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Speed Control Analysis of Frequency Changes in Three Phase Synchronous Motor With Variable Speed Drive (VSD)

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ABSTRACT

This study investigates the impact of frequency adjustment via a Variable Speed Drive (VSD) on the performance of a three-phase synchronous AC motor under both no-load and load conditions. Industrial systems often suffer from inefficiencies due to mismatches between motor speed and load requirements. The motor was tested at frequencies ranging from 20 Hz to 50 Hz to observe variations in speed, input power, torque, and efficiency. Unlike previous studies that focused solely on speed, this research incorporates additional performance indicators such as torque and efficiency to provide a more comprehensive evaluation. Results show that increasing frequency leads to higher motor speed and electrical power consumption but causes a decrease in torque output. Under no-load, motor speed rose from 607 RPM at 20 Hz to 1506 RPM at 50 Hz, while torque dropped from 1.57 Nm to 0.63 Nm. Under load, speed increased from 88 RPM to 683 RPM, but torque declined from 10.9 Nm to 1.39 Nm. This reduction is attributed to a declining voltage-to-frequency (V/f) ratio, which weakens the magnetic field strength at higher frequencies. Although VSD offers flexible speed control, it does not necessarily improve energy efficiency, particularly in fixed-load applications. Efficiency tends to decline as frequency increases under constant load. Therefore, optimal motor performance requires frequency settings that adapt dynamically to varying load conditions. Further research is recommended to develop intelligent control strategies that enhance energy efficiency in industrial operations.

Keywords:
Variable Speed Drive; Speed Control; Three-Phase Synchronous Motor; Energy Efficiency; Experimental Research.

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1. INTRODUCTION

The development of electric motors is currently progressing rapidly, and their use has expanded across all sectors including industry, transportation, agriculture, commerce, and households. In fact, in the industrial sector, electric motors dominate power consumption. This significant utilization of electric motors has encouraged many researchers to develop more efficient motors [1].

Three-phase synchronous motors have long been applied in industrial settings that require constant-speed operation [2]. A synchronous motor is a type of electric motor that uses AC input current, operates at a constant speed, and has low energy losses, making it highly efficient. Despite these advantages, synchronous motors have the drawback of producing no starting torque. In principle, they operate at a constant speed [3]. A sudden and significant change in load can cause the synchronous motor to lose synchronism [4]. Furthermore, the inability to manage load speed effectively can pose major challenges in machine maintenance and energy usage [5].

Since the behavior of these drives is nonlinear, unpredictable, and influenced by varying load torques over time [6], the motor speed must be regulated to address these issues and to save power [7]. Scalar control (V/F control) is one method of regulating the speed of a synchronous motor by adjusting voltage and frequency [8]. Speed control can be achieved by modifying the frequency variable during motor operation, which is done using an inverter commonly referred to as a Variable Frequency Drive (VFD) or Variable Speed Drive (VSD) [9].

The control of inverter voltage and frequency is based on scalar control using the V/F (voltage-to-frequency) ratio, which is essential for automatic control, controlled start-up, acceleration and deceleration, as well as maintaining constant motor flux [10]. One of the primary functions of modern Variable Frequency Drives (VFDs) is to maintain controlled coordinate values at signal levels despite various disturbances [11]. Variable frequency generates pulse-width modulated (PWM) current that is adjusted according to the power and frequency supplied to the motor, resulting in reduced stress and energy consumption. It uses a fixed-frequency AC source and converts it into a variable-frequency AC output, regulating power usage and mechanical output so the motor can operate at the most efficient speed [12].

In addition to providing stable speed response [13], Variable Frequency Drives (VFDs) allow for smooth motor startup by reducing inrush current and improving the power factor, which consequently decreases overall power consumption [14]. The electrical current produced during the operation of a synchronous motor plays a significant role in determining its reliability and long-term performance under load conditions [15]. In industrial environments, efficient energy utilization is essential, and over the past few decades, VFDs have become critical components in both industrial and commercial applications [16]. Their ability to simplify traditionally complex control systems[17], and deliver high efficiency in power conversion applications has made them an integral part of modern electrical systems [18] .

This study was conducted to analyze the performance of a three-phase synchronous motor controlled using a Variable Speed Drive (VSD), focusing on its effects on speed, voltage, power consumption, and efficiency. It builds upon previous research by Abdul Kodir et al. (2022), which only examined motor speed in a lift door system using a BG202-XM inverter, without considering aspects such as power, torque, or efficiency. By incorporating an analysis of power quality, this study provides a more comprehensive assessment of motor performance. The main contribution of this research is to offer a deeper understanding of the efficiency and operational characteristics of a synchronous motor controlled by a VSD, serving as a reference for designing more energy-efficient and effective motor control systems.

Literature Review

1.1.1 Synchronous Motor

A synchronous motor is a type of motor that operates at synchronous speed. Synchronous speed is a constant speed at which the motor produces electromotive force (EMF). The synchronous motor functions to convert electrical energy into mechanical energy. The stator and rotor are the two main components of a synchronous motor. The stator is stationary, and the rotor winding is wound on it; the rotor winding is the main winding as it generates the Electromagnetic Force (EMF) that induces the motor. The rotor carries the field winding, and the main magnetic flux induces the stator. The rotor is designed in two variations: salient pole rotor and non-salient (cylindrical) pole rotor.

Synchronous motors have low starting torque, making them suitable for driving light loads. They are appropriate for initial applications with low loads such as air compressors, frequency converters, and motor generators. These applications are suitable because the motor has low starting torque and requires direct current (DC) for power generation. Synchronous motors are also commonly used in systems that require high electrical power usage, as they can improve the system's power factor [19].

In a synchronous motor, the stator winding is identical to that found in an induction motor. When connected to a three-phase power supply, it produces a rotating magnetic field. However, the rotor is cylindrical and equipped with windings. Unlike squirrel cage rotors, synchronous motors use either a DC-excited rotor winding or permanent magnets designed to lock or synchronize the rotor with the rotating magnetic field generated by the stator. Once synchronized, the rotor operates at exactly the same speed as the magnetic field, regardless of load variations. Therefore, under constant supply frequency, the motor speed remains steady [20].

1.1.2 Principle of Synchronous Motor

Figure 1 the illustration shows the fundamental operation of a synchronous AC motor powered by a three-phase AC source. In this system, the rotor—regardless of its excitation method—has two magnetic poles: a north pole (shown in red) and a south pole (shown in green). Meanwhile, the stator is equipped with several windings that produce three-phase alternating currents, typically represented by red, green, and blue.

When the three-phase AC current is applied to the stator, it generates a rotating magnetic field formed by alternating magnetic poles. These poles interact with the rotor's opposite poles. As the stator's magnetic field rotates due to the alternating current, it pulls the rotor along, causing it to rotate in step with the magnetic field.

The rotor's north pole continuously aligns with the stator's south pole, and the rotor's south pole aligns with the stator's north pole. This magnetic interaction ensures that the rotor turns at the same speed as the rotating field of the stator. This constant alignment and equal rotational speed are what define it as a synchronous AC motor [21] .

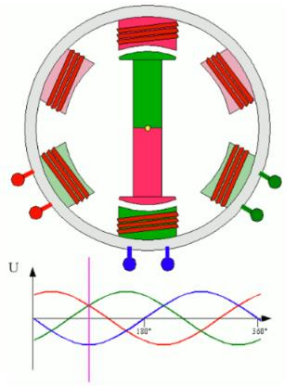

Figure 1. Principle of a Synchronous Motor
Source : *A. W. Hermanto and S. P. Chairandy (2022)*

1.1.3 Frequency Speed Control of Synchronous Motor

Frequency adjustment is directly proportional to the speed of a synchronous motor [8]. A variable speed drive (VSD) is a practical choice for operating a synchronous motor, as it helps address the limitation of constant speed determined by the main frequency operation and provides an opportunity for a simple open-loop system to be controlled quickly. This method is known as separate control and can also be applied to achieve smooth starting and regenerative braking. An example of the application of this method is speed control using an open-loop (V/f) configuration.

1.1.4 Three Phase Power Usage

9 The motor has power, and in motors, there are three types of power: active power, reactive power, and apparent power. To determine the active power, the following equation can be used. This is used to calculate the active power or input power of a three-phase AC synchronous motor [22]. The Formula power is shown in Equation (1).

$$P = \sqrt{3} \times V \times I \times \cos\varphi \quad (1)$$

Where :
P : Power
$\sqrt{3}$: Constanta
V : Volt
I : Current
$\cos\phi$: Power Factor

1.1.5 Power Efficiency

Power efficiency can be defined as a measure that indicates how effectively the motor converts the electrical energy it receives into useful mechanical energy without significant energy losses [23]. The formula to calculate the efficiency of a synchronous motor can be determined using the following equation (2).

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (2)$$

Where :
η : Power Efficiency
P_{out} : Power Out
P_{in} : Power In
100% : Efficiency

The output power of a synchronous motor, which is in the form of mechanical power, can be calculated using the following equation (3).

$$P_{out} = \omega \times T \quad (3)$$

Where :
P_{out} : Power Out
ω : Angular Velocity
T : Torque

6 1.1.6 Variable Speed Drive

A Variable Speed Drive (VSD) is a device designed to regulate the rotational speed of a motor. Although it can be used with both AC and DC motors, VSDs are most commonly applied to AC motors. The VSD controls
24 motor speed by altering the frequency of the input voltage when this frequency is changed, the motor's speed adjusts accordingly to meet operational requirements. This can be observed in the VSD circuit shown in Figure 2. [24].

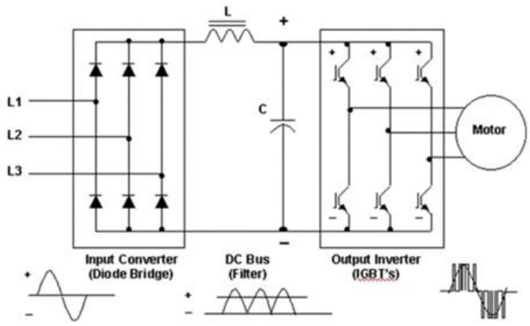

Figure 2. Block diagram variable speed drive [16]

In general, a Variable Speed Drive (VSD) is commonly used to perform the following functions:

1. Adjusting the control speed according to the required operating speed.
2. Matching the controller's torque to the torque requirements of the process.
3. Saving energy and increasing efficiency [25].

2. RESEARCH METHODS

2.1 Definition of Methods

A quantitative method with a direct experimental approach was applied in this study. The process began with a literature review to explore fundamental concepts related to three-phase AC synchronous motors, using sources such as reference books and scholarly journals. The review covered motor characteristics, operating mechanisms, and the function of Variable Speed Drives (VSD). The experiment involved testing the motor under two conditions—unloaded and loaded. Each test was repeated five times, and the average values were calculated to ensure representative data. The main parameters measured included motor speed in RPM at various frequency settings, torque and rotational behavior, as well as current, voltage, power consumption, and system efficiency. The experimental setup for the three-phase synchronous motor control using a Variable Speed Drive (VSD) is illustrated in Figure 3.

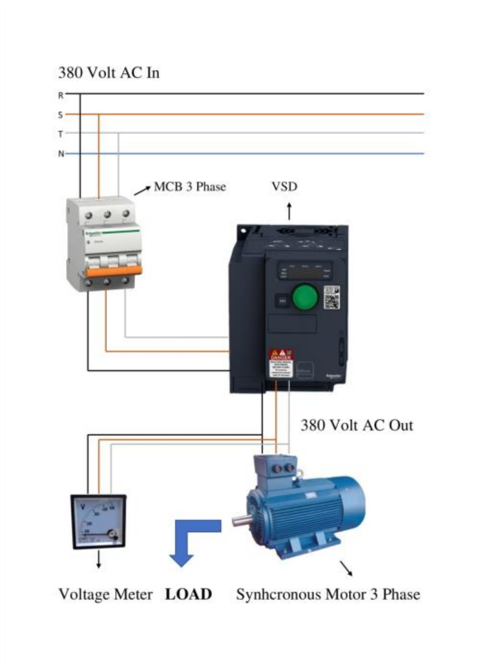

Figure 3. Single Line Diagram

The object of this research is a three-phase synchronous motor with the following specifications: 100 W, 415 VAC, 4 poles, 1400 RPM, 50 Hz, and a rated current of 0.6 A. The motor's rotational speed is measured using an NJK-5002C NPN Hall proximity sensor, with the output displayed on a digital tachometer featuring the following specifications: Power requirement: DC 8–24V, Measurement range: 3.8 ~ 99999 RPM, and an error margin of 0.5–1.5 RPM. This study aims to analyze the motor's performance under various supply frequency conditions, controlled via a Schneider Variable Speed Drive (VSD), model ATV 320U04N4C. The test frequencies applied during the experiment are 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz, and 50 Hz.

2.2 Data Collection

The experimental setup is illustrated in Figure 4. In this configuration, the synchronous motor acts as the driving motor, with its speed and voltage controlled by the VSD. A second motor, a single-phase induction motor with specifications of 250 W, 240 VAC, 1725 RPM, 50 Hz, and 2.2 A, serves as a mechanical load. Both motors are directly coupled via their shafts to ensure efficient mechanical power transmission and to simulate realistic loading conditions.

Measurements are conducted using instruments integrated into the GOTT trainer, including a tachometer for rotational speed, a voltmeter for monitoring the supplied voltage, and ammeters for measuring the current in each phase. This setup enables a comprehensive performance evaluation of the synchronous motor under both no-load and load conditions. By adjusting the frequency through the VSD, the experiment allows detailed observation of the motor's behavior in terms of speed, current, voltage, and torque, making it highly valuable for performance analysis and control optimization in industrial applications.

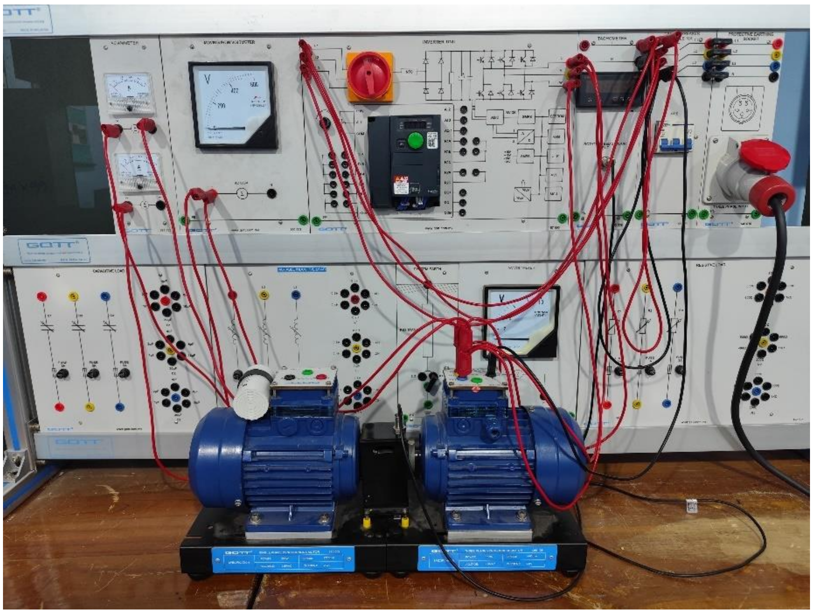

Figure 4. Motor Control Experiment Using VSD

2.3.1 Research Flowchart

7 Figure 5 illustrates the experimental workflow carried out in this study, which aims to analyze the effect of frequency variation on the speed and efficiency of a three-phase synchronous motor. The process begins with the design and setup of experimental equipment, consisting of a Variable Speed Drive (VSD), tachometer, and voltmeter as the primary instruments for testing.

2 The next step involves applying various frequency values to the motor, specifically 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz, and 50 Hz. These frequency variations directly influence the motor's rotational speed (RPM), which is then observed and measured using a pre-installed speed sensor, namely the NJK-5002C sensor, connected to a digital tachometer for display.

If the experiment proceeds successfully and yields valid data, the collected measurements are then used to 19 calculate the synchronous speed and power efficiency of the motor. The subsequent stage is the Result and Discussion, which evaluates the motor's performance based on the observed parameters.

The experiment concludes with the formulation of conclusions, summarizing the key findings of the test and providing recommendations regarding optimal frequency settings for the operation of synchronous motors in industrial applications.

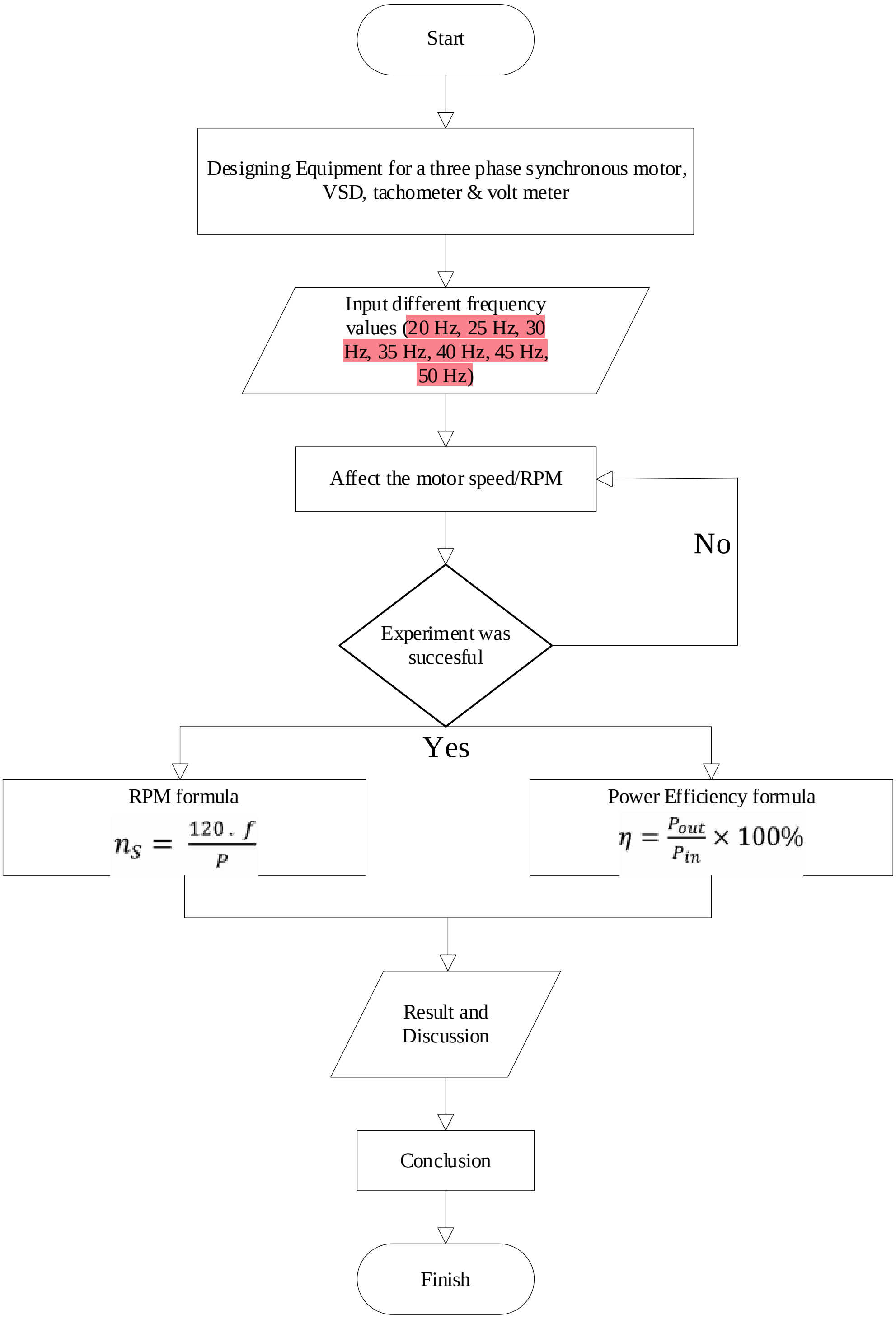

Figure 5. Research schematic.

3. RESULTS AND DISCUSSION

3.1 Research Results Without no-Load

The no-load testing was carried out to observe the basic characteristics of a three-phase synchronous motor operating without any mechanical load attached to its shaft. This experiment aimed to analyze the effect of frequency variation on key performance parameters such as voltage, current, rotational speed (RPM), electric power (Watt), and torque output. The motor was tested at seven different frequency levels: 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz, and 50 Hz. Each frequency point was tested five times to obtain accurate and representative average values. The measured data were recorded and presented in tabular form for easier analysis. Table 1 presents the average values of voltage, current for phases R, S, and T, rotational speed, and electric power consumption. Meanwhile, Table 2 shows the average torque produced by the motor at each frequency level.

Table 1. Average Voltage, Ampere, Speed and Watt

Frequency	Voltage	Average of Ampere			Average of Speed	Average of Watt
		R	S	T		
20 Hz	140,6	0,554	0,54	0,542	607,4	100,59
25 Hz	185,4	0,53	0,53	0,564	755,8	137,704
30 Hz	225	0,544	0,55	0,608	907	181,1
35 Hz	261	0,492	0,574	0,616	1057,4	202,518
40 Hz	301	0,522	0,55	0,594	1205,4	230,874
45 Hz	341,2	0,532	0,554	0,58	1336,4	260,976
50 Hz	381,2	0,556	0,582	0,662	1506	314,822

Table 2. Results of no-load torque calculations

Frequency	**Average of Torque**
20 Hz	1, 57 N.m
25 Hz	1,25 N.m
30 Hz	1,05 N.m
35 Hz	0,9 N.m
40 Hz	0,79 N.m
45 Hz	0,7 N.m
50 Hz	0,63 N.m

3.1.1 Effect of Frequency on Voltage and Power Consumption

The variation in frequency from 20 Hz to 50 Hz has been proven to affect both voltage levels and power consumption. Based on five measurements, the lowest voltage was recorded at 140.6 V at 20 Hz, while the highest reached 381.2 V at 50 Hz. This condition also impacted power consumption, with the lowest recorded at 100.59 Watts and the highest at 314.82 Watts. These findings indicate that frequency regulation through a Variable Speed Drive (VSD) can be utilized as a strategy to improve energy efficiency. This is in line with the findings of R. N. Rachmadita et al. (2024), whose research showed that the application of VSD can reduce power consumption. The average no-load voltage values are presented in Figure 6, while the no-load power results are shown in Figure 7.

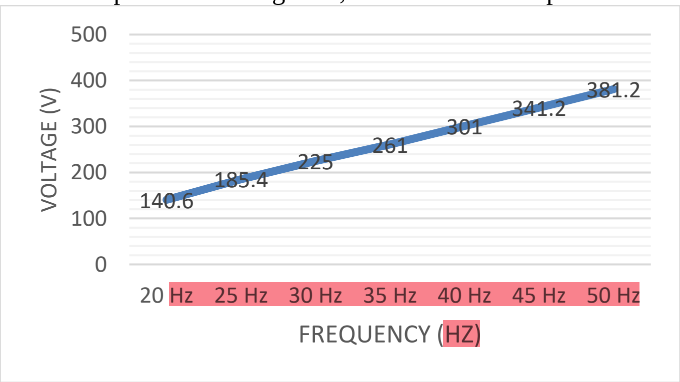

Figure 6. Graph of no-load voltage measurement results

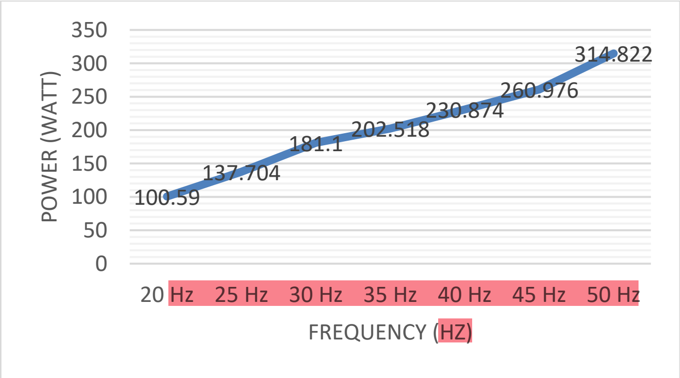

Figure 7. Graph of no-load electrical power measurement results

3.1.2 Effect of Frequency on Speed

After conducting observations and collecting data five times, it was found that the average motor speed changed with the increase in frequency from 20 Hz to 50 Hz. The lowest speed was recorded at 607.4 RPM at 20 Hz, while the highest speed reached 1506 RPM at 50 Hz. This indicates that frequency is directly proportional to motor speed, which is in agreement with the findings of R. Gafar et al. (2022**).** The results are shown in Figure 8.

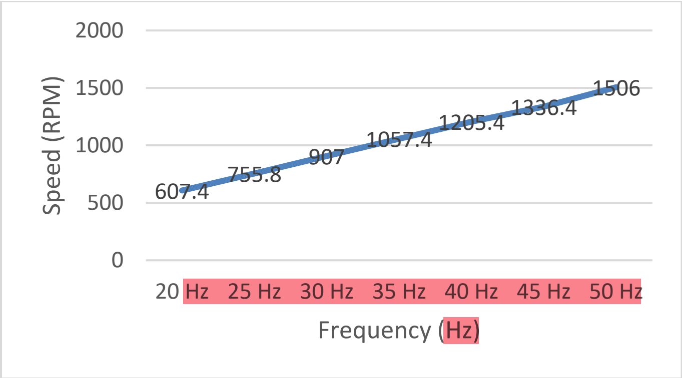

Figure 8. Graph of no-load speed measurement results

3.1.3 Effect of Frequency on Torque

Adjusting the frequency affects the motor's speed, which in turn impacts its torque output. Based on the data obtained, the highest torque of 1.57 N·m occurred at the lowest speed (20 Hz), while the lowest torque of 0.63 N·m was recorded at the highest speed (50 Hz). This supports the general principle of electric motors, where an increase in speed tends to result in a decrease in torque, and a decrease in speed generally leads to an increase in torque. This principle is consistent with the findings of Fitzgerald et al. (2003), who stated that in both induction and synchronous motors, there is an inverse relationship between speed and torque, especially during no-load or light-load operation [26]. as shown in Figure 9

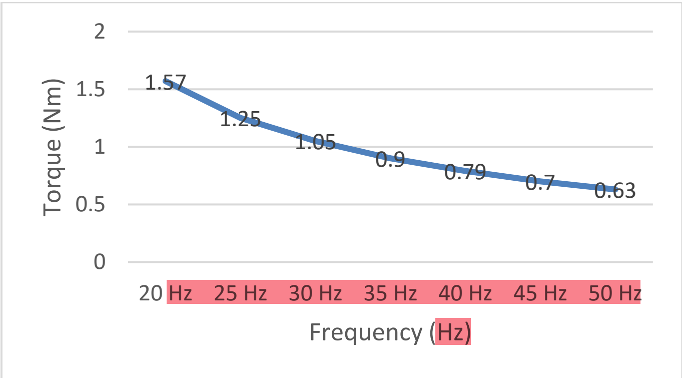

Figure 9. Graph of Torque Measurement Results without load

3.2 Research Result With Load

Table 3 shows the effect of frequency changes on several electrical parameters, namely voltage, current in three phases (R, S, and T), speed, and output power. It can be observed that as the frequency increases from 20 Hz to 50 Hz, there is a significant rise in voltage, from 142.4 Volts to 382 Volts. Similarly, speed increases drastically from 88 rpm to 683.6 rpm, indicating a linear relationship between frequency and motor speed. The current in each phase shows a pattern that is not entirely linear. For example, the current in phase R decreases from 0.61 A (at 20 Hz) to 0.49 A (at 35 Hz), then increases again to 0.544 A at 50 Hz. A similar trend is observed in phases S and T, which fluctuate but generally remain within the range of 0.42–0.64 A.As for output power (Watt), there is a fairly consistent increase with rising frequency. The power increases from 123.914 Watts (20 Hz) to 290.358 Watts (50 Hz). This indicates that the electrical load receives more energy as the frequency, voltage, and motor speed increase.Overall, this data shows that increasing the frequency in this system directly contributes to an increase in voltage, speed, and power, which is essential for managing the performance of electric motors in variable speed control systems.

Table 3. Results of Voltage, Current (R, S, T), Speed, and Power Measurements at Various Frequencies

Frequency	**Voltage**	**Average of Ampere**			**Average of Speed**	**Average of Watt**
		R	**S**	**T**		
20 Hz	142,4	0,61	0,64	0,636	88	123,914
25 Hz	185,4	0,544	0,538	0,42	145	127,414
30 Hz	223,2	0,644	0,422	0,54	221	164,526
35 Hz	283	0,49	0,57	0,546	266,6	207,826
40 Hz	313,8	0,544	0,548	0,6	297,2	243,492
45 Hz	341	0,524	0,55	0,572	315,4	255,15
50 Hz	382	0,544	0,54	0,57	683,6	290,358

The measurement results of torque, output power, and efficiency of a three-phase synchronous motor at various frequency levels (20 Hz to 50 Hz) under load conditions are presented. It can be seen that the highest torque of 10.852 N·m was achieved at the lowest frequency of 20 Hz, while the lowest torque of 1.39 N·m was recorded at 50 Hz. Although the output power remained relatively stable at around 99 Watts, the motor's efficiency showed a decreasing trend as the frequency increased. The highest efficiency was recorded at 0.80% at 20 Hz, and the lowest at 0.34% at 50 Hz. These results indicate an inverse relationship between frequency increase and both torque and efficiency under load conditions, as shown in Table 4.

Table 4. Torque, Power Output, and Efficiency Results under Loaded Conditions

Frequency	**Torque**	**Power Out**	**Efficiency**
20 Hz	10,852 N.m	99,89 Watt	0,80%
25 Hz	6,582 N.m	99,38 Watt	0,78%
30 Hz	4,32 N.m	99,79 Watt	0,60%
35 Hz	3,58 N.m	99,736 Watt	0,48%
40 Hz	3,208 N.m	99,832 Watt	0,40%
45 Hz	3,026 N.m	99,672 Watt	0,39%
50 Hz	1,39 N.m	99,464 Watt	0,34%

3.2.1 Effect of Frequency on Voltage and Power Consumption

During testing under load with five sets of data, it was found that voltage varied depending on the frequency. At 20 Hz, the lowest frequency, the average voltage was recorded at 142.4 V, while at 50 Hz, the highest frequency, it reached 382.2 V. This also affected the amount of power used, which was 123.91 Watts at 20 Hz and 290.36 Watts at 50 Hz. These results indicate that adjusting the frequency can help save energy and improve power usage efficiency. This finding is consistent with the study by R. N. Rachmadita et al. (2024), which showed that the implementation of VSD can reduce power consumption. The average voltage values under load are presented in Figure 10, while the power results under load are shown in Figure 11.

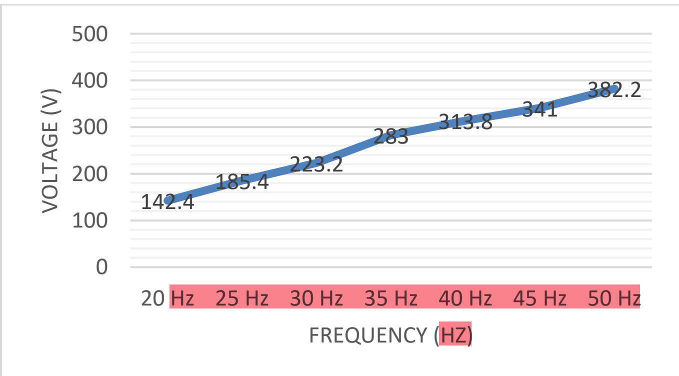

Figure 10. Measurement results of load voltage under various test conditions.

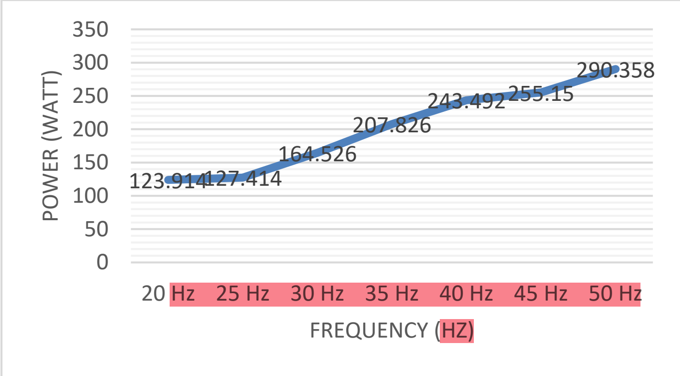

Figure 11. Load power measurement results (in watts) at different operating frequencies.

3.2.2 Effect of Frequency on Speed

Figure 12 shows that after testing the motor under load and conducting five sets of measurements, the average speed ranged from 88 RPM at 20 Hz to 688.6 RPM at 50 Hz. These speeds were significantly lower compared to when the motor was operating without a load. This decrease in speed occurs due to the motor being under load, especially when the load is too heavy. This was also stated in the study by Abdul Kodir et al. (2022), which noted that significant changes in load will affect the motor's speed.

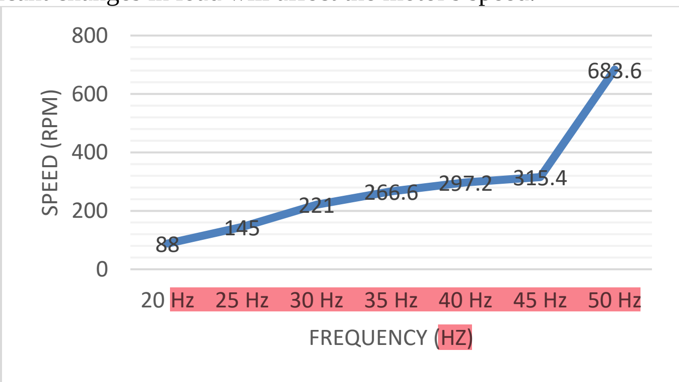

Figure 12. Motor speed measurement results (in RPM) at different operating frequencies.

3.2.3 Effect of Frequency on Torque

In Figure 13, the results show that when the motor was tested under load conditions, the torque increased significantly. At a frequency of 20 Hz, the torque reached 10.852 N·m, and at 50 Hz, it decreased to 1.59 N·m. This occurs because the load slows down the motor's rotation, causing the torque to increase. Compared to no-load conditions, the motor produces greater torque when operating under load. This supports the general principle of electric motors, where an increase in speed tends to result in a decrease in torque, and a decrease in speed generally leads to an increase in torque. This principle is also in line with the findings of Fitzgerald et al. (2003**)**, who stated that in both induction and synchronous motors, there is an inverse relationship between speed and torque.

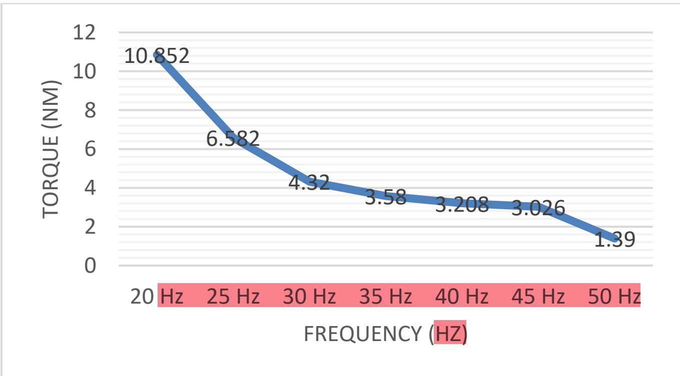

Figure 13. Torque measurement results (in N·m) at different operating frequencies.

3.2.4 Power Out

Power output refers to the mechanical power generated by the synchronous motor. Based on the measurement data, the average mechanical output power (P_out) within the frequency range of 20 Hz to 50 Hz remains relatively stable at around 99 watts, as shown in Figure 14. This P_out value is then used to calculate the motor's efficiency. The efficiency is calculated according to Equation 2.

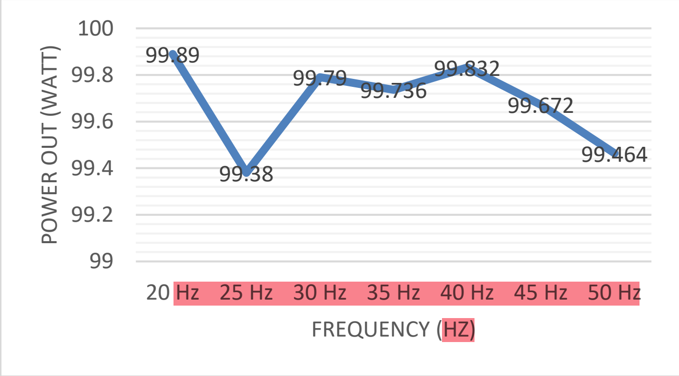

Figure 14. Power Out

3.2.5 Effect of Frequency on Efficiency

In Figure 15**,** the test results under load conditions clearly show that frequency affects the efficiency of a three-phase synchronous motor. As illustrated in the graph, the motor achieved its highest efficiency at a frequency of 20 Hz with 0.80%, and its lowest efficiency at 50 Hz with 0.34%. This indicates that by adjusting the frequency, the motor's efficiency can be improved. The low efficiency is caused by the fact that, at low speeds, the magnetizing current remains high because the V/f ratio is kept constant. This leads to an increase in core losses. This finding is in line with the study conducted by L. Latchoomun et al. (2019), which stated that one of the factors affecting motor efficiency is that, at low speeds, core losses increase, resulting in lower efficiency.

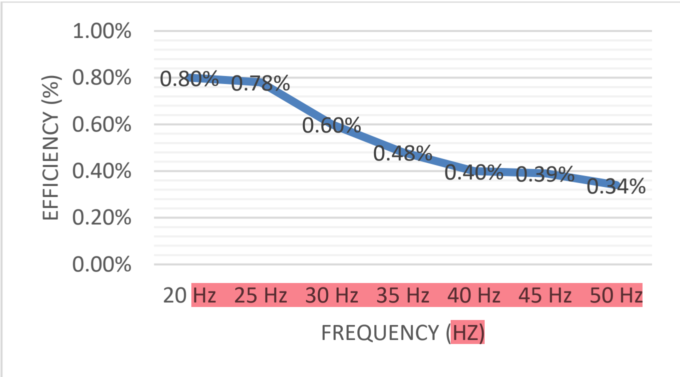

Figure 15. Efficiency of the motor at different operating frequencies under load conditions.

4. CONCLUSION

This study shows that frequency control using a Variable Speed Drive (VSD) has a significant impact on the performance of a three-phase synchronous motor, particularly in terms of speed, power consumption, torque, and efficiency under both loaded and unloaded conditions. The research findings reveal that although increasing the frequency results in higher motor speed, efficiency remains low, with a maximum value of only 0.80%. The low efficiency is caused by the fact that, at low speeds, the magnetizing current remains high due to the constant V/f ratio, which leads to increased core losses. In comparison, the study conducted by Abdul Kodir et al. (2022) focused solely on analyzing motor speed in an elevator door system using the BG202-XM inverter. While their study confirmed a linear relationship between frequency and motor speed, it did not include analysis of power consumption, torque, or efficiency. Therefore, although both studies observed a positive correlation between frequency and motor speed, the present study provides a more comprehensive evaluation of motor performance across various operational parameters. As such, VSD can be considered a viable solution in the industrial sector for addressing speed control issues in machines such as pumps and others, as well as for improving energy efficiency.

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