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Research Original Article

Implementation of Industrial Internet of Things-Based Scalar Control Method Using PID Controller for Multiple Three-Phase Induction Motor Control

Angga Wahyu Aditya✉[1], Restu Mukti Utomo[2], Nur Rani Alham[3], Faisal Faiiz Ramadhanu[4]
[1] Department of Electrical Engineering, Politeknik Negeri Balikpapan, Jl. Soekarno – Hatta, Balikpapan City, 76129, Indonesia, angga.wahyu@poltekba.ac.id
[2] Department of Electrical Engineering, Universitas Mulawarman, Jl. Kuaro – Gn. Kelua, Samarinda City, 75119, Indonesia, restuutomo@ft.unmul.ac.id
[3] Department of Electrical Engineering, Universitas Mulawarman, Jl. Kuaro – Gn. Kelua, Samarinda City, 75119, Indonesia, nurrani.alham@ft.unmul.ac.id
[4] Department of Electrical Engineering, Politeknik Negeri Balikpapan, Jl. Soekarno – Hatta, Balikpapan City, 76129, Indonesia, faisalfaiiz46@gmail.com
✉Corresponding Author: angga.wahyu@poltekba.ac.id | Phone: +6287865215425

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Abstract
Developing industrial standard induction motor control devices is inseparable from the advantages and ease of implementation. Induction motor control has developed rapidly since the development of semiconductor technology, which allows for more efficient, flexible, and accessible settings. The third industrial revolution makes it easier to control induction motors by meeting device standards and data communication systems. The development of cloud technology and the industrial Internet of Things in the fourth industrial revolution makes it easier to quickly control multiple induction motors from various places. Industry-standard devices such as human-machine interface, programmable logic control, and inverters are used to determine the performance of multiple induction motors using a scalar method based on PID controllers with a mobile phone remote control. PID performance is analyzed under transient conditions by measuring the rise time value and overshoot percentage. Meanwhile, the parameters measured in steady-state conditions are the average steady-state error values. The parameters on the PID controller are adjusted intuitively. The parameters used in data collection consist of the first parameter with the value of K_p = 26, K_i = 14, and K_d = 12, and the second parameter with the value of K_p = 29, K_i = 15, and K_d = 0. The rise time value will increase along with the given speed reference. The overshoot percentage value depends on the speed reference and the PID parameter value. At the same time, the average steady-state error value is below 5% for almost all speed references under loaded and unloaded conditions.
Keywords: Multiple Induction Motor; IIoT; Scalar Control; Industrial Instrument

Introduction
The use of induction motors, especially three-phase induction motors in the industrial sector, is inseparable from the various advantages such as high efficiency, simple but robust construction, low operating costs, high reliability, and low maintenance costs (Aditya et al., 2019; Happyanto & Aditya, 2022). However, the main disadvantages of induction motors are that they are challenging to regulate and have very high starting currents. Nevertheless, induction motors remain the main driving force in various industrial sectors, especially manufacturing and transport (Sieklucki, 2018).

The use of induction motors has increased significantly in recent years. It was driven by the development of induction motor control devices caused by the Industrial Revolution 4.0. This industrial revolution causes massive changes in the automation system in the industry. Remote control and the involvement of artificial intelligence technology change the industry's system of regulating actuators, sensors, and control devices. The development of Internet of Things technology in the industrial world, better known as the Industrial Internet of Things (IIoT), allows control and monitoring of sensors, actuators, and control devices from anywhere and anytime in real-time. In addition, the Industrial Revolution impacted the development of actuator control devices, especially induction motors. The development of control devices on induction motors is focused on the constant voltage/frequency (v/f constant) method, better known as the scalar method. The scalar method has the advantage of being easily implemented in industrial devices with low operational costs. The development of induction motor control devices by the automation industry has involved the utilization of IIoT by utilizing communication protocols such as Modbus communication on both input and output parameters. The utilization of IIoT developed with artificial intelligence technology has made it possible to determine the age and condition of hardware devices, determine the timing of hardware replacement, and manage device performance in real time from anywhere (Gundewar & Kane, 2021; Tran et al., 2021).

Research development related to inverter-based induction motor control with scalar methods has been carried out by many researchers (Hareesh & Jayanand, 2021; Lee & Han, 2022; Prasetia & Santoso, 2018). For example, the development of a scalar method for Field Programmable Gate Array (FPGA)-based induction motor control is carried out to control rotor speed, stator current, and electromagnetic torque both in no-load and load conditions (Dutta et al., 2024; Nayli A., 2015). FPGA-based induction motor regulation with scalar methods can be implemented in electric vehicles and electric steering learning devices (Barbosa et al., 2023; Waleed et al., 2021). Industrial Revolution 4.0 affected the induction of motor regulation systems in various sectors, especially the manufacturing industry. Research related to cloud computing-based remote control systems as induction motor settings began to be developed. Internet of Things devices such as ESP8266 and ESP32 provide instructions for setting points in the form of reference speed in induction motor settings (Dwiyaniti et al., 2023; Metwly et al., 2020; Prabudha & Madhusudhanan, 2019; Syawali & Meliala, 2023). The development of Internet of Things technology on an industrial scale or IIoT is embedded in human-machine interface (HMI) and programmable logic control (PLC) devices by utilizing the internet network (Dehbashi et al., 2022; Pavithra & Rao, 2018; Vadi et al., 2022). Meanwhile, controllers in the scalar method for induction motor speed regulation are developed based on FPGA and digital signal processing boards (Lima et al., 2014; Orfanoudakis et al., 2024; Saffar et al., 2023; Suetake et al., 2011). This paper focuses on regulating two induction motors using the conventional control method. The controller used is PID with an intuitive parameter tuning method. IIoT is designed based on a human-machine interface connected to the internet network, which is data communication on a variable speed drive with a human-machine interface using Modbus communication.

Materials & Methods

Induction motors are inherently complicated to regulate. Mechanical control of the induction motor using a gear comparator is the simplest method of controlling the speed of an induction motor. In addition to changing the motor speed, this method will directly increase the motor torque as the motor speed is inversely proportional to the torque. Although it is easy to use, this method has many disadvantages, including high cost, difficulty setting multiple speed references, and high energy consumption due to the motor running continuously at the optimum speed.

$$\omega_r = (1 - s)\,\omega_s$$

where:

$$\omega_s = \frac{120 * f}{P}$$

ω_r = rotor speed
ω_s = stator speed
s = slip
f = frequency
P = number of pole pairs

therefore:

$$\omega_r = \frac{120 * f}{P}\,(1 - s) \quad (1)$$

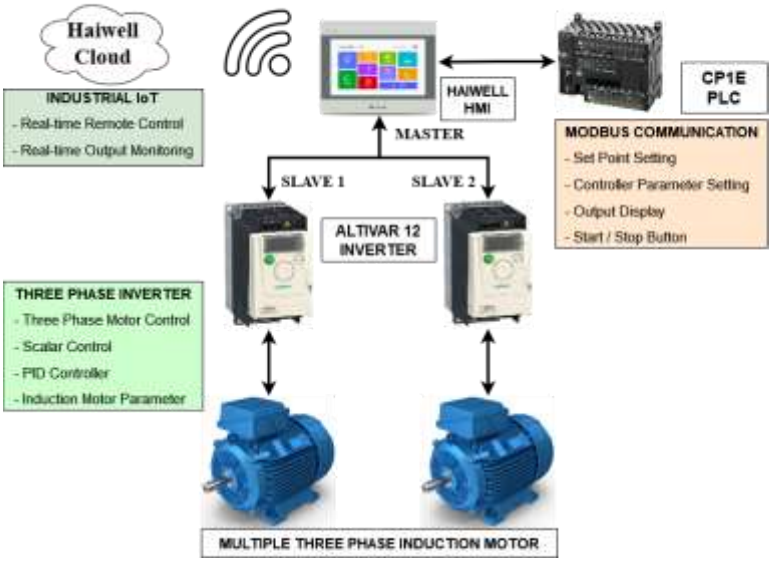
Another method to control the speed of an induction motor is by using the induction motor speed equation, as shown in Equation (1). Speed regulation can be achieved by changing the number and frequency of pole pairs. There are several methods for regulating the speed of an induction motor based on the number of pole pairs (Matsumoto & Sakai, 2022). These methods include consequent poles, multiple stator windings, and pole amplitude modulation (Kim & Jung, 2021; Latif et al., 2023). In the consequent poles method, a single stator winding is divided into several groups of coils, and the number of poles can be changed by altering the coil connections. Multiple stator windings involve two windings in the stator, wound on different numbers of poles. By connecting the windings to different numbers of poles, the speed of the induction motor can be altered. Pole Amplitude Modulation (PAM) is a flexible solution for applications requiring speed ratios other than 2:1. Motors designed using PAM, known as PAM motors, offer efficient speed-changing capabilities (Abdel-kader et al., 1999; Bobojanovo, 2023). However, speed control methods based on changing the number of pole pairs have several disadvantages, including high costs, difficulty in maintaining speed when disturbed, and low efficiency in induction motors (Latif et al., 2023).

Apart from changing the number of pole pairs, the speed of the induction motor can be regulated by changing its frequency. Setting an induction motor by changing the frequency requires a constant ratio of terminal voltage to frequency, so this method is better known as constant volts per hertz. Therefore, speed regulation using the frequency change method requires a variable voltage power source with a variable frequency supply obtained from a voltage source inverter, current source inverter, or cyclo converter (Azizipanah-Abarghooee & Malekpour, 2020; Guo et al., 2017). The fundamental difference between an inverter and a cyclo converter lies in the converted voltage type. The inverter changes DC voltage into AC with a variable frequency, while the cyclo converter changes the AC voltage with a specific frequency into AC voltage with a variable frequency (Setiyono & Dwinanto, 2021; Venugopal et al., 2023). Industrial standard induction motor control devices have been widely implemented since the industrial revolution 3.0.

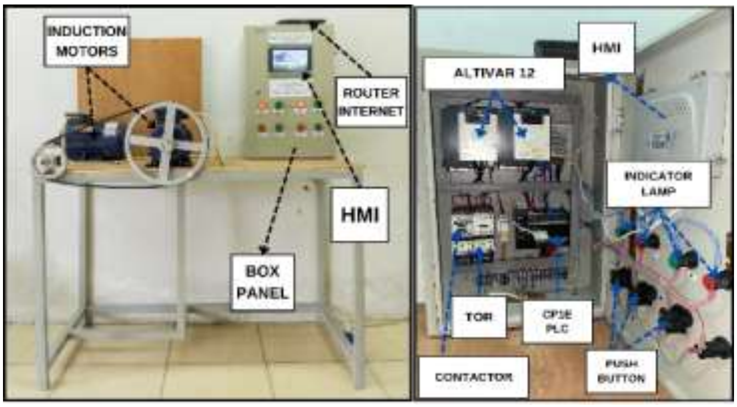
The development of industrial automation technology and modern computing devices has made induction motors one of the main drivers in various strategic industrial sectors. Along with technological developments, the Industrial Revolution 4.0 allows control of a device to be carried out anywhere and anytime using IIoT.

This research design utilizes standard industry equipment to control induction motors by adjusting the frequency using a voltage source inverter, shown in Figure 1. Multiple induction motors are linked to an Altivar 12 voltage source inverter, which employs a constant volt per hertz method. The Altivar 12 utilizes a closed control system with a proportional-integral-differential controller. The PID equation used is demonstrated in Equation (2). Input parameters such as the desired frequency or speed value, system start/stop instructions, and proportional, integral, and differential constants are configured on the Haiwell C7s HMI using the Modbus communication protocol. The Haiwell C7s HMI also presents output data through graphs and numbers, including the rotor speed of the induction motor. All this data can be stored in tabular form for induction motor performance analysis. The implementation of IIoT-based remote control is highlighted in Figure 2. The remote control is designed based on a mobile application using the Haiwell cloud for data storage.

$$PID\ Controller\ \rightarrow u(t) = K_p e(t) + K_i \int e(t) + K_d \frac{de(t)}{dt} \tag{2}$$



a.



b.

Figure 1. Experimental setup. a. diagram design; b. hardware implementation

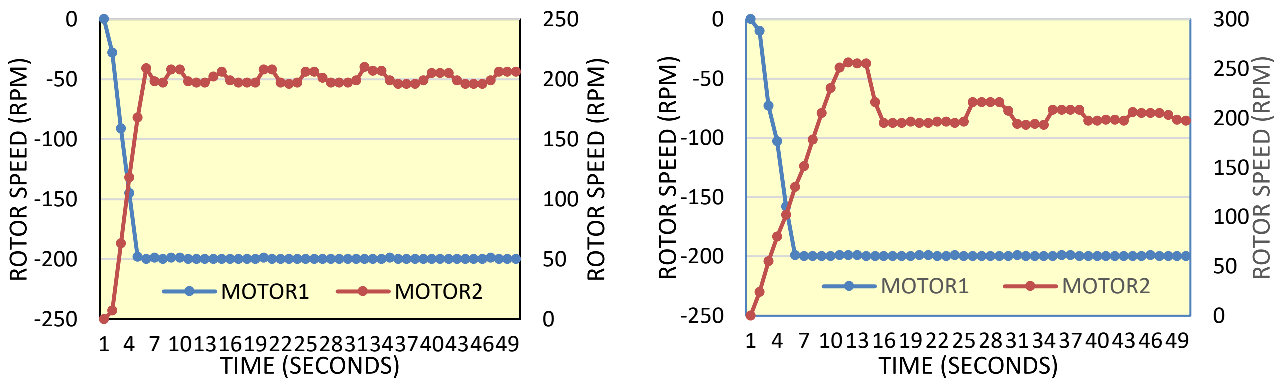
Figure 2. User interface of IIoT based induction motor control

Results and Discussion

Experimental testing was carried out by providing input parameter values as rotor speed references for multiple induction motors. Giving parameter values can be done via mobile phone by utilizing the IIoT mechanism that has been built or entering parameter values directly via the HMI. In addition to the rotor speed parameter value, proportional, integral, and differential constant parameters can be entered through the exact mechanism as shown in Figure 3. The user interface display on the HMI and mobile phone is designed to perform control and data display functions. The control function is carried out by providing parameter values. At the same time, the data display is intended to display the speed response data of the first and second induction motors in the form of graphs and numbers. In addition, the data display function is intended to record data related to induction motor control performance based on rotor speed response values and proportional, integral, and differential constants.

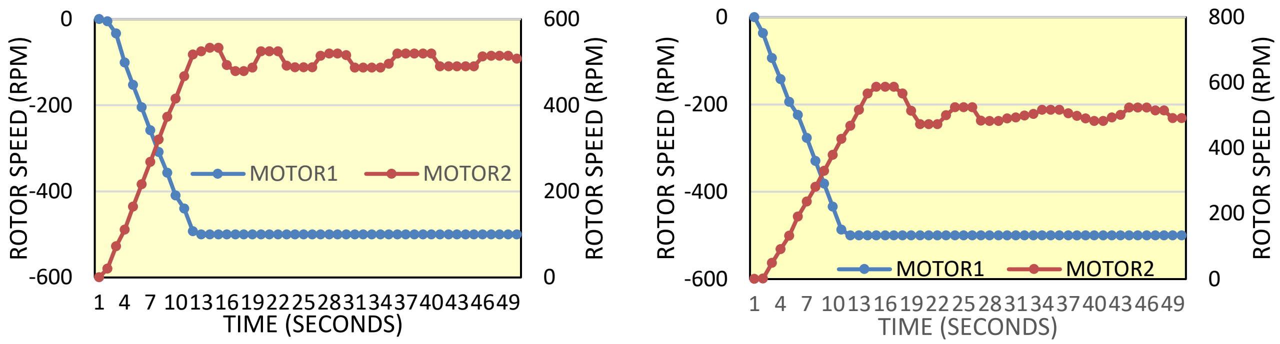
Figure 3. IIoT control of induction motor using mobile phone

The performance of induction motor control based on the IIoT is evaluated at low, medium, and high speeds with proportional, integral, and differential constant parameters that modify intuitively. The low-speed references employed are 200 rpm and 500 rpm. In addition, the medium-speed reference is 800 rpm, while the high-speed reference value is 1100 rpm and 1400 rpm. The distribution of speed reference values is based on the nominal speed of the induction motor, which is 1500 rpm. The tests with various speed references are based on the operational characteristics of induction motors in industrial contexts. This is because induction motors in industrial contexts do not operate continuously at their nominal speed. In the experimental testing phase, the first and second induction motors exhibited identical speed reference values with the same proportional, integral, and differential constant values. Performance testing of the PID controller is conducted by introducing disturbances at the point when the second induction motor has reached a steady state condition. Meanwhile, the first induction motor is not subjected to any disturbances. Furthermore, the performance of the PID controller on the induction motor was evaluated during transient conditions by measuring the rise time value of the first and second induction motors. The overshoot value under transient conditions and the steady-state error (SSE) value were only measured on the second induction motor, as this was the only motor subjected to a disturbance.



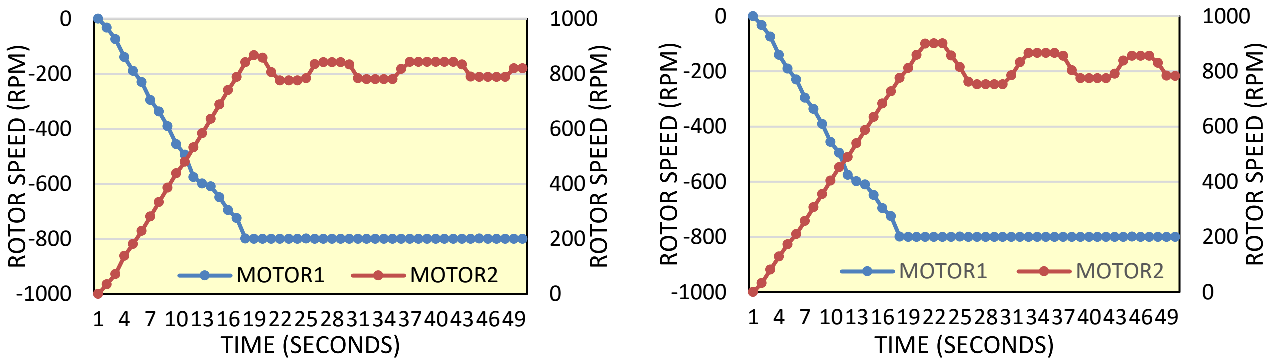
K_p = 26, K_i = 14, K_d = 12 K_p = 29, K_i = 15, K_d = 0

Figure 4. Rotor speed response in 200 rpm of reference speed



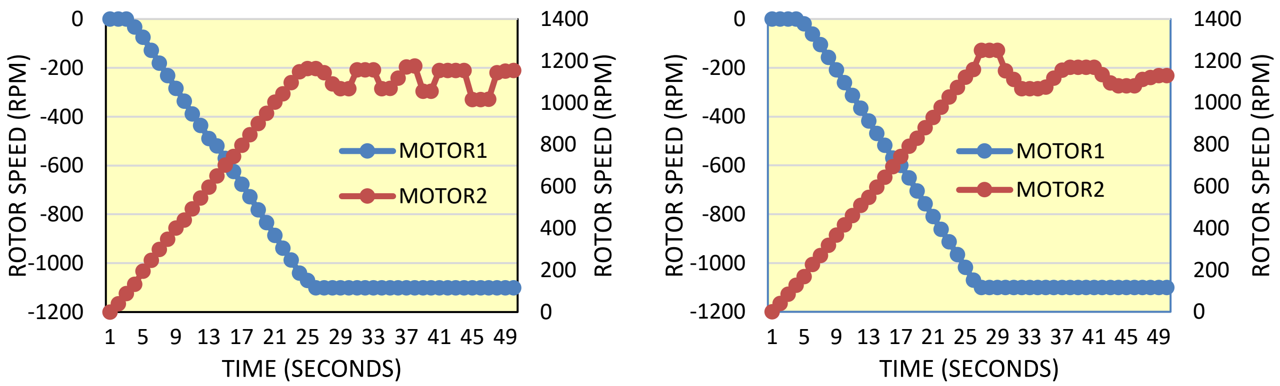
K_p = 26, K_i = 14, K_d = 12 K_p = 29, K_i = 15, K_d = 0

Figure 5. Rotor speed response in 500 rpm of reference speed



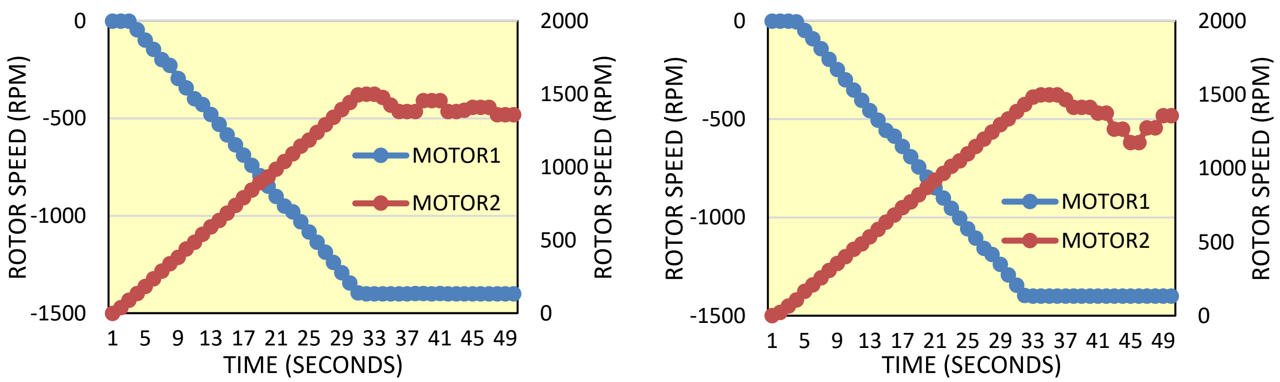
K_p = 26, K_i = 14, K_d = 12 K_p = 29, K_i = 15, K_d = 0

Figure 6. Rotor speed response in 800 rpm of reference speed



K_p = 26, K_i = 14, K_d = 12 K_p = 29, K_i = 15, K_d = 0

Figure 7. Rotor speed response in 1100 rpm of reference speed



K_p = 26, K_i = 14, K_d = 12 K_p = 29, K_i = 15, K_d = 0

Figure 8. Rotor speed response in 1400 rpm of reference speed

The rotor speed data collection of the first and second induction motors was carried out by operating the induction motors for 50 seconds. The time interval selection was based on the time the induction motor reached a steady-state condition when the nominal speed had been reached. Both induction motors reached nominal speed in about 30 seconds. The difference in data collection duration with the time the induction motor reached nominal speed was used to determine the performance of the PID controller by providing disturbances when reaching a steady-state condition. The PID constants used the first parameter values K_p = 26, K_i = 14, K_d = 12 and the second parameter values K_p = 29, K_i = 15, K_d = 0. The speed performance of the reference induction motor with a motor speed of 200 rpm is shown in Figure 4. At the first PID parameter value, the analysis under transient conditions showed that the rise time value of the first induction motor was 6.93 seconds. In contrast, the rise time value in the second induction motor was 9.45 seconds, with an overshoot percentage value reaching 3.00%. Under load conditions, the second induction motor has an average SSE value of 1.38% and 3.10% under no-load conditions. The transient and steady-state response of the first PID parameter is better than the second under transient conditions because the rise time of the first motor is 4.41 seconds, and the second motor is 5.67 seconds with an overshoot percentage of 28.00%. However, under steady-state conditions, the performance of the first PID parameter is better than the performance of the second PID parameter, with an average SSE value of 2.03% under load conditions and 8.16% under no-load conditions. The speed response of the induction motor with a reference of 500 rpm is shown in Figure 5. The transient condition performance with the first PID parameter shows that the first and second induction motors have a rise time value of 7.56 seconds, with an overshoot percentage value of 3.60% for the second induction motor. Under steady-state conditions, the second induction motor has an average SSE value of 2.53% under load and 3.97% for no-load conditions. The first induction motor does not experience a change in the rise time value on the second PID parameter. However, on the second induction motor, the rise time value becomes higher, namely 8.19 seconds, with an overshoot percentage value of 17.40%. In steady state conditions, the second induction motor with the second PID parameter has a higher SSE value than the first PID parameter by 2.78% when loaded and 4.05% when unloaded. Figure 6 shows the speed response of the induction motor at a reference of 800 rpm. The rise time value on the first induction motor's first PID parameter is smaller than the second induction motor by a difference of 1.26 seconds. The overshoot percentage value of the second induction motor on this PID parameter is 8.38%. In steady-state conditions, the second induction motor has an average SSE value of 2.24% when loaded and 4.19% when unloaded. The second PID parameter shows that in transient conditions, the first induction motor has the same rise time value as the first PID parameter of 11.97 seconds. While in the second induction motor, it is 15.12 seconds with an overshoot percentage of 12.62%. Steady-state condition analysis shows that the second PID parameter has an average SSE value more significant than the first PID parameter, with a value of 3.27% in no-load conditions and 6.18% in loaded conditions. The speed response of the motor at a high reference of 1100 rpm and 1400 rpm is shown in Figure 7 and Figure 8. The transient condition analysis of the first induction motor with reference of 1100 rpm on the first PID parameter shows a rise time value of 16.38 seconds and an increase in the second PID parameter of 17.01 seconds. The second induction motor has a smaller rise time value than the first induction motor, with a value of 15.12 seconds, but has an overshoot percentage value of 5.81% on the first PID parameter and a rise time value of 15.75 seconds with an overshoot percentage of 13.63% on the second PID parameter. The steady-state condition of the second induction motor shows that the first PID parameter has an average SSE value smaller than the second PID parameter under loaded conditions, namely 4.11% and 2.35%. The opposite occurs under unloaded conditions, with an average SSE value of 5.25% for the first PID parameter and 7.48% for the second PID parameter. At the reference of 1400 rpm, the first and second induction motors are the same, with the first PID parameter having the same rise time value of 20.16 seconds and an overshoot percentage value of 7.00% on the second induction motor. In the second PID parameter, the rise time value increases to 20.79 seconds on both induction motors with the same overshoot percentage value on the second induction motor. Steady-state condition analysis shows that the average SSE value on the first PID parameter is 1.82% under load conditions and 3.30% under no-load conditions. This value increases in the second PID parameter to 9.38% and 3.71% under no-load conditions.

Conclusions

Scalar method-based induction motor control has been carried out since the third industrial revolution. The application of IIoT in the Industrial Revolution 4.0 has changed the paradigm of induction motor control, which can be done anytime and anywhere. The use of industrial devices such as PLC, HMI, and Altivar inverters allows the control to be applied on a larger scale that meets the safety and operational standards of the industrial world. This study uses industry-standard devices with the Modbus communication protocol to transmit input data and control parameters. The PID controller is implemented to maintain the condition of the induction motor if there is a disturbance. PID performance is tested in three-speed references: low, medium, and high speed. The low-speed reference consists of 200 rpm and 500 rpm, while the medium-speed reference consists of 800 rpm, and the high-speed reference consists of 1100 rpm and 1400 rpm. The division of this speed reference is based on the nominal speed of the induction motor. Analysis of transient conditions shows that the rise time value increases from the low-speed reference to the high-speed reference because the time to reach steady-state conditions also increases. In addition, the overshoot percentage value experienced a significant increase, namely, 3% at a reference speed of 200 rpm to 7% at a reference speed of 1400 rpm for the first PID parameter. In steady-state conditions, the average SSE value is still below the tolerance limit of 5%. It shows that the PID control embedded in the induction motor can overcome disturbances.

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