*Mechatronics and Automation Technology*
*J. Xu (Ed.)*

*doi:10.3233/ATDE241237*

# Sensorless Speed Control of Induction Motor Drives Using Disturbance Observer and Adaptive PID Controller

Katherin INDRIAWATI[a,1], Ricko SUPRIYANTO[b]
[a] *Department of Engineering Physics, Institut Teknologi Sepuluh Nopember, Indonesia*
[b] *Digital Automation, PT. Kaldu Sari Nabati, Indonesia*

**Abstract.** This study discusses the development of a sensorless speed control method for induction motors using an adaptive PID Controller. An approach is proposed that utilizes a disturbance observer to estimate the speed of the induction motor. Subsequently, an adaptive PID Controller is implemented to regulate speed control with real-time parameter adjustments based on the motor's operating conditions. Experimental results show that the combination of these two methods enhances dynamic response performance, particularly in avoiding overshoot and steady-state error. By applying this technique, effective control is achieved without the need for additional sensor devices, leading to reduced costs and system complexity. This research makes an important contribution to the development of more efficient and reliable induction motor technology and opens avenues for further research in sensorless control applications.

**Keywords.** Sensorless speed control, induction motor, disturbance observer, adaptive PID Controller.

## 1. Introduction

Induction motors are one of the most widely used types of electric motors in industrial and commercial applications, owing to their reliability, high energy efficiency, and low maintenance costs. Speed control of induction motors plays a crucial role in improving system performance and operational efficiency. For example, in applications such as compressors and pumping systems, induction motor control is essential for minimizing electricity consumption and reducing flow rate losses during operation [1].

The PID controller is one of the simplest yet highly effective control methods for many applications. Its straightforward structure makes it easy to implement, both in hardware and software, making it a common choice in various industrial applications, including motor control. The PID method has been extensively researched and used for decades, with abundant literature and practical experience available to assist in design and implementation. As reported in [2], PI control achieves faster response times. Yet, with constant controller parameters, there are still system responses that are not appropriate and not fast enough, which led to the development of adaptive PID controllers, as proposed by [3].

[1] Corresponding Author, Katherin INDRIAWATI, Department of Engineering Physics, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia; E-mail: katherin@ep.its.ac.id

Traditionally, speed measurement for feedback to the controller has been performed using sensors, such as encoders or tachometers. However, the use of these sensors often adds complexity and cost to the system, as well as increases the risk of mechanical failure. The use of encoders for measuring the speed of induction motors reduces motor reliability and requires additional maintenance due to vibrations generated by the motor [4]. As a solution, sensorless speed control has emerged as an attractive approach. This method not only reduces the need for additional hardware but also offers advantages in terms of reliability and resistance to disturbances. Therefore, sensorless control is increasingly used in modern industrial settings [5]. It also has been reported that sensorless control provides faster dynamic response and improves system control reliability [6] [7]. In a study done by [8], sensorless control was applied to an induction motor used for pump control. This research used a Model Reference Adaptive System (MRAS) to compensate for disturbances, making it difficult to track errors accurately.

It is well known that there are two main control schemes for induction motors by manipulating the inverter supply: vector control and scalar control, or V/F control. In the context of sensorless control, a PID controller can be integrated with other techniques, such as a disturbance observer, as proposed by [9]. In that study, the control scheme used was direct torque control (DTC), which is a type of vector control. However, the research was only tested through numerical simulations, without real-time implementation. Furthermore, V/F control is often preferred due to its simplicity and stability [10]. This technique uses the basic relationship between voltage, frequency, and speed, making it easier to understand and operate. Since scalar control does not require complex hardware, such as rotor position sensors or more advanced control systems, the overall system cost tends to be lower. Moreover, tuning and adjusting parameters for scalar control is generally simpler compared to vector control, which requires more complex adjustments. In [11], V/F control was applied to an induction motor, but the control still used a speed sensor and a PI regulator.

In this study, we propose a sensorless speed control method for induction motors that utilizes a disturbance observer and an adaptive PID Controller. The aim of this study is to explore the effectiveness of the combination of these two approaches in maintaining the performance of induction motors. Real-time experimental results were reported to demonstrate the advantages of the proposed method compared to traditional control techniques.

## 2. System Description

The 3-phase induction motor used in this study is the Alliance AY3A-90L4, which has 4 poles, an input power of 1.5 kW, and a rotational speed of up to 1440 rotations per minute (RPM). The power supply for the induction motor is provided by a Toshiba VF-nC3 voltage source inverter (VSI), where the output voltage serves as the control variable to regulate the motor's speed. By default, this type of inverter has its own control over the voltage-to-frequency (V/f) ratio.

The conventional PID control algorithm for the induction motor was developed using a modified classic closed-loop V/F control approach, adapted [11]. The control scheme includes speed measurement using a proximity sensor and a PID regulator as a compensator for the difference between the actual rotor speed and the estimated rotor speed. Figure 1 shows the conventional PID control scheme for the induction motor with V/f control scheme.

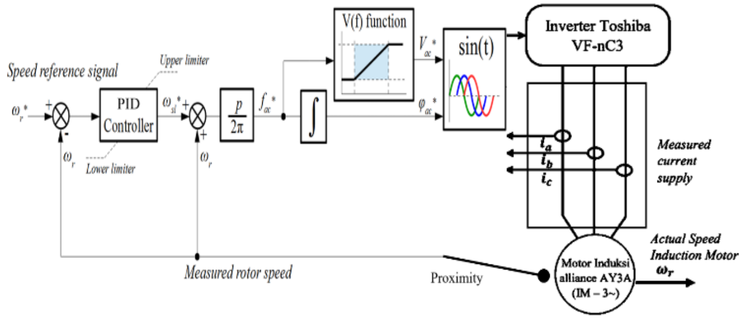


**Figure 1.** Conventional PID control scheme for a three-phase induction motor using V/f control.

The difference between the reference speed ($\omega_r^*$) and the measured speed ($\omega^*$) by the proximity sensor is known as the setpoint error. The PID controller compensates for this error to obtain the actual slip value ($\omega_{sl}^*$). The actual slip is then added to the measured speed to produce the stator reference speed ($f_{ac}^*$). The stator speed is translated into the reference voltage amplitude ($V_{ac}^*$) by the V/F linear function. The V/F linear function is used to limit the maximum and minimum operating values. The signal is then converted into three sinusoidal waveforms at a frequency of $f_{ac}^*$ , each with a 120° phase difference.

## 3. Proposed Method

### *3.1. Development of Adaptive PID Control*

The adaptive PID control is developed based on the approach outlined by [12], as shown in figure 2. In this method, a Recursive Least Square (RLS) is employed to identify the plant model parameters represented by a second-order ARMA equation, expressed as follows:

$$G(z) = \frac{b_0 z^{-1} + b_1 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \tag{1}$$

The plant model parameters, namely $\theta = [a_1, a_2, b_0, b_1]$, are identified using the input/output data pairs $[u(k-1)\ y(k-1)]$ and $[u(k-2)\ y(k-2)]$. The identified parameters are then used to update the PID controller parameters through the controller formulation stage.

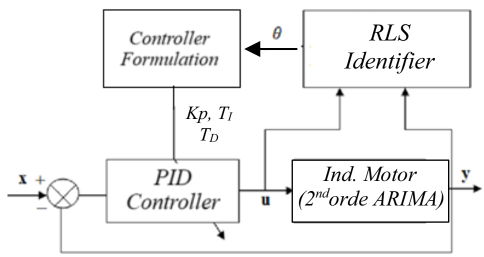


**Figure 2.** Block diagram of adaptive PID control system.

The PID control algorithm is expressed in the discrete domain with a sampling time $T_s$ as follows:

$$u(k) = K_p e_{(k)} + \frac{K_p T_s}{\tau_i} \sum_{i=1}^{K} e_{(i)} + \frac{K_p \tau_d}{T_s}\left[e_{(k)} - e_{(k-1)}\right] \tag{2}$$

with the PID controller parameters are:

$$K_p = \frac{k_1 k_0 - k_2 - (2+k_0)k_3}{(1+k_0)^2} \tag{3}$$

$$T_i = T_S \frac{K_p(1+k_0)}{k_1+k_2+k_3} \tag{4}$$

$$T_d = \frac{k_0 k_1 - k_2 k_0 + k_3}{K_p(1+k_0)^2} \tag{5}$$

The three PID controller parameters above are functions of [$k_0$, $k_1$, $k_2$, $k_3$], whose values depend on the values of the plant model parameters. All four are calculated in the controller formulation section with the following equations:

$$k_1 = \left(\frac{1}{b_1}\right)\left(\frac{2T_S}{T_S+2_\tau}\right) \qquad k_2 = a_1 k_1 \qquad k_3 = a_2 k_1 \qquad k_0 = \frac{b_2}{b_1} \tag{6}$$

*3.2 Development of Sensorless Adaptive PID Control*

The sensorless adaptive PID control is a modification of the adaptive PID control, incorporating an estimator to replace the speed sensor. The estimator used is a disturbance observer (DO), which operates according to the following dynamic estimator equations [9]:

$$\hat{x}_a(k+1) = A_d \hat{x}_a(k) + B_d u(k) + L\left(i_s(k) - \hat{i}_s(k)\right) \tag{7}$$

$$\hat{y} = C_a x_a(k) \tag{8}$$

Here, $k$ represents the time index, and $L$ is the observer gain. The parameters $A_d$ and $B_d$ are defined as follows:

$$A_d = I_{7x7} + \begin{bmatrix} A & D_d \\ 0 & \varepsilon I \end{bmatrix} T_s \qquad B_d = \begin{bmatrix} B \\ 0 \end{bmatrix} T_s \tag{9}$$

where $T_s$ is sampling time, $A$, $B$, and $D_d$ are the state-space model parameters of the induction motor, derived using the stator reference frame in the $\alpha$-$\beta$ axes, as follows:

$$\dot{x} = Ax + Bu + D_d d \tag{10}$$

where

$$x = \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \\ \varphi_{\alpha r} \\ \varphi_{\beta r} \end{bmatrix},\ d = \begin{bmatrix} d_\alpha \\ d_\beta \end{bmatrix} = \begin{bmatrix} \omega_r \varphi_{\beta r} \\ \omega_r \varphi_{\alpha r} \end{bmatrix},\ u = \begin{bmatrix} v_{\alpha s} \\ v_{\beta s} \end{bmatrix}$$

$$A = \begin{bmatrix} A_1 & 0 & A_2 & 0 \\ 0 & -A_1 & 0 & A_2 \\ A_4 & 0 & -A_5 & 0 \\ 0 & A_4 & 0 & A_5 \end{bmatrix}, B = \begin{bmatrix} B_1 & 0 \\ 0 & B_1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, D_d = \begin{bmatrix} A_3 & 0 \\ 0 & -A_3 \\ -P/2 & 0 \\ 0 & P/2 \end{bmatrix}$$

$$A_1 = \frac{L_m^2 R_r + L_r^2 R_s}{\sigma L_r^2 Ls} \quad A_3 = \frac{P\,L_m}{2\,\sigma L_r\,L_s} \quad A_5 = \frac{R_r}{L_r} \quad A_6 = \frac{2\,P\,L_m}{3\,2J\,L_r}$$

$$A_2 = \frac{L_m\,R_s}{\sigma L_r^2 L_s} \quad A_4 = \frac{L_m\,R_r}{L_r} \quad B_1 = \frac{1}{\sigma\,L_s} \quad \sigma = 1 - \frac{L_m^2}{L_r\,L_s}$$

The block diagram of the speed sensorless adaptive PID control is represented in figure 3. In parallel, the estimated speed result is also used as the input of the RLS estimator. The input of the RLS estimator is the estimated speed $\widehat{\omega}_r$ and the control signal $u$. The RLS estimator will produce a tuning parameter $\theta$ which will then be entered into the controller formulation to adjust the PID parameters on the controller. To evaluate the speed estimation results and controller response, the speed sensor is still used to determine the actual speed value of the induction motor.

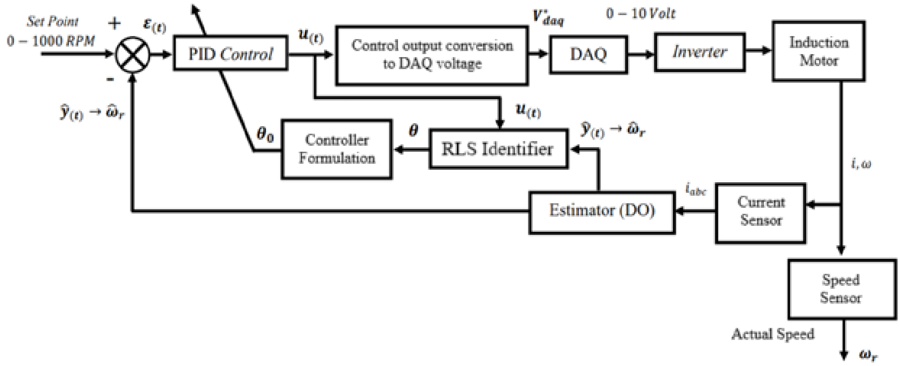


**Figure 3.** Block diagram of the sensorless adaptive PID control system.

## 4. Experimental Results

The equipment setup is shown in figure 4. The current sensor used is the SCT013 sensor. A low-pass filter circuit is required before connecting the sensor output to the DAQ. A personal computer serves as the controller, necessitating a digital and acquisition module (DAQ). The software utilized for this research is MATLAB - SIMULINK. The DAQ device is the NI USB-6008, featuring 8 analog inputs, 2 analog outputs, and 12 digital I/O. The range of the analog input and output voltage signals is 0 – 10V, with the analog input connected to the computer and the analog output connected to the inverter.

Figure 5 illustrates the response of the sensorless adaptive PID control during the experiment with a speed setpoint of 200 rpm. It is evident that the sensorless adaptive control system demonstrates superior response, exhibiting no overshoot. Both systems have a similar settling time of approximately 25 seconds when approaching the setpoint. The delay in measurement with the speed sensor contributes to feedback delay. Systems with minimal dead time or computational and measurement delays provide faster control feedback, leading to quicker responses to setpoints and reduced overshoot [13]. This phenomenon is more pronounced at higher speed setpoints, as depicted in figure 6 for a speed setpoint of 600 rpm. Here, the sensorless adaptive control system not only achieves a response without overshoot but also responds faster than the adaptive control system with a sensor.

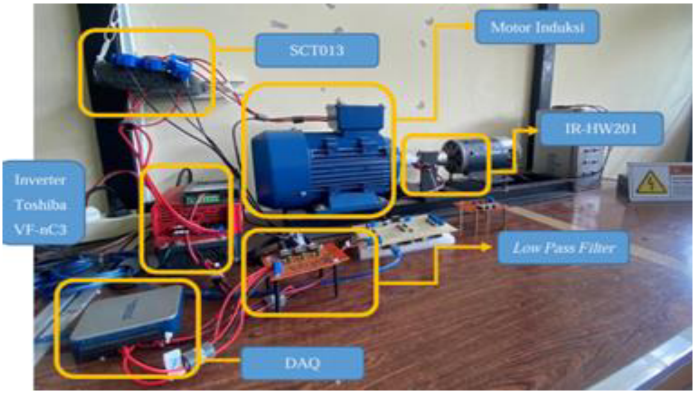


**Figure 4.** Experimental setup of the proposed control system.

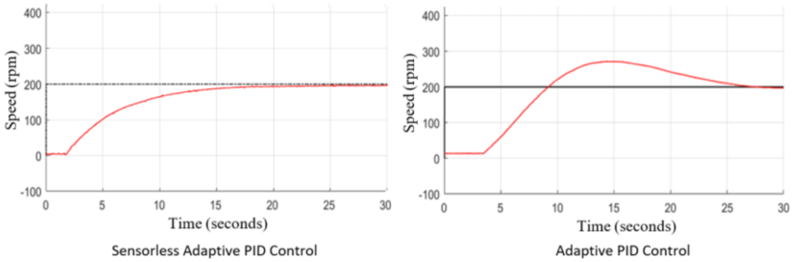


**Figure 5.** Comparison of speed responses between the sensorless adaptive PID control system and the adaptive PID control system at a setpoint of 200 rpm.

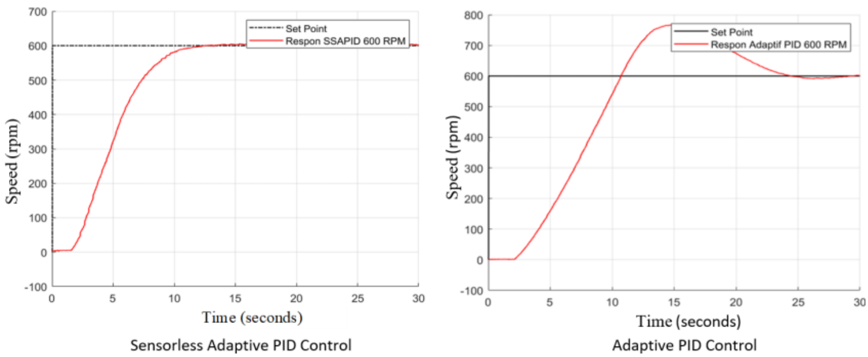


**Figure 6.** Comparison of speed responses between the sensorless adaptive PID control system and the adaptive PID control system at a setpoint of 600 rpm.

A comparison of responses is also conducted between the sensorless adaptive PID control and the sensorless PID control (non-adaptive) tuned using Cohen-Coon (CC) and Ziegler-Nichols (ZN) techniques, as shown in table 1. The results indicate that the responses of the PID controllers are nearly identical, with the CC tuning method appearing superior to the ZN tuning method. Furthermore, the sensorless adaptive PID control proves to be advantageous due to its lack of overshoot and minimal steady-state error.

**Table 1.** Comparison of control sensor speed response between adaptive PID and conventional PID

| Characteristic | Sensorless Adaptive PID | Sensorless PID CC | Sensorless PID ZN |
|---|---|---|---|
| Rise Time (s) | 11.288 | 3.621 | 3.782 |
| Settling Time (s) | 20.47 | 16.11 | 20.27 |
| Overshoot (%) | 0 | 17.02 | 17.49 |
| Steady State Error (%) | 1.51 | 1.84 | 2.51 |

## 5. Conclusion

This paper has developed a sensorless speed control method for induction motors that combines Disturbance Observer (DO) and Adaptive PID Controller. Overall, the results of this study demonstrate the significant potential of using sensorless adaptive PID control to enhance the performance of induction motor control systems, particularly in applications that require accurate responses and no overshoot. These findings open opportunities for further research in developing more efficient and reliable control systems for various industrial applications.

## References

[1] S. Oshurbekov, V. Kazakbaev, V. Prakht, V. Dmitrievskii, and L. Gevorkov, Energy Consumption Comparison of a Single Variable-Speed Pump and a System of Two Pumps: Variable-Speed and Fixed-Speed[J]. Applied Sciences, 2020, Vol. 10, Page 8820, vol. 10, no. 24, p. 8820.

[2] H. Hartono, R. I. Sudjoko, and P. Iswahyudi. Speed Control of Three Phase Induction Motor Using Universal Bridge and PID Controller[C]. Journal of Physics: Conf. Series, 2019, vol. 1381, no. 1.

[3] Y. Zhao and C. Luo. Adaptive PID Control with Forgetting Factor for Three-phase Asynchronous Motor[C]. Journal of Physics: Conference Series, 2020, vol. 1626, no. 1, p. 012091.

[4] R. Marino, P. Tomei, and C. M. Verrelli. Tracking Control for Sensorless Induction Motors with Uncertain Load Torque and Resistances[C]. IFAC Proc. 2010,Vol., vol. 43, no. 14, pp. 771–776.

[5] S.-K. Sul, Y.-C. Kwon, and Y. Lee. Sensorless control of IPMSM for last 10 years and next 5 years. CES Transactions on Electrical Machines and Systems, 2020, vol. 1, no. 2, pp. 91–99.

[6] Proceedings of International Conference on Artificial Intelligence, Smart Grid and Smart City Applications[C]. Proceedings of International Conference on Artificial Intelligence, Smart Grid and Smart City Applications, 2020.

[7] Y. Ren, R. Wang, S. J. Rind, P. Zeng, and L. Jiang. Speed sensorless nonlinear adaptive control of induction motor using combined speed and perturbation observer," Control Engineering Practice, 2022, vol. 123, p. 105166.

[8] A. Nazelan et al., "Dynamic Analysis of Sensorless Controlled Industrial Pump Drive[C]. IOP Conference Series: Materials Science and Engineering, 2020, vol. 906, no. 1, p. 012029.

[9] K. Indriawati, B. L. Widjiantoro, B. L. Widjiantoro, and N. Rifa'i Rachman. Disturbance observer-based speed estimator for controlling speed sensorless induction motor[C]. 3rd International Seminar on Research of Information, 2020.

[10] M. A. Awdaa, A. A. Obed, and S. J. Yaqoob. A Comparative Study between V/F and IFOC Control for Three-Phase Induction Motor Drives[C]. IOP Conference Series: Materials Science and Engineering, 2021, vol. 1105, no. 1, p. 012006.

[11] M. Sztykiel et al. Adaptive V/f-based control for induction machines in distributed electric propulsion systems[C]. IEEE International Conference on Electrical Systems, 2018

[12] H. Mudia, R. Effendie. Perancangan dan Implementasi Kontroler PID Adaptif pada Pengaturan Kecepatan Motor Induksi Tiga fasa. download.garuda.kemdikbud.go.id, Accessed: Oct. 14, 2024.

[13] H. Wu, H. Ni, and G. T. Heydt. The impact of time delay on robust control design in power systems[C]. Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, 2002, vol. 2, pp. 1511–1516.