Journal of Electrical, Marine and Its Application Technology **Vol. ….…, No. …….**
ISSN xxxxxx **Publication Periode**

Design and Analysis of a Single-Phase Full-Wave Inverter with Constant V/f Control for Induction Motor Speed Regulation

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Abstract

Induction motors, especially three-phase types, are widely used in industrial and marine applications for their ability to operate near synchronous speed. Motor speed is primarily influenced by load torque, with only slight variations as the torque increases, making them ideal for systems requiring constant speed. This study focuses on designing a single-phase full-wave inverter with constant voltage-to-frequency (V/f) control for regulating induction motor speed. The goal is to develop an efficient method to adjust motor speed while maintaining optimal performance. The methodology involves systematic data collection, processing, and analysis. The inverter design allows precise speed control through V/f regulation, enabling flexible operation under varying load conditions. Experimental results show an average constant V/f ratio of 2.34, with the inverter producing a square wave output, typical of simple inverter designs. Analysis of the relationship between input frequency and motor speed reveals a proportional increase in motor speed with higher input frequency. This finding highlights the significance of frequency control in motor speed regulation. The study contributes to the development of more efficient and cost-effective speed control systems for induction motors, particularly in marine propulsion and industrial drive applications. Further improvements to the inverter design could enhance waveform quality and overall system efficiency, addressing limitations in simple inverter configurations.

Keywords: Induction motor, Inverter, Speed

1. Introduction

A 3-phase induction motor is an essential electromechanical device that efficiently converts electrical energy into mechanical power. Operating on 3-phase AC power, the induction motor is widely utilized in various applications, including industrial machinery, electric vehicles, and marine propulsion systems, due to its robust performance and simplicity (Siswoyo, 2008). These motors are designed to operate at speeds that are nearly constant and very close to synchronous speed, which makes them ideal for drive systems requiring consistent speed control. The motor speed typically decreases only slightly as the load torque increases, providing stable performance across a wide range of operating conditions.

Induction motors, however, can also be equipped with advanced control mechanisms that allow for dynamic speed adjustments based on varying load conditions. One of the most effective methods for controlling motor speed is through continuous V/f control, a technique where both the voltage and frequency are adjusted while maintaining a constant ratio between them. This method ensures that the torque generated by the motor remains steady across the entire range of speed variations, making it suitable for applications where precision and reliability are paramount.

A constant V/f control strategy works by regulating both the voltage and frequency applied to the induction motor. By keeping the voltage-to-frequency ratio constant, this method allows for a linear relationship between the motor’s speed and the input frequency. The result is smoother speed control and efficient torque generation, which is particularly important in drive systems that demand precise control. The most common implementation of this method involves the use of a rectifier, which functions as an inverter. An inverter is a critical component in converting AC motor voltage into DC voltage and subsequently back into AC at the desired frequency.

This paper presents the design and analysis of a single-phase full-wave inverter equipped with constant V/f control to regulate the speed of a 3-phase induction motor. The goal of the study is to develop an effective and reliable system for controlling motor speed, particularly in applications such as marine propulsion systems or industrial drive systems, where consistent and adjustable motor performance is essential. The design incorporates advanced inverter technology that allows for the conversion of AC voltage to DC and then back to AC, with precise frequency control to match the motor's speed requirements. This approach offers significant benefits over traditional methods, ensuring both efficiency and stability in motor operations.

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2. Material and methods

2.1. Rectifier

A power rectifier is an electronic power circuit designed to convert an AC input source into a constant DC in the form of a sine wave. Single-phase and three-phase AC voltages can be used as input voltage sources to supply the main rectifier circuit. A single-phase rectifier is a power rectifier circuit using a single-phase AC input. The rectifier circuit can be implemented in the form of 1/2 wave rectifier & full wave rectifier. Power Rectifier Loads are generally equipped using resistive-resistive loads or resistive-inductive loads. The effect of this load affects the quality of the output voltage obtained by the rectifier circuit (Septarangga, 2019). The single-phase rectifier circuit has a working principle of replacing the AC current as a DC current. Filter C (capacitor) is used at the end of the rectifier circuit to achieve the desired output voltage, for example to reduce voltage ripple. However, the use of a C filter in a rectifier circuit must be balanced with an output that allows the rectified current waveform to contain harmonics. This increases the harmonics and temperature of the electronic components (load on the electronic components), which reduces the quality of the rectifier circuit network (Bastari & Mesah, 2019). The single-phase rectifier is divided into two parts: one phase half-wave rectifier and one-phase full-wave rectifier. Many house hold electronic devices, such as televisions, laptops, cell phones, DVD players, radio cassette recorders, components, and other communication devices, use a single phase full-wave rectifier circuit as a power source. The advantage of a full-wave single-phase rectifier circuit over a half-wave rectifier circuit is that the output voltage and current are relatively good with little ripple. Also, the output voltage is higher than the half-wave rectifier circuit (Ali, 2018).

A. Single Phase Full-Wave Rectifier R

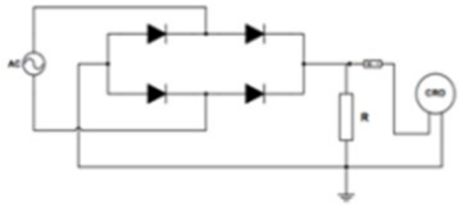

Figure 1. R load single phase power supply circuit

Figure 1 shows the output waveform of the circuit for a capacitive load. If the half wave rectifier rectifies only half a cycle, the full wave rectifier rectifies to 2 cycles, forming a better waveform & higher voltage value. The output voltage of a full-wave single-phase rectifier circuit can be calculated using the following equation:

Average voltage (VDC):

$$V_{DC} = \frac{2V_m}{\pi}$$

While the RMS voltage (VL):

$$VL = \frac{V_m}{\sqrt{2}}$$

B. Single Phase Full Wave Rectifier L

Filter L is used to equalize the current. If the input current is positive, the inductor will be charged, and if the negative period is the inductor, the inductor will be discharged. At infinity, the output current is uniform and the input current is square (Wulandari, 2015). For load rectifiers R and L, the average output voltage is defined as:

$$V_{DC} = I_R R = \left(\frac{VR}{Z}\right)R$$

$$Z = \sqrt{R^2 + (2\pi f L)^2}$$

C. Single Phase Full-Wave Rectifier C

Filter C is used to equalize the output voltage. If diode 1 turns on, the capacitor will charge. When the voltage is minimum, the capacitor discharges to power the load (Basri & Irfan, 2018). The output voltage never becomes zero. The magnitude of the discharge voltage is as follows: Voltage ripple:

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$$\Delta V = V_{r(PP)} = V_m - V_{min} = \frac{Vm}{2fRC}$$

Average voltage :

$$V_{dc} = V_m - \frac{V_{r(PP)}}{2fRC} = V_m - \frac{Vm}{4fRC}$$

AC component voltage approaches rms :

$$V_{AC} = \frac{V_{r(PP)}}{2\sqrt{2}} = \frac{Vm}{\sqrt{2}(4fRC-1)}$$

D. Full-wave Single Phase Rectifier RL

Load Inductive load affects the output voltage form of the circuit because it causes the diode to permanently turn on temporarily even though the diode is reverse biased due to load L.

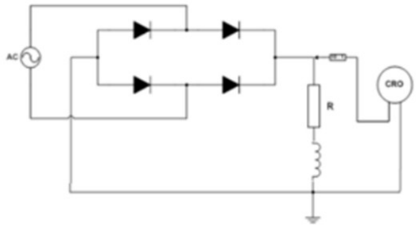


Figure 2. Load single phase power supply circuit

2.2. Single Phase Uncontrolled Rectifier

Uncontrolled Rectifier An uncontrolled rectifier is a circuit that converts an AC current voltage source into a fixed DC (Basri & Irfan, 2018). It is called an uncontrolled single-phase rectifier because the output of this rectifier cannot be adjusted or controlled so that the output value depends on the input voltage (Novaliendry, 2013) .

Uncontrolled rectifiers usually use a diode as a switch. Diodes are used for single phase uncontrolled 1/2 wave rectifiers. Single phase uncontrolled rectifier is divided as 1/2 wave rectifier & full wave rectifier.

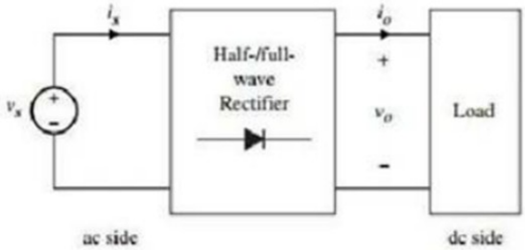


Figure 3. Single Phase Uncontrolled Rectifier Circuit

There are 2 kinds of full wave uncontrolled rectifier circuit, namely center tap rectifier (two diodes) & bridge rectifier (4 diodes), both of which have the same output. The following is a full-wave rectifier circuit that is not single-phase controlled (Surjono, 2007).

A. Center Tap Rectifier (2 Diodes)

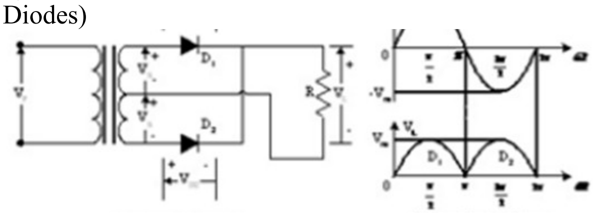
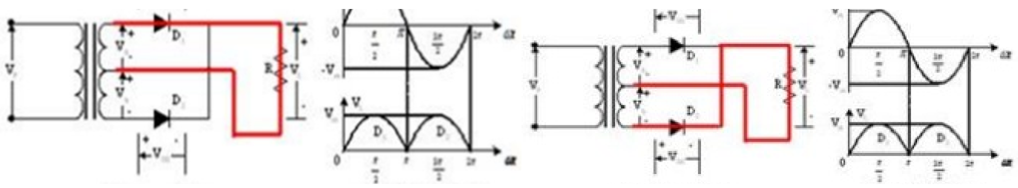


Figure 4. Circuit Diagram and Waveform of a center tap rectifier (two diodes)

The figure is a center tap rectifier (two diodes). Based on the picture, it can be seen that this circuit has two main work processes, namely: 1.If the upper arm of the transformer is positive, diode 1 (D1) will be forward biased. While the lower arm of the transformer is negative, as a result diode 2 (D2) is reverse biased. When the diode is forward biased, current flows. Since the forward bias is diode 1 (D1), current flows through diode 1 and the load, then returns through the center leg to the transformer.



(a) (b)

Figure 5. (a) Upper Arm is Positive; (b) Upper Arm is Negative

B. Bridge Rectifier (Bridge / 4 Diodes)

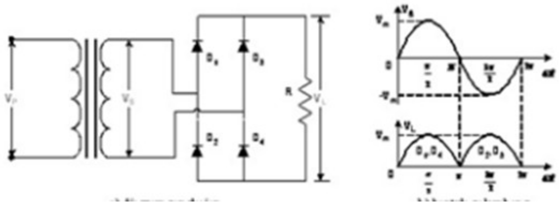
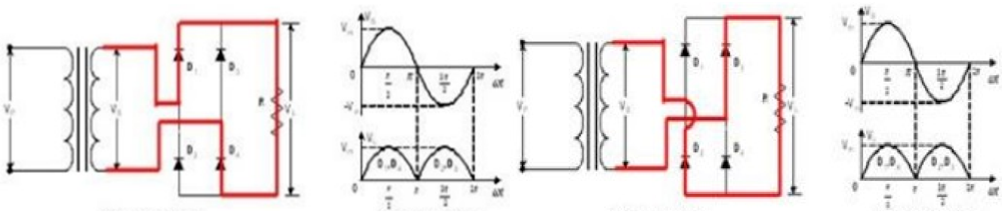


Figure 6. Circuit Diagram and Bridge Rectifier Waveform

Based on the figure, it can be seen that the circuit has 2 main work cycles, namely:

1. When the input voltage on the top side of the transformer is positive, D1 and D4 are forward biased. As long as the input voltage on the underside of the transformer is negative, diode
2. (D2) and diode 3 (D3) are reverse biased. When current flows through the forward bias diode, current flows from the top leg of the transformer to D1, then to the load, then to D4, and back to the transformer through the bottom leg.
3. When the input voltage on the top side of the transformer is negative, diode 2 (D2) and diode 3 (D3) are forward biased. In this case, the forearm input voltage is positive, and diode 1 (D1) and diode 4 (D4) are reverse biased. When current flows through the forward bias diode, current flows from the lower leg of the transformer to D3, then to the load, then to D2, and through the upper leg back to the transformer



(a) (b)

Figure 7. (a) Input Voltage at the Top of the Transformer is Positive; (b) Input Voltage at the Top of the Transformer is Negative

2.3. Single Phase

Inverter Inverter An inverter is a circuit that converts a direct current (DC) source with adjustable voltage and frequency into alternating current (AC) (Nugraha, 2020). he AC voltage is generated in the form of a square wave, and some applications require a filter to generate a sine wave. Voltage control is carried out in two ways. Set the DC input voltage to the outside first, but wider when setting the switch. Next, set the width when switching with a fixed DC input voltage.

The inverter consists of a main circuit based on a controlled or uncontrolled rectifier circuit, an inverter (using various frequencies to convert current into alternating current), and an ignition control circuit/control circuit to regulate the voltage and frequency. The inverter gets (Sinaga, Samosir, & Haris, 2017).

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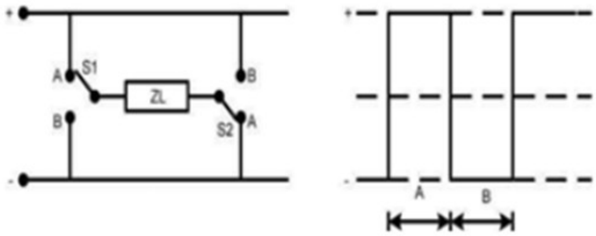

Figure 8. Simple Circuit Inverter

2.4. 3 Phase AC Motor

A 3 phase induction motor is an electrical device that renews electric power as mechanical energy, the converted electricity is 3 phase electricity. Asynchronous motors are also considered to use asynchronous motors. (Sinaga, Samosir, & Haris, 2017). Basically, a 3- phase induction motor will have a continuous speed when there is no load (zero/idle) as well as full load. Since the speed of a 3-phase induction motor depends on the operating frequency, it is difficult to adjust the speed. Detailed structure of induction motor.

The induction motor consists of two parts, namely the stator and the rotor (Nugraha et al., 2022). The stator is a fixed part of the motor, which consists of the motor body, stator iron core, stator windings, bearings and junction box (Pattiapon, Rikumahu, & Jamlaay, 2019). The rotor is a rotating machine part, consisting of a cage rotor and a rotor shaft. In an induction motor, the rotor is in contact with the stator. The stator and rotor are separated by an air gap (Ravi, Widodo, & Nugraha, 2021). The structure of an induction motor is simpler than a DC motor because it has a commutator, carbon brushes, and maintenance of an induction motor is only a mechanical component, induction motors are very tough and fail electrically (Nugraha, Priyambodo, & Sarena, 2022).

The working principle of an induction motor is simply that when a 3-phase voltage source is connected to the stator coil, a rotating magnetic field is generated at a certain speed. The rotating stator magnetic field cuts the rotor conductor rods and creates an induced voltage of electric mobility (Haryanto, 2011). The closed circuit of the motor coils impacting the electric mobility force produces a current. The current in the magnetic field creates a force in the rotor. If the initial coupling obtained by the force in the rotor is relatively large to support the load clutch, then the rotor will rotate in the same direction using a rotating stator field (H & P, 2008)

2.5. Speed Control of Single-Phase Induction Motors Single-phase

Induction motors usually rotate at near-continuous speeds when connected to a continuous voltage and frequency, very close to synchronous speed (Evalina, Azis, & Zulfikar, 2018). As the load torque increases, the rotational speed decreases slightly, making induction motors ideal for drive systems that require continuous rotational speed. But in practice, especially in industry, sometimes the speed needs to be adjusted. The speed of the induction motor can be adjusted in several ways, including (Suherman & Harumanto, 2016)

a. Changing the number of poles
b. Set resource frequency
c. Set the terminal voltage
d. Arrangement of external prisoners
e. Constant V/f Control

The speed of an induction motor is proportional to the frequency of the power supply as well as the number of poles on the motor. The number of poles is affected by design, so the best way to change the speed of an induction motor is to change the frequency of the power supply. The torque generated by an induction motor is proportional to the ratio of the applied voltage to the mains frequency. By keeping the ratio of the two constant while changing the voltage and frequency, the torque generated can be kept constant throughout the speed control range. This control is known as constant V/f control (Nasution, 2012)

3. Results and discussion

3.1. Testing of Rectifiers Before the Voltage Leveling Process

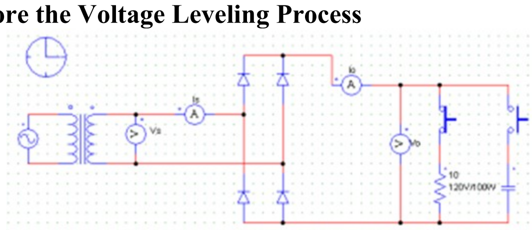

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Figure 9. Phase Full Wave Rectifier Test Circuit Before Voltage Leveling Process

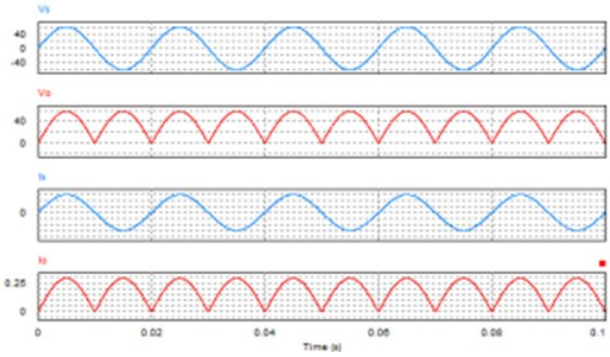

Figure 10. Output Waveform of Single Phase Full Wave Rectifier Before Voltage Leveling Process

The value of the output voltage measured by a multimeter from a single-phase full-wave rectifier circuit before the voltage grading process is 92VDC. In this test, the voltage source measured by the multimeter is 104 VAC from the secondary side of the transformer and is lowered from 220 VAC to 110 VAC using a step down

$$V_{DC} = \frac{2}{T} \cdot \int_0^{T/\pi} Vm \sin \sin \omega t \, dt = \frac{2\,Vm}{\pi} = 0{,}636$$

$$VDC = 0{,}363 \times 104 \times \sqrt{2} = 93{,}540 \text{ Volt}$$

The results obtained using mathematical formulas in theory and measurements using a multimeter do not change the magnitude of the output voltage produced significantly. There is a slight difference in the value of the resulting output voltage, such as an unstable mains voltage, the coefficient of the components used, etc. The resulting output waveform is as expected, but due to the use of a bridge diode, it gives a complete waveform.

3.2. Testing of Single-Phase Inverter Circuit Without Load

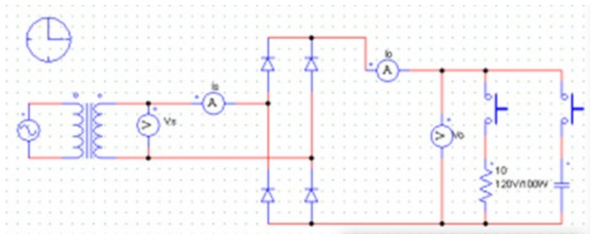

Figure 11. Phase Full Wave Rectifier Test Circuit Without Load

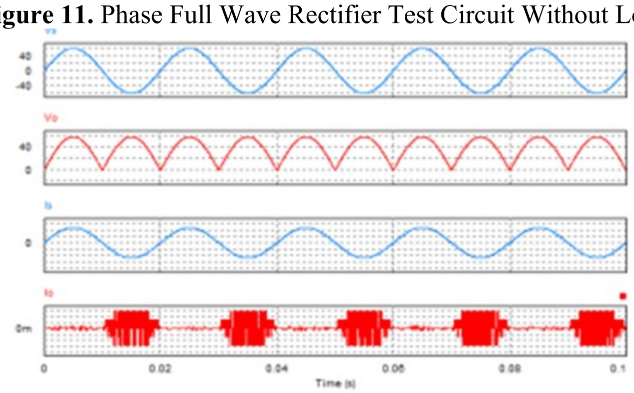

Figure 12. Output Waveform of Single Phase Full Wave Rectifier Without Load

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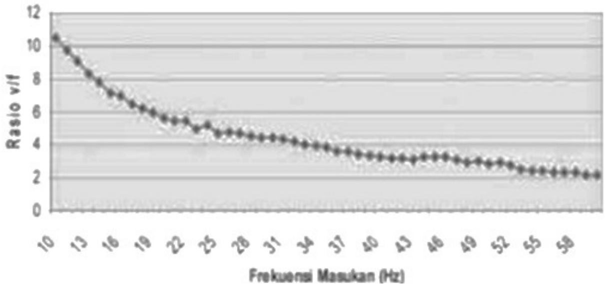

Figure 13. Graph of Input Frequency Against V/f Ratio Constant Value In Testing Single Phase Inverter Without Load

Based on the circuit in Figure 11, there are differences in the waveforms produced by Vs and Vout. In these two measuring instruments, namely Vs and Vout, the waves obtained show full AC waves, it can be said that the voltage is still AC-shaped voltage and has not been filtered. Meanwhile, in the simulation results of Is and Io, it can be seen that waves in the form of waves are irregular because of the many ripples that occur in them. Ripples occur because the current is still in the form of AC current and there is no strong filter to stabilize the ripples. In Figure 13, although the input frequency changes regularly, the resulting constant V/f ratio is still not constant because the output signal from the inverter is still square waves, which makes the output signal unstable.

3.3. Testing Single Phase Inverter Circuit With Load

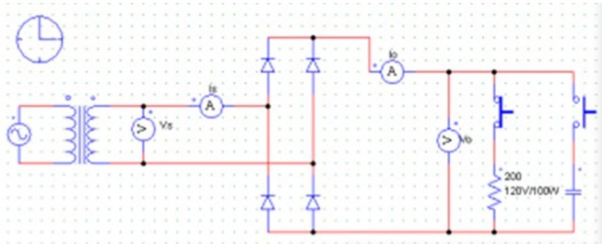

Figure 14. Phase Full Wave Rectifier Test Circuit with Load

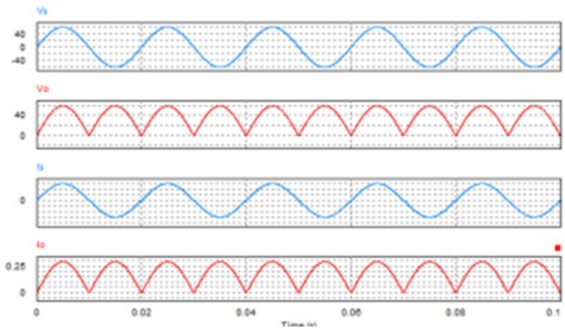

Figure 15. Graph of Input Frequency to Output Voltage in Single Phase Inverter Testing with Load

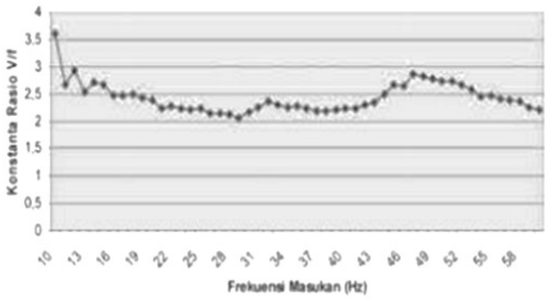

Figure 16. Graph of Input Frequency to V/f Ratio Constant Value in Single Phase Inverter Testing with Load

From figures 14 and 15, it is found that the full wave seen on the Vs measuring instrument and also in the form of a full wave seen on the Is, Vo, and Io tools. In the measuring instrument vs. the wave output is in the form of a full wave, meaning that the source voltage issued in the circuit is still in the form of a voltage or AC signal that causes the formation of a full wave. In a measuring instrument with a full wave output, it means that the AC signal flowing in the circuit has been equalized by the diode to a DC signal, but not completely by eliminating the negative signal in the full wave only tells the positive signal, therefore the wave released by the oscilloscope is in the form of a full wave. In figure graph 16, the output voltage of the inverter changes as the input frequency changes, since the frequency is designed to change as the voltage changes. That is, changing the value of the PWM signal pulse width period and the cycle of its value remains at 50%. The homogeneous value of the V/f ratio constant obtained was 2.34. The resulting V/f ratio constant value is suitable using the initial design. The constant value of the V/f ratio can be designed or obtained using replacing the PWM frequency pulse width period value. Cycles are worth always 50%.

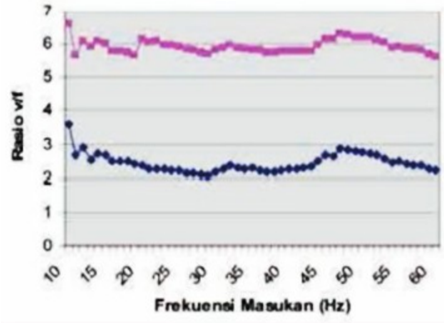

Figure 17. Comparative Graph of the Relationship Between Input Frequency and V/f Ratio Constant Value

Based on Figures 4.9 and 4.10, a comparison diagram of the inverter design (Navy) results using the Omron 3G3JV-A2007 inverter (Purple) is shown regarding the relationship between the input frequency and motor speed as well as a diagram of the relationship between the input frequency and the value of the V/ ratio f constant. Based on figure 17 the motor speed is slightly different, but not significant at the same input frequency. In the comparison diagram, the relationship between the input frequency and the value of the V/f ratio is constant. Based on the results of the same test, namely using an inverter test, the value of the resulting ratio constant V/f did not change much, while the ratio constant V/f was constant.

3.4. Measurement of Single Phase Inverter Circuit with Load

Table 1. Measurement Table of One-Phasa Inverter Circuit with Resistor Load

Frequency	Is (rms)	Vo (dc)	Io (dc)	Vo (rms)	Io (rms)
15	0,097	17,71	0,088	19,95	0,097
30	0,15	27,25	0,13	30,55	0,15
50	0,20	36,79	0,18	41,15	0,20

4. Conclusion

1. Uncontrolled Rectifier and Inverter Function: An uncontrolled rectifier converts AC to DC current and is classified into two types: half-wave rectifiers and full-wave rectifiers. The developed single-phase inverter can adjust the speed of the induction motor with various settings, producing an output in the form of a square wave AC voltage.
2. Inverter Performance and Frequency Impact: Based on the tests, the average constant V/f ratio achieved by the inverter is 2.34. The analysis of the relationship between input frequency and motor speed shows that as the input frequency increases, the speed of the induction motor also increases, since frequency is directly proportional to motor speed.
3. Suggestions for Future Development: For further improvement, it is recommended to design a PWM signal generator that allows the inverter to produce a sinusoidal output voltage. This would reduce harmonics, which can extend motor life, stabilize the output voltage, and prevent mechanical resonance, which can disturb motor rotation when an AC motor is connected as a load..

Credit authorship contribution statement

Author Name: Conceptualization, Writing – review & editing. **Author Name**: Supervision, Writing – review & editing. **Author Name**: Conceptualization, Supervision, Writing – review & editing.

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