance under constant load conditions using 2 kg and 4 kg masses at reference speeds of 500 and 700 RPM, comparing the PIDAT method with Ziegler–Nichols tuning. Across all test cases, PIDAT consistently achieved faster rise and settling times with lower steady-state errors. For example, at 500 RPM with a 2 kg load, PIDAT recorded a rise time of 0.52 s, settling time of 2.10 s, and a steady-state error of 0.4%, while Ziegler–Nichols tuning showed slower dynamics with a 1.46 s rise time and 2.0% error. Similar improvements were seen at 700 RPM, where PIDAT achieved 0.29% error and only 1.32 s settling time. Even under heavier loads (4 kg), PIDAT maintained better performance, with settling times nearly half of those under Ziegler–Nichols tuning. Although PIDAT resulted in slightly higher overshoot in some cases—such as 18 RPM at 700 RPM with 4 kg load—it compensated with quicker recovery. These findings are illustrated in Figure 5, which depicts the experimental speed response at 500 RPM under a 2 kg load. The graph clearly shows how the PIDAT method allowed the motor to reach the target speed more quickly and stabilized faster, thereby validating the numerical results in Table III and confirming the method's effectiveness in handling constant mechanical disturbances with high accuracy and adaptability.

The performance trends shown in both tables clearly underscore the superior adaptability and precision of the PIDAT approach in dealing with real-world disturbances. By automatically recalibrating control parameters based on real-time system response—triggered when the steady-state error exceeded a defined threshold—the PIDAT strategy effectively minimized manual tuning efforts and ensured high reliability in maintaining motor speed stability. These experimental outcomes validate the implementation of PIDAT as a robust, self-correcting control solution that can accommodate both sudden and sustained load variations, making it highly suitable for deployment in industrial automation systems where dynamic performance and consistency are essential.

V. CONCLUSION

This research successfully developed and implemented a PIDAT–based speed control system for three-phase induction motors using the Omron CP1H PLC. The adaptive algorithm dynamically retuned the PID parameters when the steady-state error exceeded 5%, allowing the system to maintain performance under varying load conditions. Experimental results confirmed that the system maintained speed stability with steady-state errors below 1.70% under no-load and below 0.80% under load, along with settling times below 9 s and disturbance recovery times under 4 s. Compared to the classical Ziegler–Nichols method, the PIDAT strategy offers improved accuracy, faster response, and greater adaptability without requiring manual tuning. These features make the system highly suitable for real-time, adaptive motor control in industrial automation environments.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest with any party regarding the conduct of this research, data analysis, or the preparation of this manuscript.

AUTHORS' CONTRIBUTIONS

Conceptualization, Nanang Rohadi and Liu Kin Men; methodology, Nanang Rohadi; software, Nanang Rohadi; validation, Nanang Rohadi, Liu Kin Men, and Akik Hidayat; formal analysis, Nanang Rohadi; investigation, Nanang Rohadi; resources, Nanang Rohadi; data curation, Nanang Rohadi ; writing—original draft preparation, Nanang Rohadi; writing—reviewing and editing, Nanang Rohadi; visualization, Nanang Rohadi; supervision, Nanang Rohadi; project administration, Nanang Rohadi; funding acquisition, Liu Kin Men.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the Electrical Engineering Laboratory, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, for providing technical and facility support throughout the research. Appreciation is also extended to colleagues who offered constructive feedback during the system development and manuscript preparation.

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