© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722561

Speed Control of Induction Motor Under Changing Load Torque Using PWM-PID Controller

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Abstract- ***Three-phase induction motor is widely applied in many applications requiring speed control precision such as milling machines and robotic systems and therefore, maintaining constant speed at a predefined value is essential. Several methods of speed control having been applied to three-phase induction in literature. This paper designs Pulse Width Modulation-discrete time Proportional Integral and Derivative (PWM-PID) controller to maintain a predetermined speed for three-phase induction motor in under constant and changing load condition. The mathematical model of the three-phase induction is presented and simulated in MATLAB/Simulink environment. Simulation results revealed that the motor exhibited excellent starting characteristics at no load, with minimal overshoot of 0.9036%and a relatively fast settling time of 0.2295 s. Under constant load of 50 N-m and changing load of 20 N-m and 50 N-m, the motor speed was characterised by settling time, peak time, and overshoot of (5.1107 s and 6.5983 s), (0.3 sand 0.3445 s), and (0.9394% and 1.003%), respectively. When compared with PI, the developed PID offered better performance in all transient response characteristics considered including improved stability.***

Keywords: speed control, pulse width modulation, pid, induction motor

I. INTRODUCTION

Induction motors are the most common motors used in industrial motion control systems. Low-cost, simple and rugged design and low maintenance is the main advantages of induction motors. Due to that, these motors are often called the workhorse of the motion industry. Also, several studies have been carried out on different aspect of induction motor to enhance its performance characteristics such as the studies regarding stray losses induction motor, rotor temperature analysis, transient analysis of induction motor dynamics, stator current control, and speed control. [1,2,3,4,5].However, the most widely focused aspect is the speed control of induction because it is largely applied in industry for drives to increase production.

The applications of induction motors in high accurate drives require more advanced control techniques so that those nonlinear and strongly coupled induction motors whose parameters are time-variant can be effectively controlled. At present, Proportional-Integral-Derivative (PID) controller, due to its simplicity, stability, and robustness, is a type of controller that is most widely applied [6]. However, it is difficult to design when the accurate model of plant is unknown. For induction motors, factors such as unknown load characteristic and parameter variation influence seriously the controlling effect of speed controller. Therefore, some advanced control techniques such as variable structure control and adaptive control etc. have been presented. However, the design of these controllers is based on known system model parameters and if the parameters can't be achieved, it is very troublesome in designing these controllers too.

Direct and indirect vector control methods for the speed and torque control of induction motor have found intensive application through the last two decades. For the indirect control on induction motor, in addition to the rotor speed, accurate knowledge of the slip frequency is required. On the other hand, direct control of induction motor necessitates accurate information on the rotor speed, as well as rotor flux as referred to the stator stationary frame.

Several speed control systems have been implemented. For instance, [7] used Pulse Width Modulation (PWM) Technique based Proportion-

Integral (PI) controller to improve the transient response of three-phase induction motor. The study evaluated the performance of the speed control system under different operational speed at changing time interval. [8] compared the performance of different control approaches for induction motor speed regulation, specifically examining the proportional–integral (PI), proportional–integral–derivative (PID), and fuzzy logic controller (FLC) methods. The comparative analysis was conducted across various reference speeds. For a target speed of 1800 rpm, the PI controller achieved a response of 1798 rpm, the PID controller produced 1794 rpm, and the FLC yielded 1793 rpm. At 1700 rpm set point, the PI, PID, and FLC gave 1702 rpm, 1689 rpm, and 1687 rpm respectively. Similarly, at a 1500 rpm reference, the responses were 1502 rpm (PI), 1498 rpm (PID), and 1493 rpm (FLC). [9] presented a comparative study of different induction motor speed control strategies through an extensive literature review. Their analysis encompassed voltage and current control techniques such as Pulse Width Modulation (PWM), phase control, and vector control for three-phase induction motors. The comparison provided insights into the performance, complexity, and implementation challenges of each approach.[10] developed a fuzzy logic-based speed control system for induction motors, where the FLC functioned as an AC voltage controller that generated firing signals for thyristors according to operating torque, motor speed, and load conditions. MATLAB/Simulink simulations confirmed that the FLC offered improved accuracy, robustness, and safety compared to conventional numeric firing angle computation techniques. The fuzzy logic design proved particularly effective in enhancing overall system precision and responsiveness.[11] proposed an improved Integral Sliding Mode Control (ISMC) method for induction motor speed control, designed within the d–q synchronous reference frame using indirect Field-Oriented Control (FOC). The ISMC scheme achieved global asymptotic speed tracking even under model uncertainties and varying load torque. The enhanced design utilized a switching sigmoid function to suppress chattering and relied on Lyapunov stability theory to ensure overall system stability. [12]conducted a comparative study between classical voltage/frequency (V/F) control and Indirect Field-Oriented Control (IFOC) for a 10 HP three-phase squirrel cage induction motor. The research incorporated SPWM and PI control to manage the three-phase inverter voltage. Simulations in MATLAB/Simulink revealed that IFOC achieved smoother speed transitions, better dynamic performance, and higher response speed than the conventional V/F method. [13] employed pulse width modulation (PWM) techniques and a universal bridge configuration to regulate the speed of an induction motor. A PID controller was integrated to manage the DC link voltage of the voltage source inverter. MATLAB/Simulink simulations were conducted for both open-loop and closed-loop configurations. In open-loop mode, the system recorded a speed response of 1500 rpm, rise time of 0.7 s, delay time of 0.55 s, and settling time of 0.9 s. Under closed-loop operation, the response improved significantly, achieving a speed of 1420 rpm, rise time of 0.02 s, delay time of 0.015 s, and settling time of 0.2s.

The various works reviewed have shown significant improvement in speed control against the induction motor operating without advance control techniques. However, low accuracy regarding reaching the desired operating speed still persists. Thus, a reliable speed at the output of the induction motor to efficiently drive connected loads is not completely guaranteed. The issue regarding varying setpoint (or desired operating speed) and changing load torque scenario has not been well investigated. The goal of this work is to improve the speed of induction motor and maintain high level accuracy under changing load torque conditions.

II. METHODS

In this section, the mathematical model of three-phase induction motor and the developed discrete time PID controller are covered. The block diagram of the developed three-phase induction motor speed control system is presented including the motor's parameter.

2.1. Mathematical model

The mathematical descriptionof three-phase induction motor in d-q frame is stated in Equations (1) to (10) as in [14]and [15].

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_e \lambda_{qs} \tag{1}$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} + \omega_e \lambda_{ds} \tag{2}$$

$$V'_{dr} = R_r i'_{dr} + \frac{d}{dt}\lambda'_{dr} - \omega_{sl} \lambda'_{qr} \tag{3}$$

$$V'_{qr} = R_r i'_{qr} + \frac{d}{dt}\lambda'_{qr} + \omega_{sl} \lambda'_{dr} \tag{4}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i'_{dr} \tag{5}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i'_{qr} \tag{6}$$

$$\lambda'_{dr} = L'_r i'_{dr} + L_m i_{ds} \tag{7}$$

$$\lambda'_{qr} = L'_r i'_{qr} + L_m i_{qs} \tag{8}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda'_{dr} i_{qs} - \lambda'_{qr} i_{ds}\right) \tag{9}$$

$$\dot{\omega}_r = \frac{T_e - T_L}{J} \tag{10}$$

Where V_{ds}, V_{qs}, V'_{dr}, and V'_{qr} are stator and rotor voltages. i_ds,i_qs,i_dr^', and i_qr^' are the currents for the stator and rotor windings, respectively. λ_ds,λ_qs,λ_dr^', and λ_qr^' stand for the flux linkages in stator and rotor. R_s and R_r are the stator and rotor windings' resistances. L_s and L_r^' are the stator and rotor windings' self-inductances. L_m is the mutual inductance of the motor windings, ω_e and ω_sl are supply and slip angular frequency, respectively. T_e and T_L are the motor's electromagnetic torque and load torque, respectively. J is the rotor initial and the connected load.ω ̇_r is the rate of change of the rotor's speed.ω_r (s) is the motor's rotor speed.

2.2.PID control system

A discrete time real PID controller is implemented in this work rather than the ideal type. The block diagram of PID control system is shown in Figure 1.

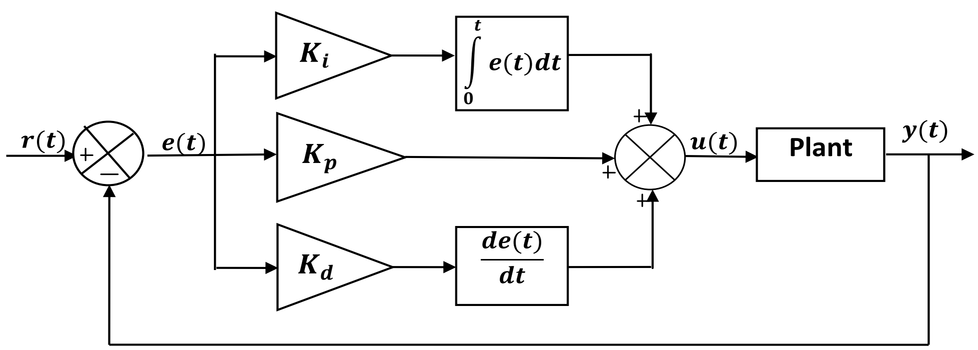


Figure 1: Block diagram of PID control system

From Figure 1, the mathematical model of PID controller can be established in terms of the control variable, $u(t)$ by:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{11}$$

Assuming zero initial conditions, Equation (11) can be expressed in s-domain as in Equation (12) or in simplified form representing an ideal PID controller.

$$U(s) = K_p E(s) + K_i \frac{1}{s} E(s) + K_d s E(s) \tag{12}$$

$$C(s) = K_p + K_i \frac{1}{s} + K_d s \tag{13}$$

where $C(s)$ is the PID controller and K_p, K_i, and K_d are the proportional, integral, and derivative gains respectively. Nevertheless, real PID controller is often implemented in practice with a pre-filter of coefficient, N. The pre-filter included in the derivative component addresses noisy effect that may impact the controller through derivative element. Mathematically, the real PID is defined in continuous-time form as in Equation (14) [16,17] and in discrete-time form by Equation (15) [18].

$$C(s) = K_p + K_i \frac{1}{s} + K_d \left(\frac{sN}{s+N}\right) \tag{14}$$

$$C(z) = K_p + K_i \frac{T_s}{z-1} + K_d \frac{N}{1 + \frac{NT_s}{z-1}} \tag{15}$$

The gains of the PID controller were determined by nonlinear tuning in MATLAB. This yielded $K_p = 0.009$, $K_i = 0.856$, $K_d = 0.001$, and N=10. The continuous-time real PID controller was converter into discrete-time using Forward Euler based integrator and filter methods. A sampling time, $T_s = 0.001$ s was used for the conversion of the PID from continuous-time to discrete-time. The structure of the three-phase induction motor speed control system in Simulink is shown in Figure 2.

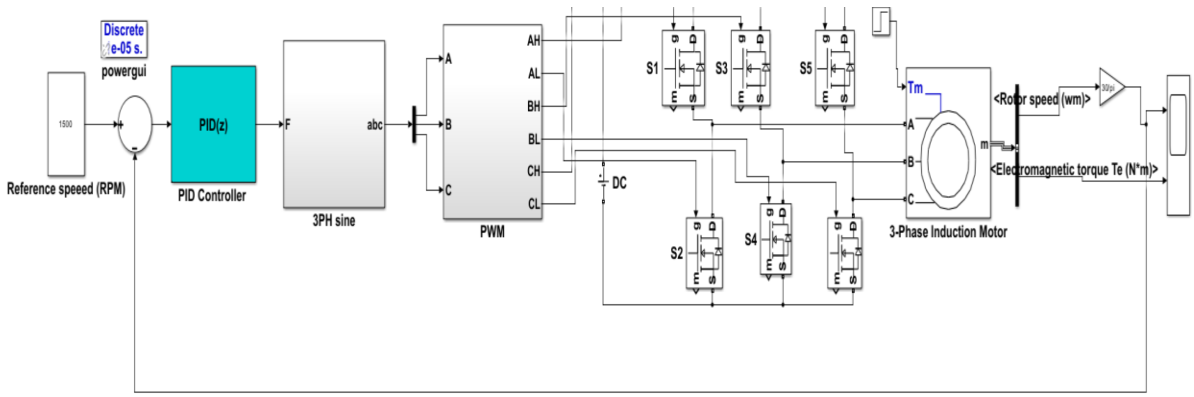
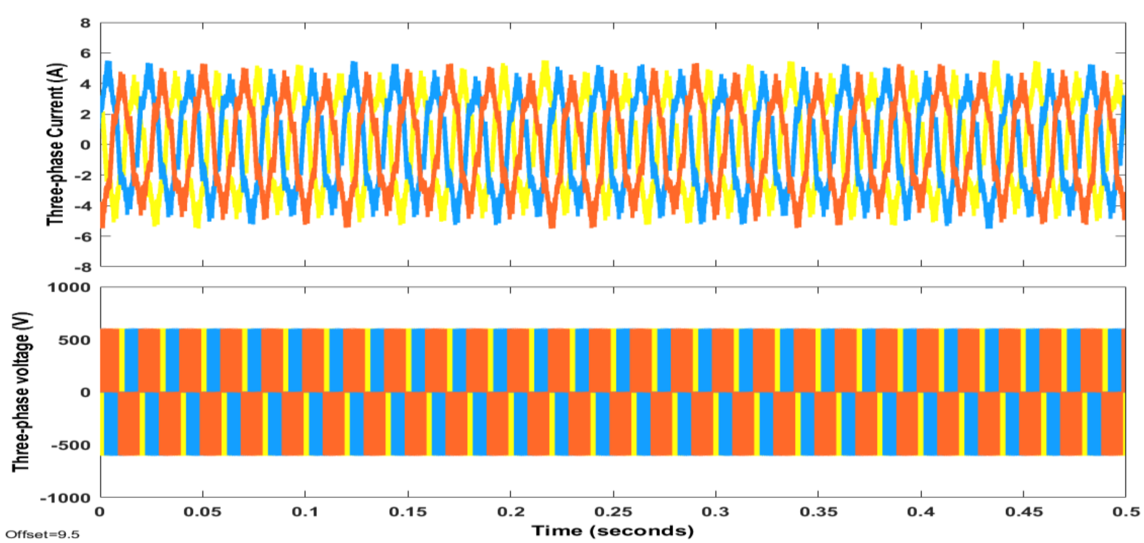


Figure 2: Structure of induction motor speed control system

III. RESULTS

In this section, the simulated waveforms of speed control system for the three-phase induction motor are clearly presented for different scenarios. The system was modelled and simulated using MATLAB Simulink to evaluate the performance characteristics of the motor under various operating conditions.Basically,the speed response performance of the motor was analysed at different load torques. Figures 3 and 4 show the electrical quantities (current and voltage) and the mechanical parameters (speed and torque) responses of the motor at no load condition.



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DOI: https://doi.org/10.64388/IREV10I2-1722561

Figure 3: Three-phase electrical quantities used by the motor

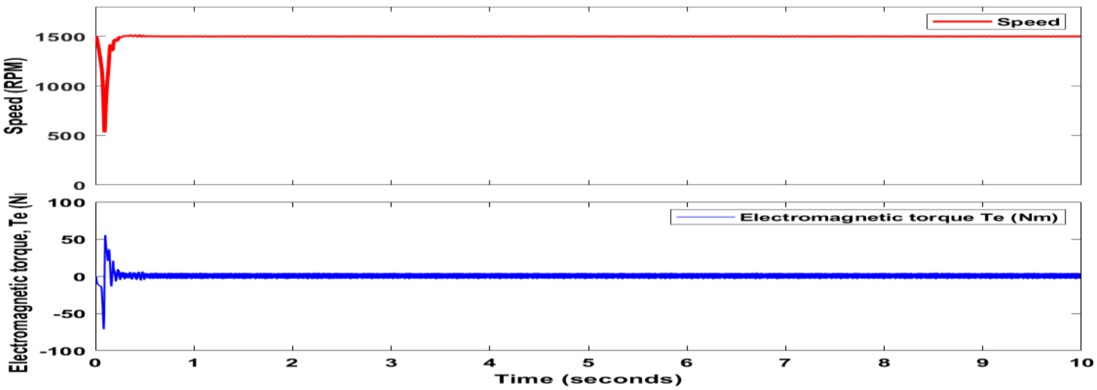

Figure 4: Motor speed and torque responses at no load

Figure 3 shows the three-phase alternating current (AC) quantities, currentand voltage. It illustrates the wave forms of the three-phase supply to the induction motor. The three components of the AC voltage for the a, b, c reference axis are shown to oscillate within 500 V. From the simulated plots in Figure 4, the transient response performance of the motor speed at no load is presented in Table 1.

Table 1: Transient Response Parameters at No Load (0 N-m)

Parameter	Value
Rise Time	0.001 s
Settling Time	0.2295 s
Overshoot	0.9036%
Peak	1515.2 rpm
Peak Time	0.3445 s

The results indicate that the motor exhibits excellent starting characteristics at no load, with minimal overshoot and a relatively fast settling time. The motor reached its peak speed of 1515.2 rpm at 0.3445 s before converging to the desired speed of 1500 rpm at 0.2295 s, demonstrating a rapid acceleration profile.

When a load torque of 50 N-m is applied to the motor shaft, the resulting simulated wave forms of the electric current and voltage used by the three-phase induction motor and the changed in its speed and electromagnetic torque characteristics are shown in Figures 5 and 6.

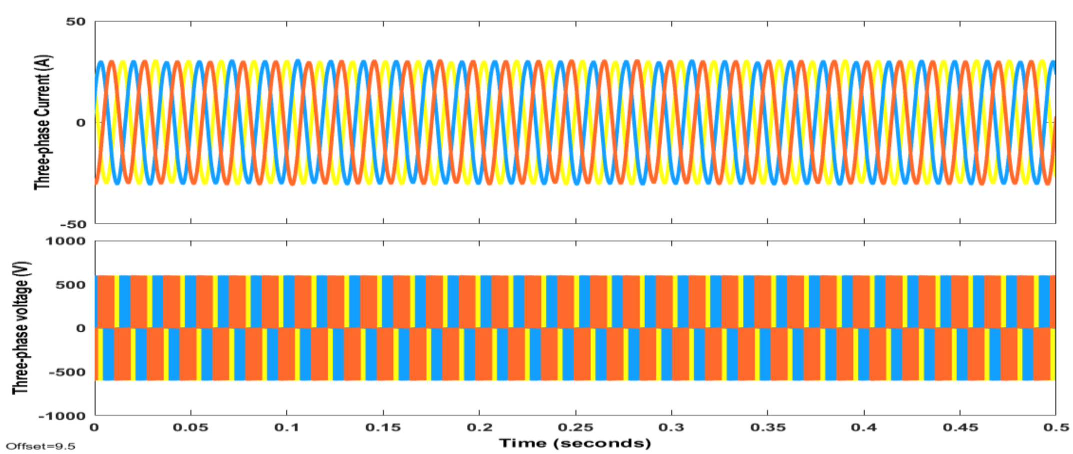

Figure 5: Three-phase electrical quantities with the motor loaded

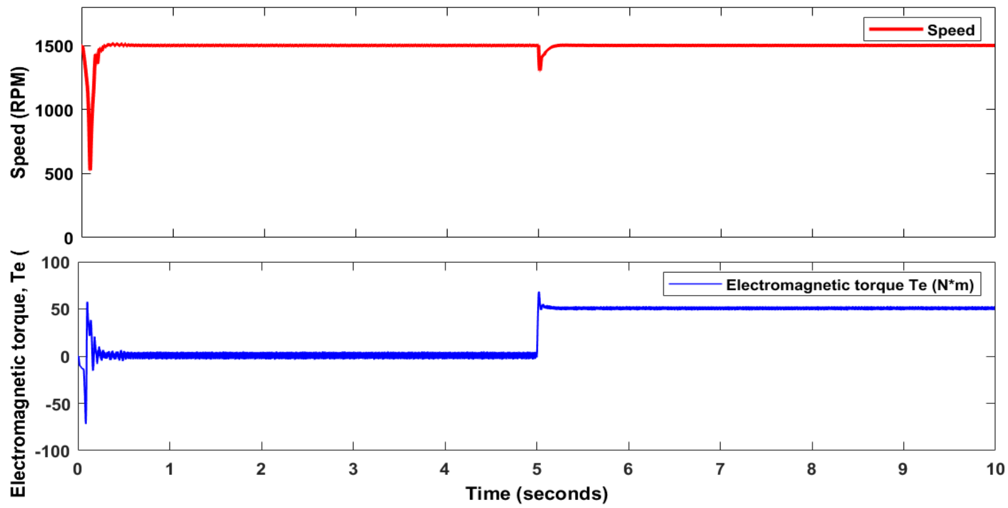

Figure 6: Motor speed and torque responses under 50 N-m load

From Figure 5, it can be clearly seen that the introduction of load caused the motor to draw more current from the supply. This results in increase in the current consumed by motor while the voltage remained the same as in the case of no load. This means that application of load to motor causes more current to flow through its winding. In Figure 6, the application of a 50 N-m load caused a slight increase in the rise time to 0.001 s and settling time to 5.1107 s. The overshoot slightly increased to 0.9394%, while the peak speed increased in the same proportion to 1516 rpm before the motor settles to desired speed later than in load condition at time t = 5.1107 s. This behaviour is expected as the motor must overcome the additional load torque, resulting in slightly degraded dynamic performance compared to the no-load condition. The numerical performance of the system transient response parameters of the speed is shown in Table 2.

Table 2: Transient Response Parameters at 50 N-m Load

Parameter	Value
Rise Time	0.001 s
Settling Time	5.1107 s
Overshoot	0.9394%
Peak	1516 rpm
Peak Time	0.34 s

The simulation of the three-phase motor is evaluated in this context considering the fact that it starts at no load from time t = 0 and subsequently, varying load torque (20 N-m and 50 N-m) occurred. That is, as the motor begins to run, the connected load torque varies from time to time. The resulting speed response and electromagnetic torque curves are shown in Figure 7. The time domain parameters of the speed response are listed in Table 3.

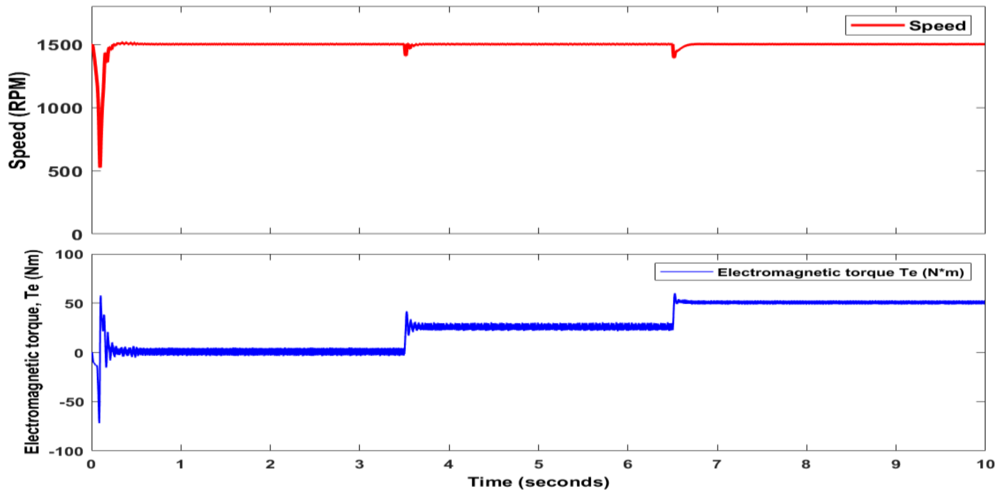

Figure7:Motor speed and torque responses under changing load

Table 3: Speed response parameters of motor at varying load torque

Parameter	Value
Rise time	0.001 s
Settling time	6.5983 s
Overshoot	1.003%
Peak	1516 rpm
Peak time	0.3445

As shown in Figure 7, the observed speed response and electromagnetic torque of the three-phase motor controlled by discrete time PID controller under varying torque indicates that the system dynamics is largely influenced. For instance, looking at Table 3, though the system still maintains the same rise time as in the case of no load and constant load, its peak time, settling time, peak value, and overshoot were largely affected by the effect of the changing load torque. This indicates that with the dynamic of the motor changing due to loading effect. Despite the variations in the dynamic response parameters of the motor, the discrete time PID controller was able to settle the speed at the referenced value (1500 rpm) after 6.5983 s.

Comparison of discrete time PI and PID controllers was simulated as shown by the dynamic responses of the motor in Figure 8. This was considered to demonstrate the limitation of PI, which has largely been implemented in three-phase induction motor speed control such as in [19]. PI controllers are largely prone to integration winding, and are susceptibility to environmental conditions. This simulation was conducted for no load condition.

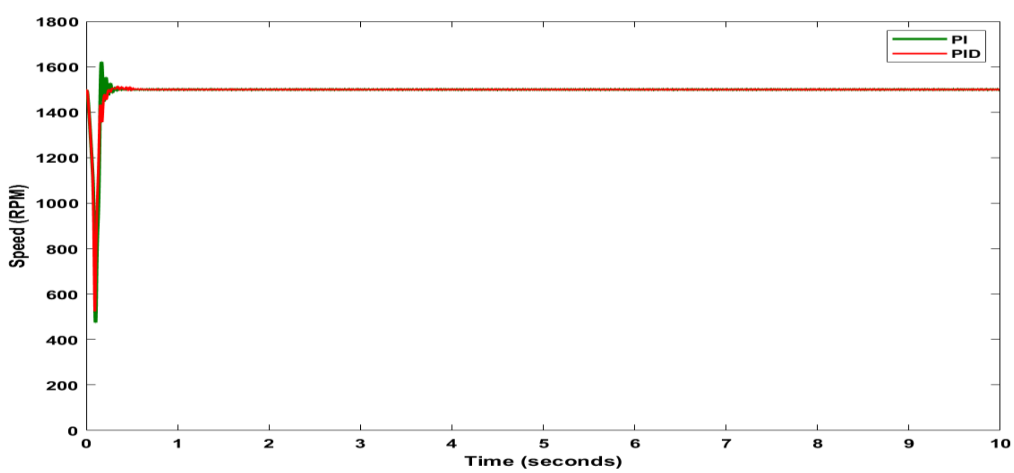

Figure 8: Motor speed response with PI and PID control systems

Table 4: Transient Response of PI and PID speed control system at no load (0 N-m)

Parameter	PI	PID
Rise Time	0.001	0.001 s
Settling Time	0.2646	0.2295 s
Overshoot	8.2416	0.9036%
Peak	16217 rpm	1515.2 rpm
Peak Time	0.1669 s	0.3445 s

The speed responses of discrete time PI and PID controllers revealed that at the start of the control process, the PI controller overshoot the speed by 8.2416% above the referenced value.In the case of thePID controller, the reference speed was overshoot by 0.9036%.After a while both controllers settled the speed at the reference value, but some trace of noisy effects like ripples were observed in the response of the PI controller. Generally, the PID controller offered faster convergence and better stability in terms of overshoot than the PI controller.

IV. DISCUSSION

The PWM-based discrete-time PID controller developed in this study showed reliable speed regulation of the three-phase induction motor under no-load, constant-load, and varying-load conditions. The controller was implemented with gains of Kp=0.009K_p = 0.009Kp=0.009, Ki=0.856K_i = 0.856Ki=0.856, and Kd=0.001K_d = 0.001Kd=0.001, using a sampling time of 0.001 s, which provided stable and responsive control throughout the simulations.At no load, the motor reached the reference speed of 1500 rpm with a low overshoot of 0.9036% and a settling time of 0.2295 s. This fast and smooth response indicates that the selected PID parameters were effective in controlling the motor during startup. When a constant load torque of 50 N-m was applied, the overshoot increased slightly to 0.9394%, while the settling time rose to 5.1107 s. This increase is expected due to the additional torque demand, yet the motor speed was still accurately restored to the reference value.Under varying load torque conditions of 20 N-m and 50 N-m, the system experienced further changes in dynamic behaviour. The settling time increased to 6.5983 s and overshoot reached 1.003%, showing the influence of load variation on the motor dynamics. Despite this, the controller maintained speed regulation and prevented sustained speed deviation.A comparison between PI and PID controllers highlighted the advantage of derivative action. The PI controller produced a high overshoot of 8.2416% and noticeable speed fluctuations, while the PID controller limited overshoot to below 1% and achieved faster settling. This confirms that the PID controller offers better stability and transient performance.

Overall, the results show that the PWM-based discrete-time PID controller provides a practical and effective solution for induction motor speed control. However, performance reduction under varying loads suggests that adaptive or intelligent tuning methods could further improve control accuracy.

V. CONCLUSION

This paper presented the PWM-PID controlled three-phase induction motor system using MATLAB Simulink. The system was successfully simulated under four different loading conditions and comprehensive performance data was collected and analysed. The results demonstrate that the system exhibits stable operation across all tested load conditions, the dynamic performance degrades progressively with increasing load, the controller maintains adequate speed regulation despite varying mechanical loading, and the transient response characteristics show predictable trends consistent with induction motor theory. These findings validate the effectiveness of PWM-PID based control for three-phase induction motor applications and provide valuable insights into system behaviour under different operating conditions. However, future study will sick to optimize the parameters of the PID controller using intelligent algorithm for tuning purpose.

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