Performance Analysis of Induction Motor Control Based on Variable Frequency Drive (VFD and Neural Network Under Load Variations

Sulton Hidayatulloh
e-mail: sulton.h2304@gmail.com
Solly Aryza
e-mail: sollyaryzalubis@gmail.com
Ahmad Dani
e-mail: ahmaddani@dosen.pancabudi.ac.id

Universitas Pembangunan Panca Budi

Abstract

The use of induction motors in industrial applications continues to grow due to their robustness, low cost, and minimal maintenance requirements. However, maintaining optimal performance under varying load conditions remains a challenge. This research aims to analyze the performance of an induction motor control system that integrates a Variable Frequency Drive (VFD) and a Neural Network-based controller to improve efficiency and dynamic re-sponse under different load variations. The VFD serves as a tool to regulate the motor's fre-quency and voltage, enabling precise speed control. Meanwhile, the neural network algo-rithm is designed to learn and adapt in real time, adjusting control parameters according to load conditions to maintain stability and efficiency. Experimental tests were conducted by applying different load scenarios to the induction motor and recording key parameters such as motor speed, torque, current, and efficiency. The results showed that the integration of the neural network with the VFD enhanced the system's adaptability and performance, especial-ly during sudden changes in load. Compared to traditional PID control, the proposed system provided faster response times, better energy utilization, and improved motor protection. This study demonstrates that a hybrid control system combining VFD and neural networks offers a promising solution for modern motor control systems requiring intelligent and adap-tive behavior.

Keywords: ***Induction Motor, Variable Frequency Drive, Neural Network, and Motor Control, Load Variation***

Introduction

Three-phase induction motors are one of the most widely used actuators in modern industrial systems due to their reliability, efficiency, and relatively low operating costs. However, induction motor performance is significantly affected by load variations and the nonlinear characteristics of the system, particularly in terms of speed and torque control. In many applications, a control system capable of maintaining stable motor speed and torque despite load changes is required. The use of Variable Frequency Drives (VFDs) has become a primary solution for regulating induction motor speed by adjusting the frequency and supply voltage according to load requirements. VFDs not only improve energy efficiency but also enable motor operation at various speeds with smooth and accurate response. However, conventional VFD-based control systems still have limitations when dealing with highly dynamic loads, especially in systems that require fast and adaptive response.

To overcome these limitations, artificial intelligence-based approaches, particularly Neural Networks (NN), are increasingly being applied in motor control systems. Neural Networks are capable of modeling complex, nonlinear relationships between system inputs and outputs without the need for precise mathematical models. The integration of VFDs and Neural Networks in motor control allows the system to learn from previous load data and adaptively optimize control signals in response to real-time load changes. This research was conducted to analyze the performance of a combination of VFD and Neural Network-based induction motor control against load variations. It is hoped that this approach will enable the motor control system to operate more efficiently, responsively, and stably under various load conditions. The results of this research can contribute to the development of more reliable and energy-efficient intelligent motor control systems, especially in modern industrial and automation applications.

Literature Review

2.1 Review of Relevant Research

To support the analysis in this thesis, the following are the results of previous research related to analysis. Muhammad Nur (2013), Research on Water Level Control Based on LG Inverter Drive – SV008IC5. This paper discusses the design, hardware creation, and program creation for water level control applications based on LG Inverter Drive – SV008iC5. This application is a simulation of water level control and stability in a reservoir. The water level simulation tool consists of a reservoir and a water source tank, a 3-phase AC motor, sensors and a control panel. The sensor used is an ultrasonic sensor to detect the water level. The control panel consists of an AVR ATMega 8535 microcontroller, an LG Inverter module – SV008iC5 and a set of connecting terminals. To determine the performance of the tool, a series of tests have been carried out. From the test results, it was found that the tool has functioned well. The LG Inverter Drive – SV008iC5 is able to control the rotation speed of a 3-phase AC motor in several water level conditions.

Andre Pratama (2010), Research on 3 Phase Inverter Design for Induction Motor Speed Control. Three-phase induction motors are the most widely used type of motor in the industrial sector compared to other types of motors. This is because three-phase induction motors have many advantages. But there is also a weakness of three-phase induction motors, namely the difficulty in controlling the speed. Because the speed control of a three-phase induction motor can basically be done by changing the number of motor poles or changing the motor supply frequency. Speed control by changing the number of poles is very difficult because it is done by changing the physical construction of the motor, so the settings will be very limited while the speed control of a three-phase induction motor by changing the motor supply frequency will be much easier and unlimited without having to change the physical construction of the motor. This inverter uses six mosfets triggered by the IR2130 IC and controlled by an ATMega 16 microcontroller. This module is tested with a three-phase induction motor using an open loop system with brake loading. The motor speed will be displayed by a tachometer controlled by another ATMega 16 microcontroller. The module in this final project can finally be used to regulate the speed of a 220 volt triangularly connected three-phase squirrel-rotor induction motor from a speed of around 150 rpm at a frequency of 5 Hz to around 1100 rpm at a frequency of 50 Hz.

Agus Salim (2012), Research on the Design of a 12V DC to 220V AC Inverter with a Frequency of 50 Hz and a Sinusoidal Output Waveform. One of the electronic systems that we know is an inverter that functions to convert DC voltage into AC voltage, one of which is 12V DC to 220 AC 50Hz voltage and a sinusoidal output waveform. This inverter is very functional as a good backup power provider.

Haryanto (2014), research on the Making of Inverter Modules as Induction Motor Rotation Speed Control. There are several ways that can be done to control the rotational speed of the induction motor, including voltage and frequency control known as constant V/f control. Constant V/f control is one way to control the rotational speed of an induction motor by changing the voltage and frequency, but maintaining a constant ratio of both. The most common way to apply this method is to use a known device. The most common way to apply this method is to use a device known as an inverter. Therefore, in this study the author designed an inverter, specifically a single-phase inverter with constant V/f control, which was applied to control the rotational speed of an induction motor.

2.2 Variable Speed Drive

Variable Speed Drive or also called Variable Frequency Drive or simply called Inverter is a circuit that converts DC voltage into AC voltage with adjustable voltage and frequency values. The function of the inverter is to change the speed of an induction motor by changing its input frequency. Variable Speed Drive is a tool to regulate the rotational speed of the motor by changing the electrical frequency according to the set motor speed, A Variable Speed Drive (VSD) is a system to control the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electricity supplied to the motor. VSD is also known as Adjustable Frequency Drive (AFD), Variable Frequency Drive (VFD), AC Drive, Microdrives or Inverter Drive. Essentially, a VSD is a device that converts alternating current (AC) from direct current (DC) by generating a waveform. However, the voltage waveform generated by an inverter is not sinusoidal but rather rectangular. The AC voltage is generated using two pairs of switches, as shown in the example in Table 1 below.

Table 1. AC Voltage Formation

Item	Method	Information	Results
Switch S1 - S4	Provide DC Voltage	In a way Alternate	Active
Switch S1 - S4	Living Conditions	Current flowing A to B	Tension is generated Positive
S2-S3 switch	Living Conditions	Current flowing B to A	Tension is generated Negative
Switch S1 - S4 and S2-S3 switch	In the first 1/2 period the current from A to B and at 1/2 of the second period the current flows from B to A		Formed current waves back and forth (Sinusoid)
Switch S1 - S4 and S2-S3 switch	Regulates ON - OFF of transistor during 0.5 seconds		Produce AC wave frequency 1 Hz

In this paper, the VSD used is the Siemens Micromaster 440 product. This inverter uses a 3-phase voltage source of 380-400 volts with a frequency of 50 Hz, which is then converted into a 3-phase AC voltage and produces variable frequencies and voltages where the output frequency starts from 5 to 50 Hz while the power capacity is 0.12 kW - 250 kW. The dimensions of this inverter are 326 x 1400 x 356 mm and are capable of working at temperatures between -10◦ C to 150◦ C. The VSD interface is a keypad.

Figure 1. VSD MM440 Panel

2.3 Variable Speed Drive Structure

The VSD structure shows a transistor that generates alternating current (AC) power with a frequency from a commercial source (50 Hz or 60 Hz). A converter circuit that converts the commercial AC source to a DC source and eliminates ripple on the DC output. The second part is an inverter circuit that converts direct current to three-phase AC current with a variable frequency (can be adjusted). These two circuits are called the main circuit. The third part is a control circuit that functions as a controller for the main circuit. The combination of all these circuits is called a VSD unit.

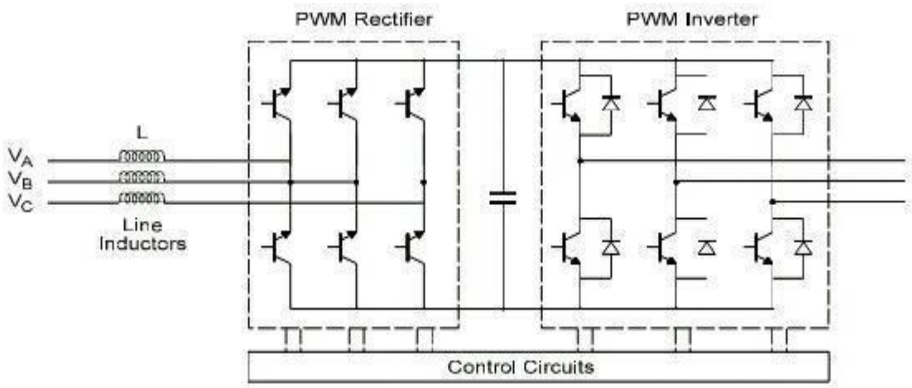

Figure 2. VSD Inverter Circuit

An inverter is a device that converts DC to AC. The basic principle will be explained using the simplest single-phase alternating current model. This model describes the method of converting direct current to alternating current, where a lamp acts as a load. Four switches S1, S2, S3, and S4 are connected to a DC power supply and alternately turned on and off to produce alternating current. Generally, S1-S4 and S2-S3 are turned on for the same duration. For example, if the duration of one cycle is one second, then the frequency (f) is:

F = 1/ t0 (Hz)……………………………………………………..……..................(1)

Three-phase alternating current. The basic circuit of a three-phase inverter. By switching S1 to S6 on and off, a pulse waveform with equal intervals passes through UV, VW, WU, and a rectangular AC voltage is received by the motor. By changing the on-off period of the switch, the desired output frequency can be received by the motor. By changing the AC voltage, the input voltage to the motor can also be changed. Where the simple working principle:

The incoming voltage from the 50 Hz mains is fed to the DC rectifier board and stored in a capacitor bank. The AC voltage is converted to DC.

The DC voltage is then fed to the inverter board to be converted back into AC at the required frequency. So, from DC to AC, the main component is an active semiconductor such as an IGBT. Using a carrier frequency (up to 20 kHz), the DC voltage is chopped and modulated to produce the desired voltage and frequency.

Three Phase Inverter Circuit Structure, Six transistors replace the function of six switches in the circuit, which are connected to a three-phase motor. The transistors are turned on and off alternately to run the motor by changing the on-off sequence of the transistors and the direction of rotation of the motor can also be reversed. A transistor consists of three terminals collector (C), an Emitter (E), Base (B), and Gate (G), for IGBT. When current flows through the base, CE is connected (switch on). The transistor can perform a switch function (on-off) like an S switch quickly closed base transistor is a term for the inverter protection function, where the base signal (gate signal for IGBT) is turned off, in the inverter all six transistors are turned off simultaneously to separate the motor and the inverter so that the motor will stop.

Various methods for converting DC voltage to AC. As explained in the characteristics of inverter-driven motors, the voltage must be adjusted to a V/f pattern to run a standard motor with Inverter. Because the transistorized inverter circuit is a voltage source inverter for the motor. There are various types of inverters, as shown below, based on how they convert voltage. Converter Circuit, the converter circuit functions to convert AC voltage source to DC voltage. The converter circuit consists of: converter, smoothing capacitor and inrush current damping circuit. Inverter control system and auto tuning function. V/f control, general-purpose magnetic flux vector control, advanced magnetic flux vector control and vector control (closed loop).

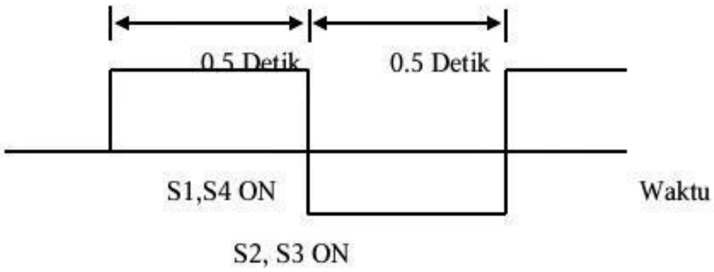

Figure 3. Hz AC Waveform

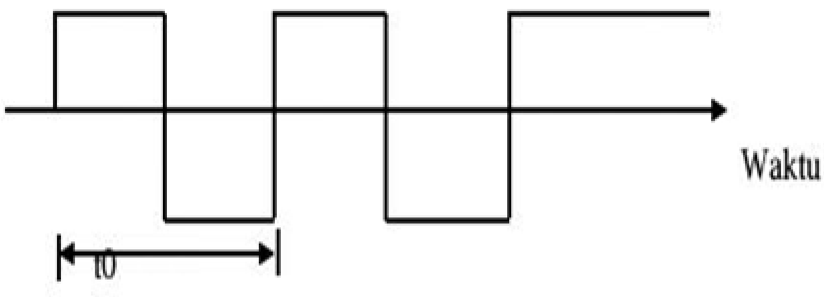

Figure 4. Number of Frequencies

Another more popular and frequently used full-wave rectifier design is the full-wave bridge system. This bridge rectifier design uses four diodes, as shown in the image below.

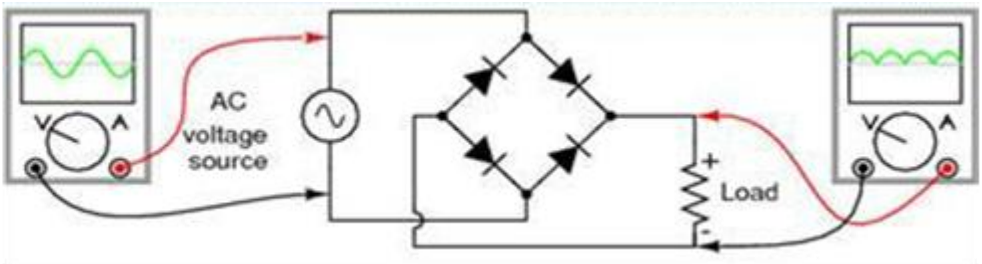

Figure 5. Full Wave Rectifier With Wheatstone Bridge

One of the advantages of remembering the rectifier layout as above is that it can be developed more easily into a polyphase version (more than one phase), such as the following 3-phase full-wave rectifier circuit version

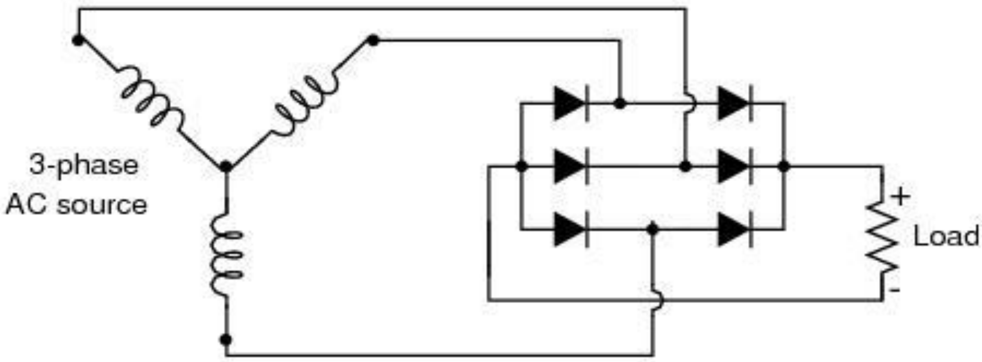

Figure 6. 3-phase full-wave rectifier (poly phase)

In this polyphase version of the full-wave rectifier, the phase-shifted pulses overlap, resulting in a much "smoother" DC voltage output compared to the single-phase version of the full-wave rectifier.

The induction motor is the most widely used alternating current (AC) motor. Its name comes from the fact that the current in this motor is not obtained from a specific source, but is induced as a result of the relative difference between the rotor rotation and the rotating magnetic field produced by the stator current. The stator windings connected to a three-phase voltage source will produce a rotating magnetic field at synchronous speed (ns = 120f/2p). The rotating field in the stator will cut the conductors in the rotor, thereby inducing current, and in accordance with Lentz's law. The rotor will also rotate following the rotating stator field. The difference in relative rotation between the stator and rotor is called slip. Increasing the load will increase the motor coupling, which therefore will also increase the induced current in the rotor, so that the slip between the rotating stator field and the rotor rotation will also be greater. Thus, as the motor load increases, the rotor rotation tends to decrease.

Asynchronous motors with a large enough power when started then the current drawn from the source is quite large, ranging from 3-4 times the nominal current, so that it will cause a momentary voltage drop on the voltage source whose size depends on the source impedance. If the voltage source is connected to other load equipment then the momentary voltage drop will interfere and reduce the starting current which is quite large, usually done by using resistance or reactance by changing the Y to D relationship.The direction of rotation of a three-phase asynchronous motor is controlled by changing the direction of rotation of the rotating field. Changing the direction of the rotating field is usually done by changing the phase sequence entering the asynchronous motor using a manual switch or contactor. The three-phase induction motor is the most widely used alternating current electric motor in industry. It is called an induction motor because the rotor current in this motor is not obtained from an electrical source, but is induced as a result of the relative difference between the rotor rotation and the rotating field. In reality, an induction motor can be treated as a transformer, with the stator coil as a stationary primary coil, while the rotor coil as a rotating secondary coil

Research Methodology

The research was conducted through several stages as follows:

1. Prepare the tools to be used from the Electrical Department of PT Lafarge Cement Indonesia, Aceh Besar District, Aceh Province, Indonesia.
2. Measuring voltage, frequency, and current on the Motor Panel for Apron Conveyor.
3. Analyze the effect of frequency on rotation speed from data obtained from measurement results.
4. Study of the frequency control process diagram on the Variable Speed Drive Inverter, checking the parameters on the Inverter from the results obtained, then relating these results to the effect of the induction motor rotation (Motor for Apron Conveyor).
5. Presenting the results in the form of tables, calculation data and graphs as research results.
6. Summarize how the Variable Speed Drive Inverter can automatically adjust the frequency so that it can change the rotation of the induction motor.

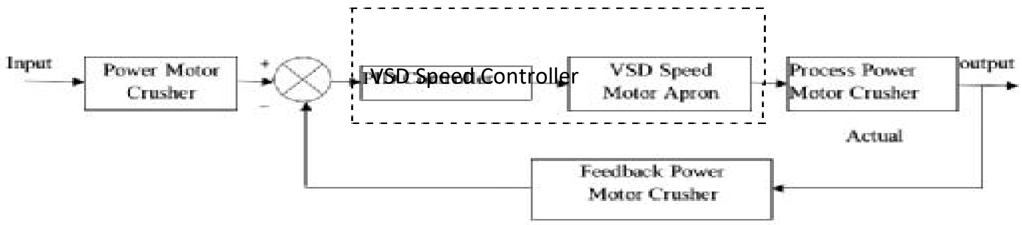

Figure 7. Block Diagram of Motor Control Process

From the Process Diagram above, it can be seen that the motor speed is regulated using the PID control method. The frequency changes depending on the maximum workload of the Crusher Machine. If the Crusher Machine is not working optimally, the Apron Motor automatically speeds up the Apron's work by increasing the frequency so that the Apron is accelerated to meet the Crusher Machine's demand.

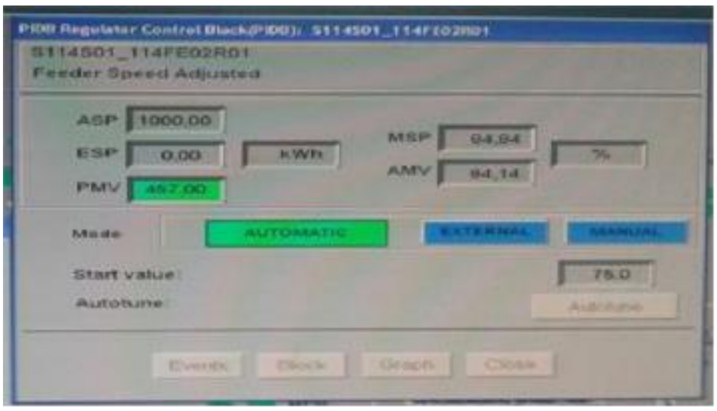

Figure 8. Crusher Machine Working View

Control can be done using a serial connection or digital and analog commands. The PLC used is a Schneider Modicon Quantum 140 CPU 651 60S PLC, and the inverter is a Siemens

Micromaster 440. The I/O modules required for this application include digital output, analog output, and analog input and output. This is a crucial step in research, especially when used to draw conclusions about the problem being studied. In this case, the analysis used is descriptive percentage analysis. The analyses to be conducted are the analysis of frequency changes on induction motor speed and the analysis of motor efficiency on induction motor speed.

Result

4.1 Data And Analysis

Data collection on the TCVY-512 VFD Motor was carried out by directly observing (field observation) the TCVY-512 operating process by the Central Control Room (CCR) operator in three conditions, namely when the work load (flowrate) varies and when there is no load (no-load). The work stages in collecting VFD Motor TCVY-512 data are as follows:

a. Operation preparation
b. Pre-start operation
c. Operation
d. Monitoring and recording of TCVY-512 motor operating data

It should be understood that the use of the flowrate workload as intended in this test is to provide an additional workload according to the needs of the TCVY-512 motor, namely to transport coal loads, and the workload measurement used is by measuring the flowrate or flow rate of coal in tons/hour units. While the no-load test is by not providing a flowrate load at all, or a flowrate value = 0 tons/hour. However, the value read in the reading and recording of operating parameters will show the value where the motor has been loaded with a belt conveyor as a fixed workload.

4.2 VFD Data Capture on a TCVY-512 Motor at No Load

The data collected during the TCV-512 VFD motor's no-load operation was random sampling, with 3 samples of VFD data collected during no-load operation (flow rate = 0 tons/hour). The data were obtained by reading the operating parameter graph on the DCS in the control room. Based on the researcher's observations, the following data were obtained:

Table 2. TCVY-512 Motor Data Without Load

Torsi (%)			Arus Motor (A)			Arus VFD (A)			Tegangan (V)			Kecepatan (rpm)			Kecepatan feedback (rpm)		
UJI 1	UJI 2	UJI 3	UJI 1	UJI 2	UJI 3	UJI 1	UJI 2	UJI 3	UJI 1	UJI 2	UJI 3	UJI 1	UJI 2	UJI 3	UJI 1	UJI 2	UJI 3
10,4	10,5	10,7	13	13	13,2	27,8	27,8	27,8	3000	3000	3000	100%	100%	100%	99,30%	99,30%	99,30%
NO LOAD																	

The data taken during the TCV-512 VFD motor operation with varying loads was random sampling, where 3 VFD data samples were taken while operating with a flow rate range of 500-1600 t/h.

4.3 VFD Test Measurement Results Calculation

The calculation of measurement data results is carried out using mathematical calculations. Based on the specifications of the TCVY-512 motor as per table (3.1), the reference for electrical calculations for several parameters according to the motor specifications is as follows:

a. Torque-Current Analysis

Based on the test results data as shown in table 4.2, it can be seen that the torque and current values at varying loads are as follows:

Table 3. Torque and Current Values of the TCVY-512 Motor at Varying Loads

Load (t/h)	Torsi (%)			Arus Motor (A)		
	UJI 1	UJI 2	UJI 3	UJI 1	UJI 2	UJI 3
500	11,8	12	11,8	13,5	13,6	13,8
900	15,9	15,8	15,8	17,2	16,9	17
1200	17,9	18,2	18,5	18,9	19	19
1300	21,9	22,2	22,3	21,9	21,8	21,7
1600	29,1	29,3	29	27,3	27,6	27,4

From the table above, we can see the relationship between the current torque in varying loads as follows:

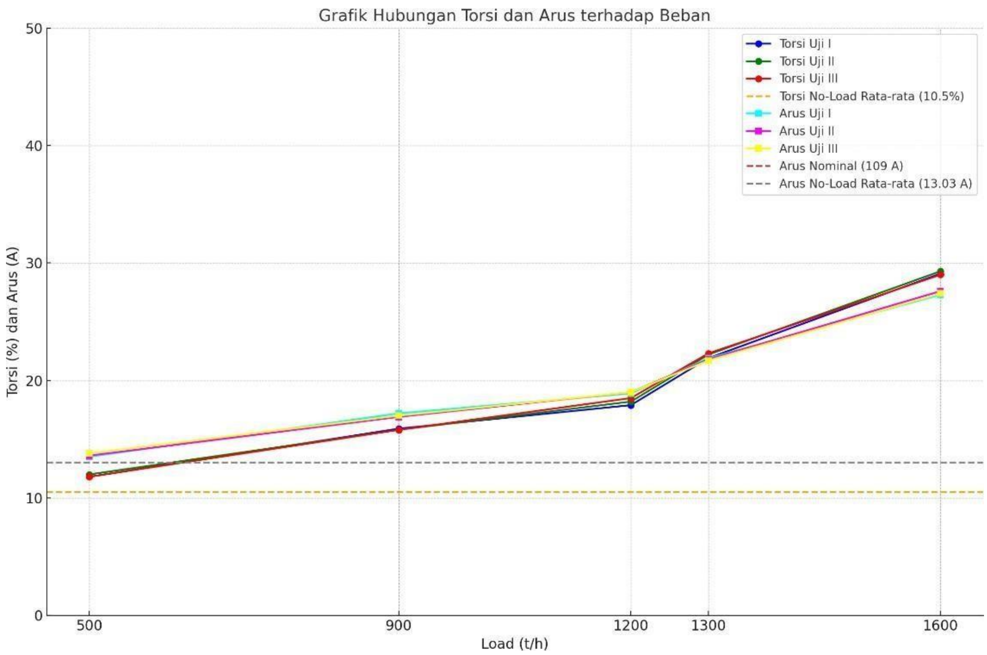

Figure 5. Relationship between current torque and working load of TCVY-512

Based on the graph above, it can be understood that the increase in the load value in the form of flow rate on the TCVY-512 motor is directly proportional to the increase in the torque value and the motor current value. This is caused by the increase in the effort that the motor must do to support a heavier load. This increase in torque and current occurs linearly in the three test data conducted from Test I, Test II and Test III, where a significant increase occurs when the flow rate workload is at 1200 tons/hour, and the increase in torque and current reaches its highest point based on the data occurs when the flow rate workload is 1600 tons/hour. Meanwhile, when the motor is in a no-load condition, the current and torque values of the motor tend to be stable at around 13.03 Amperes for the current and 10.5% for the Torque value.

Based on the graph above, it can also be seen that the increase in torque value which is directly proportional to the load is still relatively in accordance with the specifications as stated in the O&M book of PT Bhumi Jepara Services. The use of VFD as a voltage stabilizer through frequency regulation provides an effective impact so that there are no spikes in torque or current that can impact equipment damage. The role of VFD in maintaining voltage stability in the range of 3000 Volts is important considering the fluctuating workload so that the condition of the TCVY-512 motor remains reliable.

From the data it can also be understood that the increase in current and torque of the TCVY-512 motor is still relatively small from the nominal current and maximum torque according to the motor design specifications. This is possible because the VFD maintains a constant motor rotation stability at a speed of 1489 rpm (99.3% of motor speed) by means of frequency regulation. With a constant speed, the work that must be done by the motor when it has reached optimal speed becomes only dependent on the increase in flow rate and is no longer affected by the effort to change the motor rotation speed.

Based on the description above, the use of a variable Frequency Drive (VFD) on the TCVY-512 motor effectively maintains the stability of the motor's rotational speed, which further impacts the stability of the current-torque increase to the load linearly. This more stable current increase will have a positive impact on maintaining optimal motor performance, maintaining motor durability, and reducing excessive current values that can cause losses both in terms of operational costs and maintenance.

Conclusion

Based on the analysis and experimental results, it can be concluded that the integration of a Variable Frequency Drive (VFD) with a Neural Network-based control system significantly improves the performance of induction motors under varying load conditions. The system demonstrated the ability to adapt in real time to load fluctuations by adjusting the frequency and voltage supplied to the motor, thereby maintaining optimal speed and torque output. Compared to conventional control methods such as PID, the neural network-based controller offered:

1. Faster dynamic response to sudden load changes,
2. Higher efficiency in power usage,
3. Reduced current spikes, and
4. Improved system stability.

The neural network's learning capability allows the system to continuously fine-tune its control parameters, making it highly suitable for industrial applications where load conditions are unpredictable. This adaptive behavior leads to better motor protection, energy savings, and prolonged equipment lifespan. In conclusion, the use of neural networks in conjunction with VFDs presents a reliable and intelligent solution for modern induction motor control systems.

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