Energy Saving Opportunities in 3-Phase Induction Motors with Variable Speed Drive (V.S.D.) Drives

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***Abstract*— Most of the load in the motorcycles industry is motors. So, the largest energy use is in motorcycles. This study aims to prove the effect of speed change on a three-phase induction motor on energy consumption with a V.S.D. drive. The method used in this proof uses direct experiment methods and data analysis. The relationship between speed and energy use can be demonstrated through testing and data analysis. The results show that V.S.D. is set at frequencies of 20 Hz and 40 Hz to regulate the speed of the motor as a pump drive can save its energy use. This resulted in a reduction in energy consumption of 20.54% and operational costs of up to Rp 3,292.32 per month in the implementation of the motor as a pump driver.**

Keywords*— *energy efficiency, energy consumption, induction motor, rotary speed, Variable Speed Drive

I. INTRODUCTION

Technology development in the modern era has brought significant changes in various aspects of life, including the industrial sector. One of the innovations that has become the focus of attention is using a variable speed drive (V.S.D.) to control the speed of three-phase induction motors. This technology offers a more efficient and flexible solution for controlling motor rotation, a crucial component in many industrial processes. Three-phase induction motors have long been a top choice in the industrial sector due to their efficiency and reliability advantages [1]. However, the large energy consumption of these motors remains a major concern, given their impact on operational costs and the environment. This crucial aspect becomes more relevant, considering that the level of motor energy consumption is greatly influenced by its rotational speed [2]. Using V.S.D. opens up new opportunities for optimizing the performance of induction motors. This technology allows for dynamic adjustment of the motor rotation speed according to the demands of the load, potentially resulting in higher energy efficiency [3]. V.S.D.'s ability to precisely regulate motor speed improves energy efficiency, extends the motor's life, and reduces mechanical wear [4].

This study aims to prove the effect of variation in rotation speed on energy consumption in three-phase induction motors controlled using V.S.D. By understanding the correlation between rotational speed and energy consumption, valuable information is hoped to be obtained to maximize energy efficiency and reduce operational costs [5]. Optimizing energy consumption in electric motor systems is a crucial issue in an era where energy efficiency is a global priority [6]. Given the prevalence of using three-phase induction motors in industry, improving energy efficiency in this type of motor can have a significant overall energy-saving impact [7]. Controlling the motor's rotational speed using V.S.D. has been proven to significantly improve energy efficiency compared to conventional methods [5]. V.S.D.'s ability to optimize motor speed according to load requirements results in energy savings and can also improve process control precision and reduce operational noise [8].

This research is expected to contribute meaningfully to a deeper understanding of the relationship between rotational speed and energy consumption in VSD-controlled three-phase induction motors. The results obtained can be a valuable reference for industries and practitioners in efforts to improve energy efficiency, reduce operational costs, and support more sustainable manufacturing practices.

II. MATERIALS AND METHODS

The method used in this proof uses direct experiment methods and data analysis. In the first stage, the equipment is prepared, and the nameplate on the induction motor and corresponding V.S.D. requirements are identified. The next stage is to install the connection between the motorcycle and the V.S.D. Measurement instruments include measurement units and data acquisition devices per prescribed procedures well incorporated into this process. During the testing phase, the motor is run at different speeds set with V.S.D. At each speed, measurements of energy consumption, current, voltage, and other relevant parameters are taken. The data is analyzed through graphs and tables showing the relationship between speed and energy consumption.

A. *Induction Motor*

Electric motors convert electrical energy into mechanical energy through rotational power. This motor consists of two main components: the stator, the stationary part, and the rotor, the rotating part. In A.C. motors, the rotor coils do not get electrical energy directly but through induction, similar to the working principle of transformers. Three Phase Electric Motors are the most common type of motor used in various industrial applications. Its popularity is due to its simple design, affordable price, ease of access, and ability to directly connect to A.C. power sources [9].

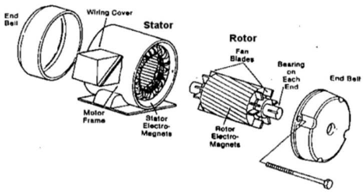

Figure 1. Induction Motor

In general, an induction motor consists of two main components: a rotor and a stator. The rotor is a moving part, cylindrical in shape and attached to the motor shaft. The rotor can be a squirrel cage or a wound rotor, with the former being more commonly used due to its simplicity and durability. Stators, on the other hand, are the parts that are stationary and surround the rotor. The stator consists of an iron frame that has slots to place the three-phase coil. Between the rotor and stator there is a very small air gap, usually only a few millimeters. This air gap is very important because it affects the efficiency of the motor and its torque characteristics. A gap that is too large can reduce efficiency, while a gap that is too small can cause mechanical friction. When the stator is connected to a three-phase AC voltage source, a three-phase current will flow through the stator coils. Each phase coil is usually distributed and arranged in such a way as to produce a magnetic flux distribution that is close to sinusoidal. The three-phase AC current flowing on this stator will produce an alternating flux in each of the coils. The flux interaction of each phase will create a rotary field. This phenomenon is known as a rotating magnetic field, which is the basic principle of operation of induction motors. This rotating field moves at a synchronous speed, which is determined by the supply frequency and the number of poles of the motor. This rotational field velocity then induces a current in the rotor through electromagnetic induction, similar to the working principle of a transformer. The induced current on the rotor interacts with the stator's magnetic field, generating an electromagnetic force that causes the rotor to rotate. However, the rotor always rotates a little slower than the stator's rotating field, this difference in speed is called slip. This slip is important because without it, no current will be induced on the rotor and the motor will not produce torque. The proper design and construction of these components, as well as a deep understanding of the underlying electromagnetic principles, are essential for achieving optimal motor performance in terms of efficiency, torque, and speed [10].

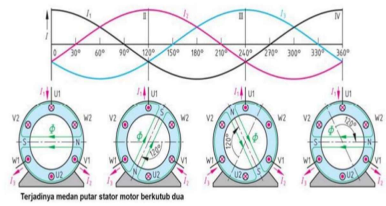

Figure 2. Sinusoidal waveform and the onset of a rotating field in the stator of an induction motor

a. At an angle of 0º, the current I_1 has a positive value, while the current I2 and I3 have a negative value. In this condition, the V2, U1, and W2 windings are crossed (signifying outflow from the reader), while the V1, U2, and W1 windings are dotted (signifying inflow to the reader). At an angle of 0º, the magnetic flux is formed on a horizontal line, with the S (south) pole and the N (north) pole.
b. At an angle of 120º, the I2 current has a positive value, while the I1 and I3 currents have a negative value. The windings W2, V1, and U2 are marked with a cross sign (the current leaves the reader), while the wires W1, V2, and U1 are marked with a dot (current to the reader). The magnetic flux of the S and N poles has shifted by 120º from the initial position.
c. At an angle of 240º, the current I3 has a positive value, while the current I1 and I2 have a negative value. The U2, W1, and V2 windings are marked with a cross sign (current away from the reader), while the U1, W2, and V1 wires are marked with a dot (current toward the reader). The magnetic flux of the S and N poles shifted by 120º from the second position.
d. At a 360º angle, the position is the same as at an angle of 0º, where the poles S and N return to their original positions.

A. Working Principle of Induction Motor

Induction motors work on the principle of electromagnetic induction between the stator coil and the rotor. When the stator coil of a three-phase induction motor is connected to a three-phase voltage source, it creates a rotating magnetic field. The conductor in the current rotor is in the line of the flux force of the stator winding, so the rotor coil is subjected to the Lorentz force. The stator rotary field will cut the conductors on the rotor so that the rotor rotates following the stator rotary field [11]. The rotational speed of this rotating field is known as synchronous speed, the values of which are as follows:

$$n_s = \frac{120 \times f}{P} \quad (1)$$

Where:

ns = synchronous speed of the motor (rpm)

F = frequency (Hz)

P = number of motor poles

Suppose the induction motor's rotor rotates at a speed, and the stator's magnetic field rotates at a speed of ω_s. The relative speed difference between the speed of the rotating stator magnetic field and the speed of this rotor is known as the slip speed, with the following values: ω_r

$$Slip = \frac{n_s - n_r}{n_s} \quad (2)$$

Where:

S = motor slip

ns = synchronous speed of the motor (rpm)

NR = Motor speed (rpm)

B. Variable Speed Drive (VSD)

A Variable Speed Drive (VSD), often referred to as an inverter, is a device that uses diodes to convert AC voltage (alternating current) into DC voltage (direct current) and then convert it back to AC voltage. [12]. Generally, VSD converts AC to DC through a rectifier circuit. A more advanced option is to use a controlled rectifier (inverter). Once the AC current is converted to DC, the next step is to flatten the DC waveform, which usually has ripples, by adding a link or DC rectifier component.

Figure 3. Variable Speed Drive (VSD)

After obtaining a stable DC voltage, the next step is to convert it back into AC using an inverter circuit. The inverter circuit converts DC currents alternately to produce AC current. Finally, a pulse width modulation circuit (PWM) is required before being applied to induction motors. This process aims to convert DC into AC current of the desired frequency[13].

C. *Working Principle of Variable Speed Drive*

In simple terms, the working principle of a Variable Speed Drive (VSD or Inverter Drive) works similarly to a simple inverter. Its working principle involves the conversion of AC to DC, which is then arranged using a defragmentation technique to convert DC into AC output voltage and frequency, which varies according to the frequency requirements to regulate the motor's rotational speed [14]. The voltage from the 50 Hz network is passed to the Board Rectifier (DC rectifier) and then stored inside the Capacitor Bank. [15] . The DC voltage is then sent to the Board Inverter to convert to AC with the required frequency. By utilizing the carrier frequency (up to 20 kHz), the DC voltage is modulated to produce the desired voltage and frequency [16].

III. Results and Discussion

A. *Motor Testing Without VSD*

This motorcycle is a three-phase induction motor of the FUKUTA brand with a frame size of 71. This motor has an output of 1/4 HP or 0.33 kW, and can operate at a voltage of 220/380 V with a frequency of 50 Hz. The required current is 0.9/1.1 A with a continuous rating. The motorcycle is manufactured by Fukuta Elec. & Mach. Co. Ltd. in 1992 in Taiwan, R.O.C., and is equipped with type 6202 bearings [17]. The serial number is 823020. The nameplate of the motorcycle can be seen in the image below.

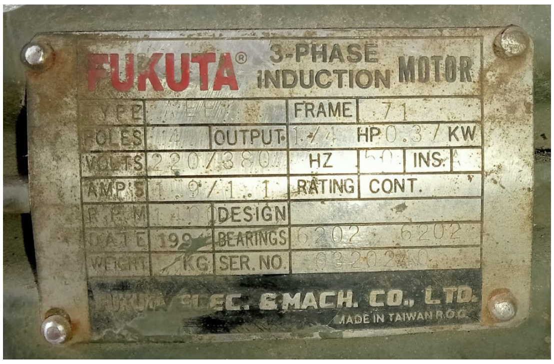

Figure 4. Induction Motor Nameplate

The motor operates 1 time in 24 hours with the loading used for the high pressure water pump motor and in one operation the motor takes 1 hour. The test will be conducted without the use of *a variable speed drive* and will be compared to a test using *a variable speed drive*. The results of measuring the use of motors without inverter can be seen in Table 1.

TABLE I. Measurement results of voltage, current, power and electrical energy of three-phase induction motors without VSD

Frequency (Hz)	Current (A)	Power Factor	Voltage (Volts)	Total Power (KW)	Speed (RPM)
50	1,19	0,745	239.77	0,392	1400.05
50	1.12	0.671	242.57	0.345	1408.93
50	1.15	0.701	241.21	0.378	1400.63
50	1.21	0.696	243.77	0.356	1402.01
50	1.19	0.731	241.98	0.353	1409.42

Frequency (Hz)	Current (A)	Power Factor	Voltage (Volts)	Total Power (KW)	Speed (RPM)
50	1.05	0.729	240.64	0.358	1393.26
50	1.15	0.703	242.94	0.364	1393.65
50	1.09	0.708	243.86	0.371	1404.85
50	1.09	0.682	243.13	0.347	1394.13
50	1.12	0.660	243.60	0.388	1409.72
50	1.11	0.693	241.73	0.379	1397.93
50	1.17	0.703	242.27	0.339	1396.26
50	1.14	0.725	241.66	0.400	1409.61
50	1.11	0.724	242.28	0.408	1407.40
50	1.12	0.629	241.37	0.394	1409.34
50	1.12	0.694	239.55	0.366	1404.53
50	1.17	0.679	243.35	0.349	1395.69
50	1.09	0.672	242.20	0.391	1409.55
50	1.12	0.666	239.74	0.362	1398.66
50	1.06	0.739	243.93	0.394	1404.01
50	0.97	0.690	241.19	0.374	1404.74
50	1.13	0.691	243.10	0.390	1399.22
50	1.14	0.675	244.46	0.377	1403.07
50	1.06	0.716	243.26	0.384	1404.61
50	1.12	0.699	242.23	0.373	1402.55

Based on the 24-hour measurement results in Table 1, the three-phase induction motor without VSD shows stable performance with some variation in operational parameters. The system frequency is recorded consistently at 50 Hz, which is the electrical frequency standard in many countries, indicating the stability of the frequency of the electrical system used.

The current drawn by the motor varies between 0.97 A to 1.21 A, with an average of 1.12 A. This variation in current is most likely due to fluctuations in the load connected to the motor, resulting in a change in the drawn current. The power factor ranges from 0.66 to 0.75, with an average of 0.699. This value indicates the presence of reactive components in the system that cause the current and voltage to be out of phase, and indicates that the efficiency of the system is not optimal because there is energy lost in the form of heat.

The measured voltage varies between 239 V to 245 V with an average of 242.23 V. These voltage fluctuations are within acceptable limits for most industrial applications and reflect normal variations in electrical distribution systems. The total power consumed by the motor ranged from 0.34 KW to 0.41 KW, with an average of 0.373 KW. This variation in total power is the result of fluctuations in current and voltage, and indicates that the load connected to the motor is not very large.

The speed of the motor ranges from 1393 RPM to 1410 RPM, with an average of 1402.55 RPM. The almost constant speed of the motor indicates that the motor operates stably and is not affected by significant load fluctuations.

Overall, the three-phase induction motor used shows fairly stable performance. Consistent voltage and frequency ensure reliable motor operation. However, the relatively low power factor indicates an opportunity to improve system efficiency. The use of devices such as capacitor banks for power factor correction can improve efficiency and reduce energy loss. Additionally, periodic monitoring of motor operational parameters and regular maintenance can be helpful in detecting problems before they become critical, ensuring more efficient and reliable motor operation.

Below is the calculation of electrical energy use without VSD based on average measurement data. [18]. The power and electrical energy consumption of a three-phase induction motor can be calculated based on the average data listed in Table 1, with the following results:

$$
\begin{aligned}
P &= \sqrt{3} \times V \times I \times Cosphi \\
&= \sqrt{3} \times 243 \times 1.1 \times 0{,}7 \\
&= 370{,}381\ Watt \\
&= 0{,}37\ Kw
\end{aligned}
$$

The use of electrical energy for one hour for one unit of three-phase induction motor that functions as a water pump is as follows:

$$
\begin{aligned}
W &= 0{,}37\ Kw \times 1\ jam \\
&= 0{,}37\ kWh
\end{aligned}
$$

The calculation of the cost of using electrical energy for a three-phase induction motor used as a pump drive motor is carried out assuming the cost per kWh of electrical energy is Rp. 1,444,- as follows:

Electrical energy usage fee (per day)

$$= 0{,}37Kw \times 1\ jam \times Rp. 1.444$$

$= Rp. 534.280, -$

B. Motor Testing Using Variable Speed Drive (VSD)

Variable Speed Drive (VSD) is an electronic device that functions to regulate the speed of an electric motor by changing the frequency. [19].

The analysis was carried out on several parameters. First, observations are made of voltage changes in response to frequency variations regulated by VSD. Second, the rotation of the motor (RPM) is measured at various frequency levels to understand the relationship between frequency and motor speed. Third, an analysis was carried out on the change in the pump flow discharge (which was carried out in the experiment), which reflects the different operational conditions in the application.

Figure 5 shows the details of the inverter specifications, including information such as output frequency range, power capacity, input and output voltage, and available control features. An in-depth understanding of these specifications is essential for interpreting the study results and ensuring that VSDs are used optimally according to the characteristics of the tested induction motor. Testing uses a Variable Speed Drive (VSD) inverter at different frequency conditions according to the inverter specifications. This test aims to evaluate the performance of a 3-phase induction motor using VSD. The motor test results using an inverter can be seen in Table 2, which includes current, voltage, power, power factor and motor speed at each frequency setting. This analysis helps to understand how frequency variations affect the efficiency and performance of 3-phase induction motors in industrial applications.

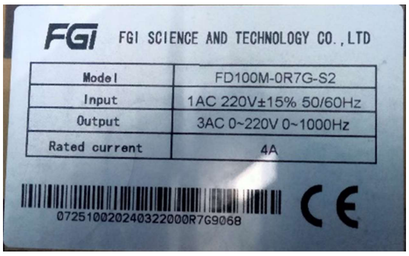

Figure 5. Specification of Variable Speed Drive Inverter

TABLE II. RESULTS OF MEASUREMENT OF VOLTAGE, CURRENT, POWER AND ELECTRICAL ENERGY OF THREE-PHASE INDUCTION MOTOR USING VSD

Frequency (Hz)	Current (A)	Power Factor	Voltage (Volts)	Total Power (KW)	Speed (RPM)	Flow (ml/min)
50	1,0	0,7	243	0,29	1400	3500
45	1,0	0,7	219	0,26	1260	3150
40	1,0	0,7	194	0,23	1120	2800
35	1,0	0,7	170	0,20	980	2450
30	1,0	0,7	146	0,17	840	2100
25	1,1	0,7	122	0,16	700	1750
20	1,1	0,7	97	0,12	560	1400
15	1,1	0,7	73	0,09	420	1050
10	1,1	0,7	49	0,06	280	700

Table 2 shows the linear relationship between motor frequency and pump flow, where a decrease in frequency leads to a proportional reduction in flow. This is by the pump's law of affinity, which states that flow is directly proportional to the speed of the motor. Although the flow decreases as the frequency decreases, the total power used also decreases. This indicates the potential for energy savings when the pump operates at lower frequencies, especially for applications that do not require maximum flow.

The system offers a wide operating range, ranging from 700 ml/min at 10 Hz to 3500 ml/min at 50 Hz, providing significant flexibility in flow control for a wide range of application needs. The speed of the motor decreases linearly with the decrease in frequency, which can extend the life of the mechanical components of the pump and motor if operated at a lower speed for an extended period.

Interestingly, the motor current remains relatively constant at 1.0 A for 30-50 Hz but slightly increases to 1.1 A at lower frequencies. This may indicate that the motor works less efficiently at very low frequencies. The voltage also decreases linearly with a decrease in frequency, a typical characteristic of the *Variable Speed Drive* (VSD) used.

However, it should be noted that operating at very low frequencies (below 20 Hz) may not be recommended for long-term use as they may affect motor cooling and pump efficiency.

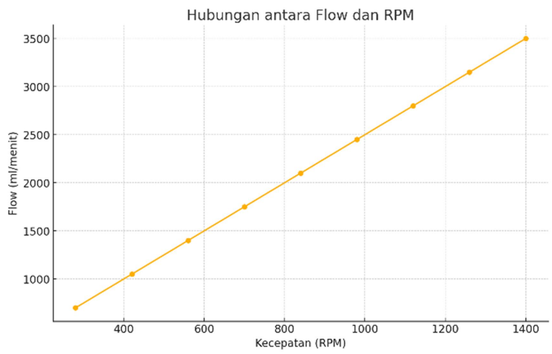

Figure 6. Motor RPM Characteristics and Voltage

The test results shown in Figure 1 show that, in general, the increase in voltage affects the motor's rotational speed. As with frequency, the output voltage from the VSD will decrease as the frequency decreases. The calculation of electrical energy consumption using VSD is presented below.

The horsepower and electrical (operational) operating costs of the three-phase induction motor used as the water pump drive can be calculated using the data in Table 2. The results of the calculation are as follows:

$$
\begin{aligned}
P &= \sqrt{3} \times V \times I \times Cosphi \\
&= \sqrt{3} \times 243 \times 1{,}0 \times 0{,}7 \\
&= 294{,}621\ Watt \\
&= 0{,}294\ Kw
\end{aligned}
$$

The following steps can be taken to determine the 1-hour electrical energy usage of a three-phase induction motor used as a water pump:

$$W = 0{,}294Kw \times 1\,Jam$$
$$= 0{,}294kWh$$

Using the motorcycle for 1 hour a day, the cost of electrical energy needed can be calculated with the following calculation.

$$Biaya\ energi\ listrik = 0{,}294kW \times 1\,Jam \times Rp.1.444,-$$
$$= Rp.424.536,-$$

Here is a comparison between Before VSD and After VSD Use:

TABLE III. COMPARISON BETWEEN BEFORE VSD USE AND AFTER VSD USE

	Frequency (Hz)	**Motor Power (KW)**	**Amount of power consumption to be paid in 1 day**
Before VSD Use	50	0,37	534.280,−
After VSD Use	50	0,294	424.536,−
Savings			109,744

The measurement results revealed that the energy efficiency obtained from the three-phase induction motor, both without VSD and with VSD, was as follows:

Electricity savings for one (1) hour in a day.

$$= \frac{0{,}370 - 0{,}294}{0{,}370} \times 100\%$$
$$= 20{,}54\%$$

If calculated in terms of costs, the total is Rp. 109,744 per day and Rp. 3,292.32 per month. The comparison of electrical energy consumption between Table 1 and Table 2 shows that the use of electrical energy with VSD is more efficient, i.e. 0.076 kWh lower compared to induction motors without VSD, which means a saving of electrical energy of 20.54%.

This can be seen in graph 2 below.

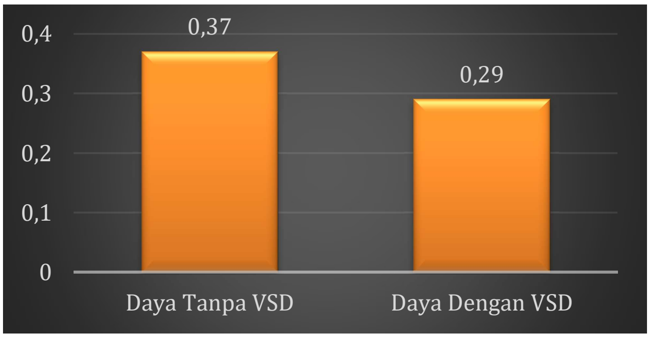

Figure 7. Comparison of electrical energy consumption

IV. CONCLUSION

This study presents the effectiveness of Variable Speed Drive (VSD) in improving the performance of three-phase induction motors. The test results show that VSD can reduce electrical energy consumption by 20.54% compared to operating without VSD, resulting in cost savings of Rp.3,292.32 per month. Adjusting the speed of the motor according to the load through VSD has proven to be effective in improving energy efficiency. These findings provide important insights for the industrial sector to improve energy efficiency and reduce operational costs associated with electric motors. Applying VSD in three-phase induction motors shows excellent potential to optimize energy consumption and realize significant cost savings in industrial environments.

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