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Research Article

Three-Phase Induction Motor Control and Monitoring Using VFD and ESP32 Based on Modbus RTU Protocol

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Abstract

The use of energy in industrial processes is required to be efficient to reduce production costs as low as possible. In general, an industry relies heavily on three-phase induction motors. In its operation, the induction motor is operated in such a way that the energy usage is not maximized, so it is more efficient. To achieve this goal, the industry has used VFD (Variable Frequency Drive) to regulate the speed of induction motors according to the desired needs as well as to avoid "magnetic weak and saturation" conditions in the motor. This paper presents a Learning module for control and monitoring of 3-phase induction motor using Microcontroller embedded WIFI (ESP32), a VFD, and Modbus RTU protocol. The existence of this learning module will be helpful to control and view the motor parameters globally and easily. The presence of Esp32 provides convenience and flexibility for control designers to provide a cheaper control system, more speed process (2 processor), and be adaptive to future needs. Another advantage of this design model is that a user is given a choice of two user friendly applications, namely WhatsApp and Blynk IoT for giving users or students more enjoyable in learning control engineering. However, selecting the type of access application in an industrial environment must be done appropriately by considering network latency, stability, safety, feasibility, and the capability to overcome potential server failures. Regarding the use of VFD on a three-phase induction motor, an initial testing should be done to determine the maximum frequency that can be applied to achieve the motor's nominal current according to its nameplate (in this experiment, the maximum motor frequency is 40 Hz). Such testing is necessary to avoid more severe damage and can extend the motor's operational lifespan.

Keywords

VFD, ESP32, Control, Monitoring, Modbus RTU

1. Introduction

In industrial processes, an important thing that must be considered is the use of energy which must be as efficient as possible. In general, almost all industries that use electric motor drives (AC) as driving force, some of their controls use VFD (Variable frequency drive) technology for energy saving purposes. Even in this decade, VFDs are a vital component in the modern industrial and commercial sectors [1] to meet two parameters, namely rotational speed and torque in induction motors. The achievements in power electronics have improved the adjustable speed induction motor drives to obtain smooth and continuous speed variation. The speed of these motors can be controlled using either scalar or vector control techniques. In scalar control techniques, the motor speed is controlled by changing the amplitude or frequency of

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the supply voltage connected to the induction motor [2].

VFD has other names, namely ASD (Adjustable Speed Drive), AFD (Adjustable Frequency Drive), AC drive, and Inverter. If the motor is operated at low speed then less energy is used, so a large amount of power can be saved with the help of Variable Frequency Drive (VFD). Thus, VFD can function both in terms of speed control and energy savings [3, 4].

The VFD system uses the v/f method which is the best method, namely the amount of motor torque is directly proportional to the voltage (v) and inversely proportional to the frequency, so that the motor torque will be relatively more stable [5]. Variable Frequency Drive (AC drives) are used to stepless speed control of squirrel cage induction motors mostly used in process plants due to its ruggedness, smoother machine operation, and reduced maintenance [6, 7]. Meanwhile, changing the frequency will change the speed of the induction motor. However, VFDs also have weaknesses at low frequencies, namely decreasing efficiency, adding harmonics to the system, decreasing torque on the motor, and when using high power loads, for example on a reciprocating pump at high pressure, it causes large spikes in current [8].

Controlling the fluid flow rate in a piping system can be done using several techniques, for example by setting actuators such as valves or automatic pumps, which can be applied as a solution among these techniques. Controlling the flow rate using automatic valves is a leading technique that is still frequently applied, but limiting flow rates using valves can also waste energy if combined with a pump. Using this kind of valve for a short time can work well to control fluid flow rates, but causes energy waste if used continuously. Currently the industry avoids using valves to control fluid flow rates. And more than 60% of industrial power use is dominated by motor-based devices. Therefore, adjusting the angular speed of the pump motor can be another solution, namely by adjusting the angular speed of the pump motor using a VFD which will have an impact on the power it consumes. Based on many studies, VFDs are able to reduce pump power expenditure by 30–88% [9].

In this decade, the control of a pumping system (PS) has experienced very rapid development through progressive modernization to achieve greater efficiency in water exploitation. This can be achieved by integrating various modern solutions that replace traditional solutions, for example the PS regulation system which uses valve settings, and the star-delta for starting centrifugal pump type induction motors has been replaced with more energy efficient power electronics. Currently, the most widely implemented commercial solution to drive a PS at its variable speed is to use a VFD. VFD has also been equipped with proportional-integral (PI) frequency controller, with P and I parameters determined by off-line tuned [10].

When using a condensate pump as a driver to drain condensate from the condenser HOTWELLS to the storage tank. The Advanced Power Reactor 1400 (APR1400) consists of three condensate pumps operated with control carried out by level control valves (LCV). This configuration presents a challenge because the condensate water flow is controlled only by the LCV. This LCV is used in a choke position in the pipe where throttling of the valve causes a loss of system efficiency by increasing resistance to flow. In general, VFDs allow motors and pumps to be operated at the precise speeds required for process and energy savings. In this study it was investigated whether there are advantages when a VFD is used to control the CP (Condensate pump) and examined the possibility of eliminating LCV. From the results of this research, it was concluded that the application of VFD on CPs has advantages in terms of energy savings and economic benefits [11].

To facilitate the process of monitoring changes in motor speed, current and other parameters, VFDs can be combined with other devices, for example the use of PLC (Programmable logic controller) and SCADA (Supervisory Control & Data Acquisition) which are proven to be reliable and efficient in anticipating faults and errors in three-phase induction motor control process [12], so that the production process can run well. The use of VFDs combined with PLCs and SCADA has grown very rapidly, for example in the canned beverage industry where PLCs and VFDs are connected via RS485 serial communication with 2 cables using the Modbus ASCII protocol. Next, the Modbus will connect a PC computer to the remote terminal unit on SCADA [13]. VFD technology combined with PLC and Scada is also widely used in conveyor belt control, so that a user can easily monitor the movement of the conveyor at each position [14].

Besides Modbus ASCII is Modbus RTU which is a compact Modbus variant and is used in serial communications. Modbus RTU has been widely used in Building Management Systems (BMS) and Industrial Automation Systems (IAS). This protocol primarily uses an RS 232 or RS-485 serial interface for communication and is supported by almost all commercial SCADA protocols, HMI, OPC Server and data acquisition software programs on the Marketplace [15]. The RTU format is equipped with a cyclic redundancy error (CRC) mechanism to ensure data reliability. Modbus RTU is the most commonly used implementation of the Modbus protocol with each data frame separated by an idle period, more economical, open source, and robust [16].

The aim of this research is to present a VFD that is used to regulate the speed of a 3-phase induction motor. The VFD will be connected to a microcontroller via an RS485 module using the Modbus RTU protocol, so that data on the VFD in the form of speed (rpm), current (I) and voltage (v) can be monitored globally via the internet network [17]. The use of the Microcontroller is intended so that the user has flexibility in reading the parameters available in the VFD or combining them with other variables outside the VFD which come from other external sensors, and at the same time it can be used to send warning signals to the operator, update controller parameters and provides oscilloscopic views in real-time and buffered models [18]. Advances in wireless industrial communications have led to the development of controllers with wireless connectivity in the industrial sector. One of the important features of IoT is that the transmitted data can be uploaded to a digital virtual memory bank called a Cloud server using a secure server connection [19]. To make control and monitoring easier, a web display (GUI) will be used that makes it easier for users to control, monitor and analysis actions based on parameters that can be downloaded at the desired time period. Advances in wireless industrial communications have led to the development of controllers with wireless connectivity in the industrial sector.

2. Method

The main objective of this study is to present a three-phase control and monitoring system based on the Modbus RTU protocol using a cheap and powerful Microcontroller (ESP32) and VFD.

2.1. Modbus RTU Protocol

Communication between the ESP32 and VFD uses the Modbus Terminal Unit (Modbus RTU) protocol, which is a type of protocol for serial communication based on master-slave relationships. In this protocol, the Modbus slave only responds when there is a request from the Modbus master, as shown in Figure 1.

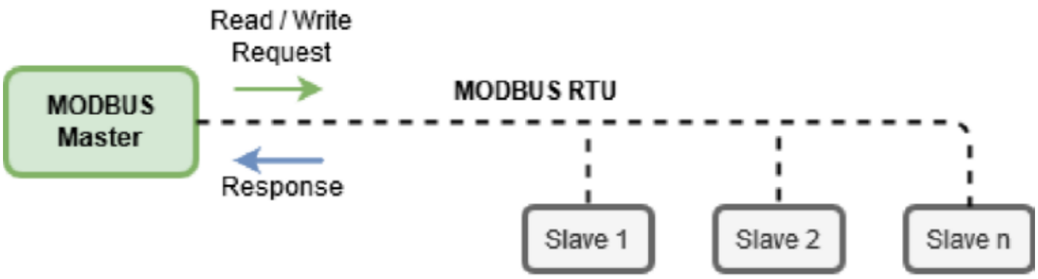

Figure 1. *Modbus RTU protocol.*

2.2. VFD (Variable Frequency Drive)

A variable frequency drive (VFD) is a device that controls the speed and torque of an AC motor by adjusting the frequency and voltage of the power supply. A VFD can also regulate the acceleration and deceleration of the motor during start-up and stop, respectively. A VFD consists of four main components: a rectifier to convert AC power to DC, a capacitor to stabilize this DC power, an inverter to convert the DC back to AC with variable frequency, and a control system as shown in figure 2.

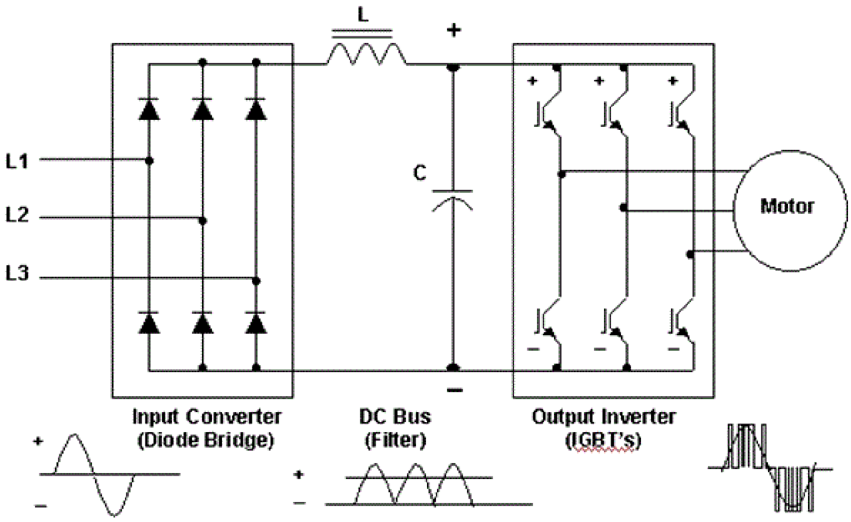

Figure 2. *VFD block diagram.*

By changing the frequency (f), the rotational speed of the three-phase induction motor (N) will change. By changing the value of the voltage ratio to frequency (V/f), the motor flux (Φ) will change, which will then change the motor torque(T). The relationship between V (Terminal voltage), T(Torque), Pm (Power), I (Stator current) and the ratio of VFD frequency to rated frequency (K) is shown in Figure 3.

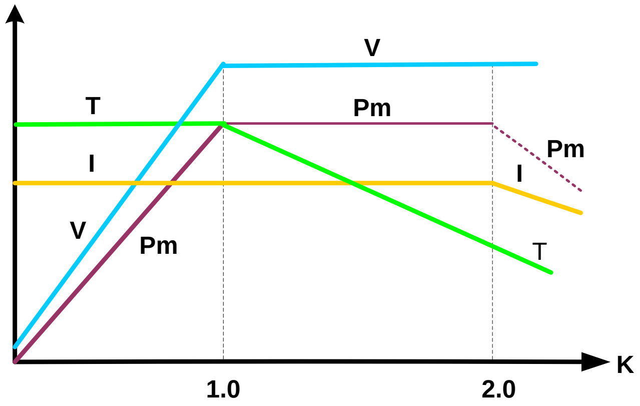

Figure 3. *V, T, Pm, I vs K.*

2.3. The V/f method

The V/f method is a form of scalar control because it relies only on the magnitude of the stator voltage. This contrasts with vector control methods (1) that use both the magnitude and the phase.

$$V_{dqs} = R_s I_{dqs} + \frac{d\Psi_{dqs}}{dt} + j\omega_s \Psi_{dqs} \quad (1)$$

In the stator flux reference frame, a steady state equation of the stator circuit become (2).

$$V_{dqs} = R_s I_{dqs} + j\omega_s \Psi_{dqs} \quad (2)$$

If neglecting the voltage drop over the stator resistance and consider only the magnitude, the stator flux becomes (3).

$$\Psi_{dqs} \approx \frac{V_{dqs}}{\omega_s} \quad (3)$$

Consequently, the stator flux can be maintained constant by keeping the V/f ratio constant. In this case, the speed of the machine becomes proportional to the stator voltage. However, there is no explicit torque control. The basic idea of a V/f control is to maintain the stator flux constant. To operate the machine under nominal conditions, the stator flux must be nominal (4).

$$\Psi^*_{dqs} = \Psi_{dqsn} \approx \frac{\sqrt{2}V_{sn}}{\omega_{sn}} \quad (4)$$

with V_{sn} the nominal RMS phase voltage. Then, from (3) and (4), the speed reference can be converted into a voltage reference (5).

$$V^*_{dqs} \approx \Psi^*_{dqs}\omega^*_s = \frac{\sqrt{2}V_{sn}}{\omega_{sn}}\,\omega^*_s \quad (5)$$

The relation in (3) was established assuming that voltage drop over the stator resistance could be neglected. However, this hypothesis does not hold at low speeds because the voltage drop becomes comparable to V_{dqs} in amplitude (3). In this situation, the stator voltage should be increased to compensate for the voltage drop. This means the V/f ratio is not constant at low speeds (3). If the machine operates above the nominal speed, the stator voltage should exceed its nominal value according to (3). To prevent an overvoltage, the voltage reference should be saturated to V_{sn}. As a result, the stator flux drops below its nominal value at high speed. This is commonly called the field-weakening region of operation (3). The constant flux, dead zone, and field weakening regions are illustrated in the voltage profile (v/f) as shown in figure 4, which describes the relationship between the amplitude and the frequency of the stator voltage.

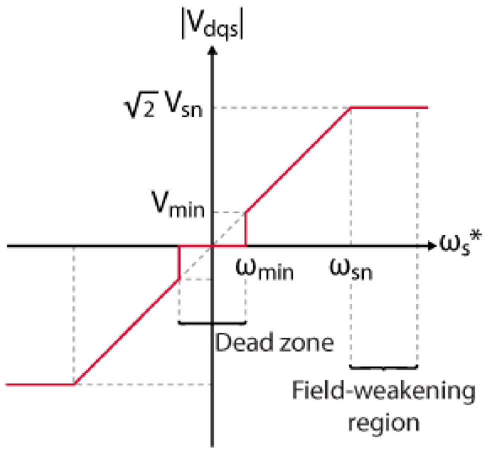

Figure 4. *V/f profile.*

2.4. Model Design

The model design in figure 5 is used to implement a three-phase induction motor control and monitoring which is realized in the form of a learning module in the laboratory of the electrical engineering. In this model there are 2 ESP32 microcontrollers which function as masters which are connected to the VFD as slaves via a TTL-RS485 converter. Serial communication between the Master and slave uses the Modbus RTU protocol which has been widely used in the industrial areas. Meanwhile, the interface used is RS485 which is able to support a maximum distance of 1200 meters with multiple devices (up to 32 devices) on the same bus.

Control activities from the external side can be done globally via the internet with a choice of applications according to consumer/operator needs. The control of a three-phase induction motor connected to a VFD can be done using the Arduino IDE software by sending the "writeSingleRegister" command to the register address of the VFD selected as the Slave.

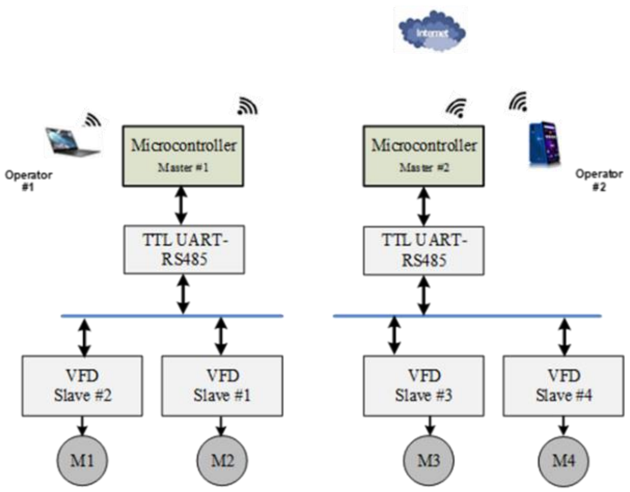

Figure 5. Model design.

Meanwhile, monitoring activity can be done by sending the "readHoldingRegisters" command to the register address of the VFD selected as slave.

3. Experimental Result

3.1. Experiment Devices

In this experiment, the main components of the model design shown in Figure 4 consist of several main devices, including a Microprocessor, TTL RS485 converter, three-phase Induction motor, and application software, as shown in Table 1.

Table 1. The main devices.

No.	Device Name	Specification
1.	Microcontroller	-ESP32 DEVKIT V1 -Wi-Fi Protocol: 802.11 b/g/n (802.11n up to 150 Mbps)
2.	TTL UART to RS485 module	-On-board MAX485 chip -A low power consumption for the RS-485 communication
3.	VFD	- LS IG5A 0,75 KW 1 Hp - -ATV312H075N4 0.75KW 1 HP
4.	Three-phase induction motor	P=300W, V=220/380V Δ/Y, 1.38/0.8A, N=2800 min-1, - Cos α = 0.74, F =50 HZ
5	WhatsApp Application:	-An instant messaging (IM) and voice-over-IP (VoIP) -End-to-end encryption
6	Blynk IoT Application:	-Designed for the Internet of Things.

3.2. Communication Setting

There are two Esp32 Microcontrollers: Esp32 #1 and #2 which functions as a master to communicate with Slave #1 which is a VFD with type LGi5A and slave #2 with type ATV312. The communication format between VFD and ESP32 is as follows:

1) Data length: 8bit
2) Start/Stop bit: 1
3) Parity: Even parity
4) Baud rate (bps): 9600
5) External Connection: RS485
6) Protocol Select: Modbus RTU

3.3. Essential Setting on VFD

The next step is to adjust the default settings on the VFD to match the three-phase motor nameplate (Table 1). The essential changes to the VFD default settings are shown in Table 2.

Table 2. VFD setting.

No.	Code	Description	Setting
1	nCr	Nominal motor current	0.8A
2	nSp	Nominal motor speed	2800 rpm
3	LSP	Motor freq. at minimum ref. (Low speed)	4 HZ
3	HSP	Motor freq. at maximum ref. (High speed)	40 HZ
4	ACC	Acceleration time	3s
5	dEC	Declaration time	3s

It is crucial to emphasize that the settings for ACC and DEC on the VFD should be adjusted according to the motor's power to reduce the motor's starting current and minimize other unwanted disturbances during start and stop operations. These values should be increased to 15-20 millisecond for motors with higher power.

3.4. Motor Testing

Before conducting the experiment, motor testing should be carried out to determine the maximum frequency value at which the motor will operate at its nominal current (In=0.8A). The test results show that the frequency value allowed to produce the nominal motor current is 40 Hz. This initial testing is necessary for two purposes: to prevent motor damage by ensuring it does not operate beyond its nominal current, and to extend the motor's operational lifespan.

3.5. Learning Module and Experiment Output

This experiment has been equipped with a wiring diagram representing VFD1, VFD2, VFD3, and VFD4 as shown in Figure 5. Meanwhile, a learning module as a container to accommodate electrical and electronic components is shown in Figure 6.

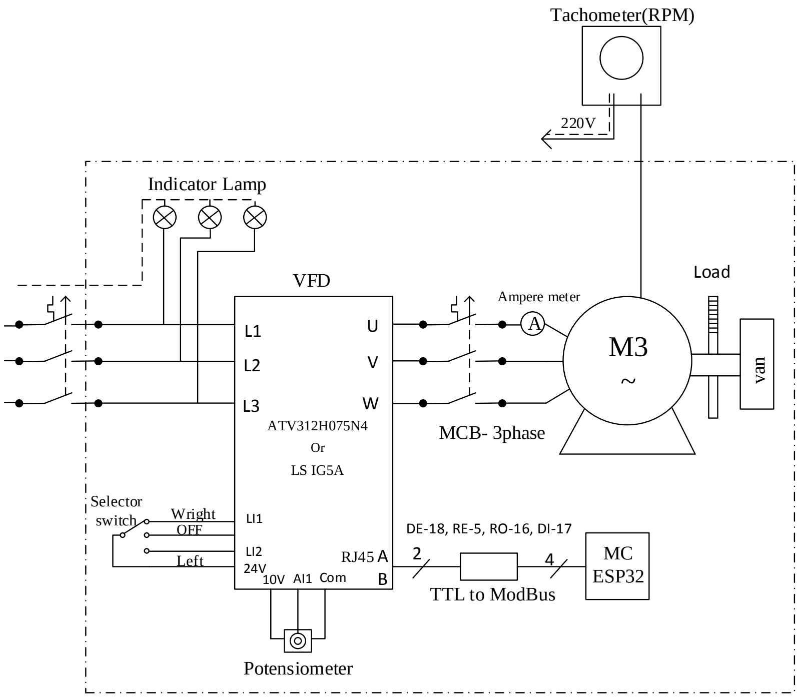

Figure 6. *The Wiring diagram of experiment.*

(a). VFD ATV312-ESP32

(b). VFD LS IG5A-ESP32

Figure 7. *Learning module.*

The Learning module (figure 6) can be operated offline (on-site) and online via the WhatsApp and Blynk IoT applications. An operator or user is given 2 options for communicating with the ESP32, namely via the WhatsApp application and Blynk IoT. WhatsApp communication uses Twilio which is a platform for building voice, video and messaging applications. The platform consists of a set of Application Programming Interfaces (APIs) that enables developers to make and receive voice and video calls, send and receive SMS, WhatsApp, and email, and perform other communication functions using its web service APIs. Then Twilio communicates with ThingESP which provides an HTTP client library on the Arduino IDE which is used to connect IoT devices to the ThingESP Cloud Platform. User communication using the WhatsApp application with ESP32 connected to the VFD is shown in Figure 7.

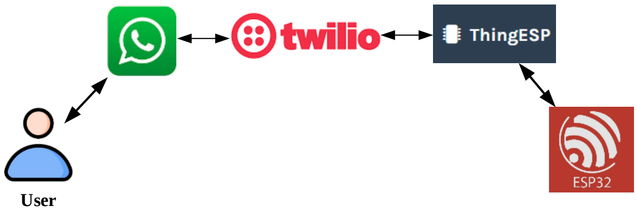

Figure 8. *Communication with WhatsApp.*

When using the WhatsApp application, a user must carry out a command using written text which will be followed by a response from the system in the form of parameter values obtained at the register address on the VFD. By using the Arduino IDE software supported by the MODBUSMASTER library, reading and writing to the register addresses for control and monitoring are shown in Table 3.

Table 3. *VFD Address register.*

No.	VFD type	Address register	Function
		(0x40005,0)	Stop
		(0x40005,2)	On forward
		(0x40004, HZ)	Speed on HZ
1.	LS IG5A	(0x40009,1)	Frequency read
		(0x4000A, 1)	Voltage read
		(0x40008, 1)	Current read
		(0x40014, 1)	Rpm read
		(8501,6)	System start
		(8502,4111)	Stop
		(8501,15)	Run forward
		(8502, HZ)	Speed on HZ
2.	ATV312	(8501,128)	Reset
		(3202,1)	Frequency read
		(3207, 1)	Voltage read
		(3204,1)	Current read
		(8602,1)	Rpm read

The second option is to use Blynk IoT which is an Internet of Things (IoT) platform that can be used to connect IoT hardware with an IoT platform. Apart from that, this platform can store data from sensors and can display the results of data measurements. Blynk IoT is available as an open source (free) and subscription (paid) which is available in the form of a website, and can be operated via a computer or smartphone based on Android or IOS. User communication using the Blynk IoT application with the ESP32 connected to the VFD is shown in Figure 8.

Figure 9. *Communication with Blynk IoT.*

After completing the design, implementation, and evaluation phases of the learning module, control and monitoring activities can be carried out both online and offline. The online method is conducted through the WhatsApp application and Blynk IoT where the motor winding connection is a star (Y), with the display on the smartphone are shown in figures 9 and 10 respectively.

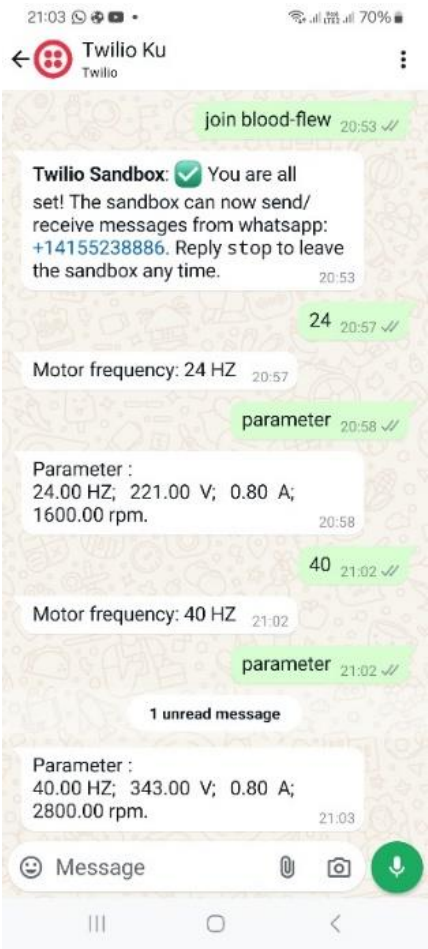

Figure 10. *Display on WhatsApp application.*

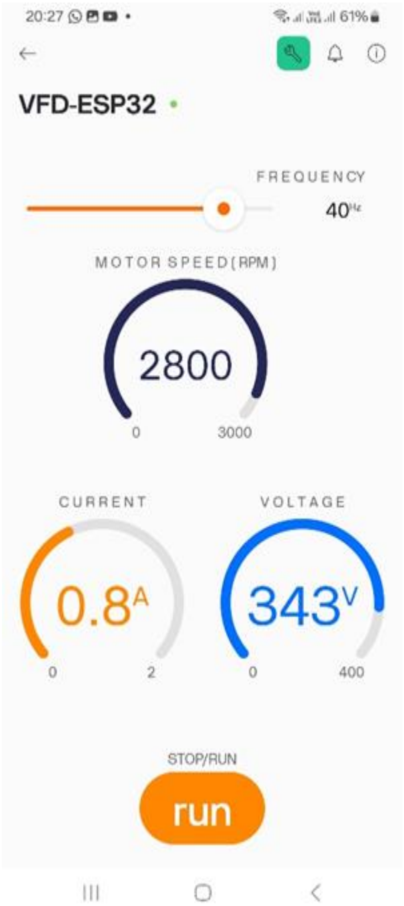

Figure 11. Display on Blynk IoT application.

The results of parameter monitoring carried out on a three-phase induction motor load with a power of 0.75 Kw (1 HP) via two applications (Blynk IoT) and WhatsApp are shown in Table 4.

Table 4. Three-phase Induction motor parameter.

No.	F(Hz)	V(V)	I (A)	N(rpm)	V/f
1	4	70.0	0.70	150	17.50
2	8	98.0	0.70	450	12.25
3	12	129.0	0.70	750	10.75
4	16	159.0	0.70	1050	9.94
5	20	189.0	0.70	1325	9.45
6	24	221.0	0.80	1600	9.21
7	28	251.0	0.80	1900	8.96
8	32	282.0	0.80	2200	8.81
9	36	313.0	0.80	2500	8.69
10	40	343.0	0.80	2800	8.58
				Average:	10.41

4. Discussion

The experimental results in table 1 were carried out with the motor under constant torque load. If the frequency is increased to the rated frequency (Fr), it will affect the value of other motor parameters, namely will increase motor speed (rpm), power (P), and Voltage (V), and vice versa if the frequency is decreased. But the current flowing in the motor (I) is relatively constant, and consequently the motor torque (T) also becomes constant. The VFD control method in this experiment uses the V/F method, which is a variable voltage-variable frequency drive. Thus, the V/F ratio is always kept constant (an average of 10.41) to produce a constant flux (Ψ), resulting in a relatively stable torque value. The results of this experiment align with the purpose of using a Variable Frequency Drive (VFD), which is to avoid magnetic weakening and saturation, and to save energy in the use of three-phase induction motors. In the upcoming experiment, it is recommended to expand the load types to include constant power and variable torque load. Meanwhile, access control and monitoring can utilize more diverse applications, whether through social media or web-based platforms, to provide optimal speed and ease of access for customers or users by considering several variables such as network latency, stability, safety, and feasibility. In this model design, control and monitoring are implemented by combining a VFD with a microcontroller (ESP32) equipped with embedded WIFI, relatively high processing speed, and a relatively low cost. This differs from prior research, which combined VFD, PLC, and SCADA that requiring a significantly higher investment cost. In this study, the combination of VFD and ESP32, which can be accessed globally via internet that is implemented in a learning module to engage students in studying control engineering. This is achieved by utilizing web-based applications and social media platforms that are already familiar in their daily lives.

5. Conclusions

This VFD learning module based on the Modbus RTU protocol provides users with the convenience of controlling and monitoring both offline and online. Online access can be done through two applications: A web-based application (Blynk IoT Application) and a social media application (WhatsApp). Besides its more economical price and relatively high speed (2 processors core 0 and 1) with WIFI capabilities, using the ESP32 microcontroller as the master provides system designers with the flexibility to add additional features not found in the VFD itself, making it more powerful and adaptable to future changes. However, it should be noted that the process of controlling a three-phase motor must be preceded by an initial test, which involves determining the maximum allowable frequency to ensure that the motor current does not exceed its nominal current to prevent potential damage to the motor. The presence of this learning module is highly essential for students as an alternative to the VFD-PLC-SCADA combination, which requires a very high investment cost. It offers a more economical solution by combining VFD and ESP32 with utilizing web-based and social media applications. However, a challenge for other researchers is how to provide control and monitoring access with low network latency, greater stability, and the capability to overcome potential server failures.

Abbreviations

APIs	Application Programming Interfaces
VFD	Variable Frequency Drive
HMI	Human Machine Interface
IDE	Integrated Development Environment
IoT	Internet of Things
GUI	Graphical User Interface
PLC	Programmable Logic Controller
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
UART	Universal Asynchronous Receiver-Transmitter

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Author Contributions

Achmad Marzuki: Conceptualization, Formal Analysis, Software, Writing Original draft, Methodology, Supervision, Writing - review & editing

Taufik Muzakkir: Data collection, Formal Analysis, Validation, Resources, Validation, Data curation, Project Administration

Muhammad Sulhan: Design implementation, Project Administration, Formal Analysis, Resources, Validation, Data curation

Conflicts of Interest

The authors declare no conflicts of interest.

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