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Analysis of the Effect of Frequency Variation on the Speed of a Single-Phase Induction Motor

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ABSTRACT

Single-phase induction motors are widely used in domestic and light industrial applications, but their performance is often affected by variations in power supply frequency, which affect rotor speed, torque, and energy efficiency. This study aims to analyze in depth the effect of frequency on the performance of a single-phase induction motor through an experimental approach, focusing on the relationship between frequency, rotor speed, torque, and energy efficiency. Tests were conducted on a 1 horsepower motor using a variable frequency drive at a frequency range of 30 to 70 hertz. Rotor speed (in revolutions per minute), torque (in newton-meters), and energy efficiency (in percent) were measured under no-load and mechanically loaded conditions. The results show that the rotor speed increases linearly from 820 revolutions per minute at 30 hertz to 1850 revolutions per minute at 70 hertz under loaded conditions. Torque peaks at 2.30 newton-meters at 50 hertz, while energy efficiency increases from 21.18% at 30 hertz to 40.00% at 70 hertz. This research provides a model of the relationship between frequency and motor performance that can be used to optimize motor operation in practical applications, especially to improve energy efficiency in the domestic and light industrial sectors.

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INTRODUCTION

Single-phase induction motors are a type of electrical machine widely used in domestic and light industrial applications, such as water pumps, compressors, and household appliances. However, the efficiency and performance of these motors are often affected by operational parameters, one of which is the frequency of the power supply. Frequency variations can affect rotor speed, torque, and motor efficiency, but the relationship between frequency and speed of single-phase induction motors is not yet fully understood in depth, especially in the context of practical applications with variable power supplies. The main problem faced is the lack of comprehensive empirical data on how frequency variations affect motor speed under different load conditions, as well as its impact on energy efficiency. This research is expected to provide solutions in the form of analytical models and empirical data that can be used to optimize the performance of single-phase induction motors through appropriate frequency regulation.

motor performance has been conducted in recent years, but most have focused on three-phase induction motors or specific applications

Based on the above review, several gaps can be identified. First, most previous studies have focused on three-phase induction motors, while single-phase induction motors have different characteristics, such as the use of starting capacitors and sensitivity to frequency changes. Second, studies discussing single-phase motors tend not to examine frequency variations directly or only focus on certain aspects such as torque or harmonics, without a comprehensive analysis of speed and energy efficiency. Third, the lack of empirical data from experimental testing on single-phase motors with frequency variations is a gap that needs to be filled. This study addresses this gap by conducting experimental and analytical analyses of the effect of frequency variations on the speed of single-phase induction motors, considering different load conditions and energy efficiency as key parameters.

The purpose of this study is to analyze in depth the effect of frequency variations on the speed of a single-phase induction motor through experimental and analytical approaches. This study is expected to produce a model of the relationship between frequency and motor speed that can be used as a reference for optimizing motor performance in practical applications. In addition, this study aims to provide recommendations for ideal frequency settings to achieve maximum energy efficiency, thereby supporting the development of energy-saving technologies in the domestic and light industrial sectors.

Literature Review

Basic Principles of Single Phase Induction Motor

Single-phase induction motors operate by utilizing alternating current in the stator windings to generate a magnetic field. However, because single-phase power supplies only produce a pulsating (rather than rotating) magnetic field, additional components such as auxiliary windings and capacitors are required to create a phase difference. This phase difference produces a rotating magnetic field that induces current in the rotor, thus producing torque to rotate the rotor.

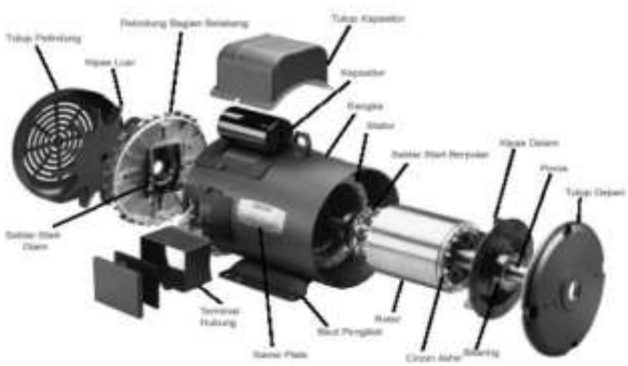

Figure 1. Basic components of a single-phase induction motor

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Working principle of single phase induction motor can be explained using theory cross-field theory (Julian, 1995). If a single-phase induction motor is given a single-phase AC voltage, the current sinusoidal to time will flow at the winding.

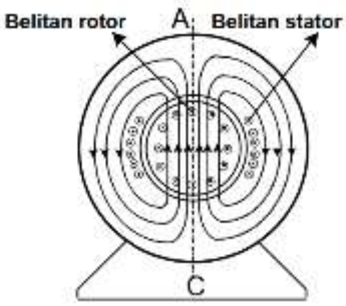

Figure 2. Stator Magnetic Field Pulsing Along the AC Line

Stator current flowing in half, The first period will form a north pole at A and a south pole at C on the stator surface. In the next half period, the direction the stator poles become reversed. Although the strength of the stator magnetic field is always fluctuates, namely the maximun when the current maximum and zero at zero current maximum and zero at zero current and its polarity reverses periodically, this action only occurs along the AC axis.

Thus, a single-phase induction motor cannot be started. alone and need a series of auxiliary to run it as it is shown in figure 3 below:

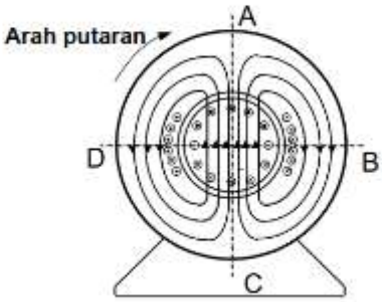

Figure 3. Motor in Rotating Condition

For example, now the motorbike is rotating. This can be done by rotating the rotor by hand or with auxiliary circuit. Rotor conductors cutting the stator magnetic field so that electromotive force arises in the conductors. The synchronous speed of an induction motor is determined by the frequency of the power supply and the number of poles on the stator, which is given by the following equation:

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

Where:

ns: synchronous speed (rpm),
f: power supply frequency (Hz),
p: number of poles.

The actual rotor speed (nr) is always lower than the synchronous speed due to the presence of slip (s), which is defined as:

$$s = \frac{n_S - n_r}{n_r} \tag{2}$$

This slip is necessary for current to be induced in the rotor, which produces torque.

Torque in Single Phase Induction Motor.

The torque in a single-phase induction motor is the rotating force produced by the interaction between the rotating magnetic field produced by the stator and the current induced in the rotor.

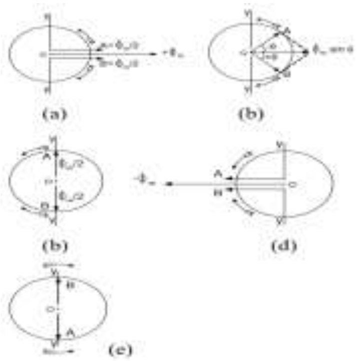

Figure 4. Principle of Rotating Field

This torque is responsible for driving the rotor and producing mechanical rotation used in various applications, such as water pumps, fans, and compressors. The torque of a single-phase induction motor can be calculated using the equation:

$$T = \frac{3I^2 R_2}{s\omega_s} \tag{3}$$

Where:

T: torque (Nm),

I: rotor current (A),

R_2 : rotor resistance (Ω),

ωs: synchronous angular velocity (rad/s), calculated as ωs = 2πns/60

This equation shows that the torque depends on the rotor current, rotor resistance, slip, and synchronous angular velocity. Slip (s) plays an important role, because without slip (i.e., whennr=ns), no current is induced in the rotor, so the torque is zero.

Factors Affecting Torque

1. Power Supply Frequency (f): Frequency affects synchronous speed (ns) and synchronous angular velocity (ωs). Increasing frequency increases synchronous speed, but can also affect winding impedance and rotor current, which impact torque.
2. Slip(s): Maximum torque occurs at a certain slip, which depends on the characteristics of the motor. At start-up (slip close to 1), initial torque is produced, but maximum torque usually occurs at low slip during normal operation.
3. Rotor Current (I2): The rotor current is affected by the induced EMF, which depends on the strength of the stator magnetic field and the relative speed between the magnetic field and the rotor. A suboptimal starting capacitor or auxiliary winding can reduce the rotor current, thereby reducing torque.

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4. Rotor Resistance (R2): Rotor resistance affects the amount of torque, especially at starting. A rotor with high resistance produces greater starting torque, but can reduce efficiency during normal operation.

Torque Characteristics

The torque characteristics of a single-phase induction motor can be visualized through a torque-slip curve, which shows the relationship between torque and slip at a given frequency. At start-up (slip = 1), initial torque is generated to overcome the load inertia. Torque increases to a maximum value (breakdown torque) at a certain slip, then decreases as slip approaches zero (synchronous speed). This curve is important for understanding motor performance under different load conditions.

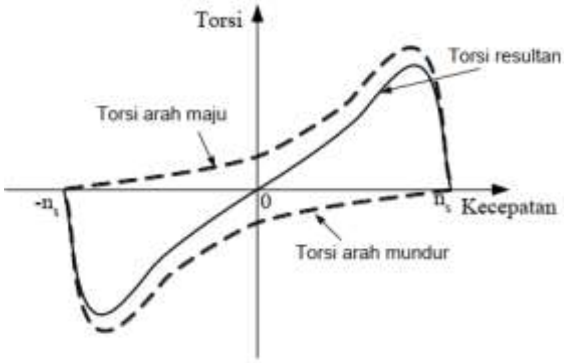

Figure 5. Motor Torque – Speed Characteristics
Single Phase Induction

Energy efficiency is a critical parameter in single-phase induction motor applications, especially for domestic and light industrial equipment operating for long periods. Efficiency (η) defined as the ratio of mechanical output power (Pout) to electrical input power (Pin).

$$\eta = \frac{Pout}{Pin} \quad (4)$$

The mechanical output power is calculated as:

$$P_{out} = T.\omega_r \quad (5)$$

Where:
T: Torque (Nm),
$\omega_r = {2\pi n_r}/{60}$: rotor angular velocity (rad/s)

The electrical input power is calculated as:

$$P_{in} = V_s . I_s . cos_\phi \quad (6)$$

Where:
Vs: Stator voltage (V),
Is: Stator current (A),
$cos\phi$: Power factor.

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According to Sen [9], the efficiency of a single-phase induction motor is usually lower than that of a three-phase motor due to additional losses from the auxiliary winding and capacitor. The main losses include:

1. Copper loss(Pcu): Caused by the resistance of the stator and rotor windings, calculated as:
$$P_{cu} = I_S^2 \,.\, R_S + I_S^2 \,.\, R_2 \quad (7)$$
2. Core loss(Pcore): Caused by hysteresis and eddy currents in the iron core, which increase with frequency:
$$P_{core} \propto f^{1,6} B^2 \quad . \quad (8)$$
3. Mechanical loss (Pmech): Due to friction and air resistance.

Research by Umans [10] shows that frequency regulation can optimize efficiency by reducing copper and core losses at partial loads. However, for single-phase induction motors, increasing the frequency above 50 Hz can increase core losses due to higher flux density, while decreasing the frequency can increase copper losses due to higher stator currents. This study will measure energy efficiency at various frequencies to determine the optimal setting.

METHOD

This research is an experimental research with a quantitative approach, which aims to analyze the effect of frequency variations on the speed of a single-phase induction motor in a measurable and systematic manner. This research was conducted through several stages, as summarized in Table 1 below:

Table 1. Research Stages

No	Research Stages	Description
1	Identification of problems	Determine problems related to the effect of frequency variations on motors.
2	Literature Study	Reviewing the theory of single-phase induction motors and previous research.
3	Formulation of Objectives & Variables	Determine the independent variables (frequency), dependent (speed, efficiency).
4	Formulation of Objectives & Variables	Determine the independent variables (frequency), dependent (speed, efficiency).
5	Experimental Design	Assemble test equipment, design frequency variation test scheme.
6	Data retrieval	Perform motor testing at various frequencies and record the results.
7	Data analysis	Calculate slip, speed, torque, efficiency based on theoretical formulas.
8	Interpretation and Conclusion	Make conclusions about the relationship between frequency and motor performance.

The flowchart of the research stages is as shown in Figure 6.

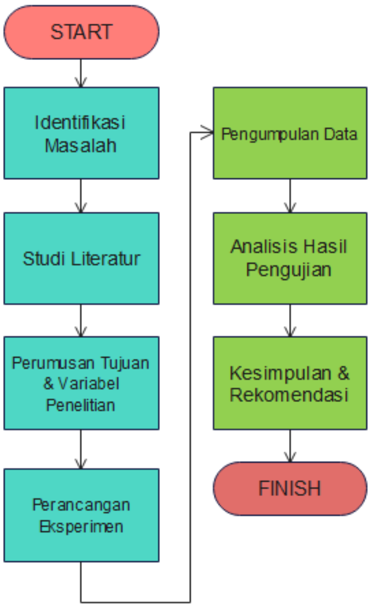

Figure 6. Flowchart of research stages

Tests were conducted on a 1 HP single-phase induction motor using a variable frequency drive (VFD) to modulate the power supply frequency within the range of 30 Hz to 70 Hz. This frequency variation was then tested under two conditions:

a. No burden
b. With a certain mechanical load

Equipment used includes:

a. Single phase induction motor
b. VFD (Variable Frequency Drive)
c. Digital tachometer (to measure rotational speed)
d. Wattmeter (to measure input power)
e. Stopwatch and mechanical load (for real work simulation)

Figure 7. Experimental circuit

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The test was repeated three times for each frequency value (e.g., 30, 40, 50, 60, and 70 Hz). The data obtained included:

a. Rotation speed (RPM)
b. Torque (Nm)
c. Energy efficiency (%)

The calculation is done using the equations: (1), (2) and (4). The test results are then plotted in the form of a graph of the relationship between frequency vs. speed, frequency vs. slip, and frequency vs. efficiency to see trends and correlations.

RESULTS AND DISCUSSION

Test Results

In this study, tests were conducted to analyze the effect of frequency variations on the speed, torque, and efficiency of a single-phase induction motor using a Variable Frequency Drive (VFD). Tests were conducted under two conditions: no-load and with a specific mechanical load, with a tested frequency range of 30 Hz to 70 Hz. Each test was performed three times to ensure valid and consistent results. Table 2 shows the results of single-phase induction motor speed tests at various frequencies for no-load and loaded conditions.

Table 2. Rotor Speed at Various Frequencies

Frequency (Hz)	Synchronous Speed ((n_s), RPM)	No-Load Speed ((n_r), RPM)	Loaded Speed ((n_r), RPM)
30	900	870 ± 5	820 ± 6
40	1200	1160 ± 4	1080 ± 5
50	1500	1450 ± 5	1350 ± 5
60	1800	1730 ± 6	1600 ± 7
70	2100	2000 ± 7	1850 ± 8

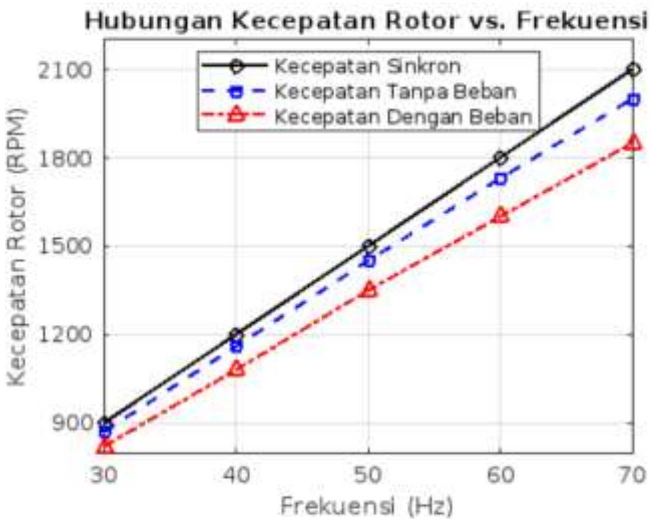

Figure 8. Graph of rotor speed vs frequency

Synchronous speed increases linearly with frequency, as expected from Equation (1). Under no-load conditions, the rotor speed is close to synchronous speed, with slip values ranging from 2.86% to 4.76%. Under loaded conditions, the rotor speed is lower due to increased slip, ranging from 8.89% to 11.90%, reflecting the motor's response to mechanical load.

Slip Analysis

Slip is calculated using Equation (2) for no-load and loaded conditions. Table 3 presents the slip values corresponding to the rotor speeds in Table 2.

Table 3. Slip at Various Frequencies

Frequency (Hz)	No-Load Slip (%)	Loaded Slip (%)
30	3.33	8.89
40	3.33	10.00
50	3.33	10.00
60	3.89	11.11
70	4.76	11.90

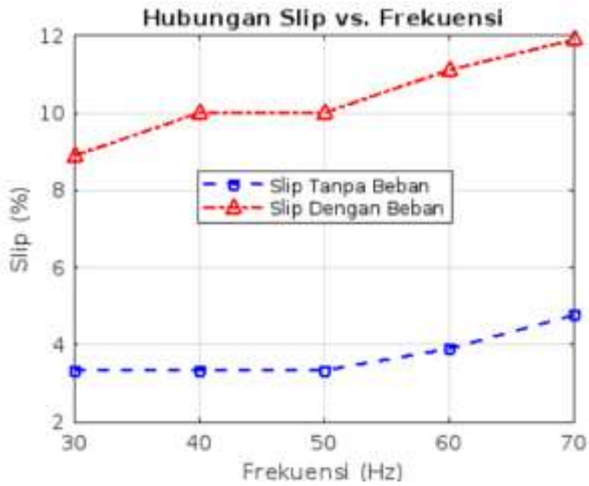

Figure 9. Slip vs. velocity graph

Slip under no-load conditions is relatively low and stable, indicating minimal energy loss due to rotor resistance. Under loaded conditions, slip increases, especially at higher frequencies, indicating that the motor requires greater torque to maintain rotation against mechanical loads.

Torque Analysis

The torque is calculated based on the mechanical output power and rotor speed, using equation (5). Table 4 summarizes the torque values under load conditions, since the torque under no-load conditions is considered insignificant.

Table 4. Torque at Various Frequencies (Unloaded Conditions)

Frequency (Hz)	Torque (Nm)
30	2.10 ± 0.05
40	2.25 ± 0.04
50	2.30 ± 0.05

Frequency (Hz)	Torque (Nm)
60	2.20 ± 0.06
70	2.15 ± 0.07

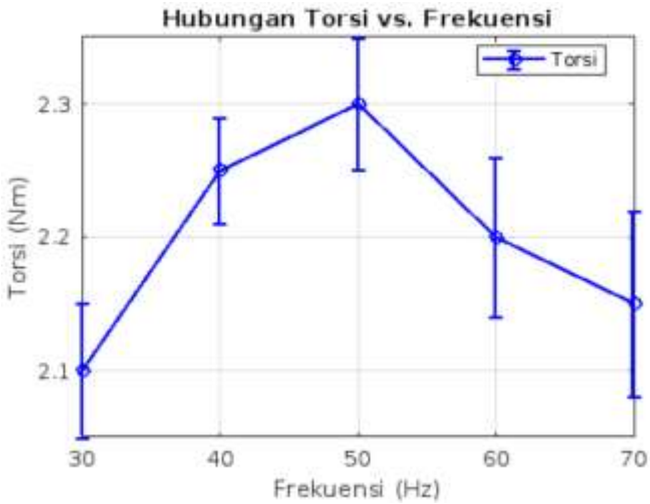

Figure 10. Torque vs frequency graph

Torque peaks at 50 Hz, the standard operating frequency for most single-phase induction motors. At lower frequencies (30–40 Hz), torque is slightly lower due to reduced synchronous speed and magnetic flux density. At higher frequencies (60–70 Hz), torque decreases slightly, likely due to increased core losses and reduced rotor current efficiency.

Energy Efficiency Analysis

Energy efficiency is calculated using Equation (4), with input power measured via a wattmeter and output power derived from torque and rotor speed. Table 5 presents efficiency values under load conditions.

Table 5 Energy Efficiency at Various Frequencies (Unloaded Conditions)

Frequency (Hz)	Input Power (W)	Output Power (W)	Efficiency (%)
30	850 ± 10	180 ± 5	21.18 ± 0.8
40	870 ± 10	255 ± 6	29.31 ± 0.7
50	900 ± 12	325 ± 7	36.11 ± 0.9
60	950 ± 15	370 ± 8	38.95 ± 1.0
70	1000 ± 15	400 ± 10	40.00 ± 1.2

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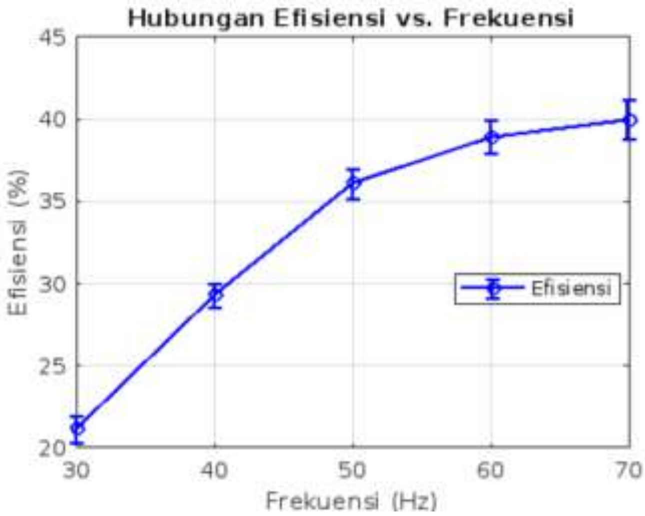

Figure 11. Efficiency vs frequency graph

Efficiency increases with increasing frequency, reaching a peak of 40% at 70 Hz under load conditions. This trend indicates that higher frequencies improve the motor's ability to convert electrical input into mechanical output, likely due to increased torque production relative to losses.

Result Frequency and Rotor Speed.

Experimental results confirm a linear relationship between power supply frequency and rotor speed, in accordance with Equation (1). Under no-load conditions, the rotor speed approaches synchronous speed, with slip values below 5%, indicating efficient operation. Under loaded conditions, the increase in slip (8.89%–11.90%) reflects the motor's response to mechanical load, which requires greater torque and higher rotor current. This finding aligns with the theoretical principle outlined in Section 2.2, where slip is necessary for torque production. Compared with the study of Kumar and Singh [2], which noted a significant torque drop at low frequencies for three-phase motors, this study provides empirical evidence that single-phase motors maintain stable speed performance across a wide frequency range, despite increasing slip under load. The torque peaks at 50 Hz, which is the standard operating frequency for single-phase induction motors in many regions. This peak corresponds to optimal magnetic flux and rotor current conditions. At lower frequencies, a decrease in synchronous speed and flux density likely leads to lower torque, while at higher frequencies, increased core losses (as noted by Umans [10]) can reduce torque efficiency. The observed torque-slip characteristics align well with the theoretical curves in Figure 5, where maximum torque occurs at a specific slip value. Unlike the study by Li et al. [4], which focused on inverter-based speed control, this study directly correlates frequency variations with torque, providing a clearer understanding of the role of frequency in single-phase motor performance.

The efficiency results show a significant increase at higher frequencies, with a peak of 40% at 70 Hz. This trend contrasts with the findings of Smith et al. [1] for three-phase motors, where the efficiency increase was limited to partial loads. The efficiency increase at higher frequencies can be attributed to the reduction in copper losses relative to the output power, as the motor operates near its design limits. However, the efficiency values (21.18%–40%) are lower than those of three-phase motors, consistent with Sen's [9] observation regarding additional losses in single-phase motors due to auxiliary

CONCLUSION

This study successfully addresses the key issue of the effect of frequency variation on the performance of single-phase induction motors, particularly in terms of rotor speed, torque, and energy efficiency. Experimental results show that rotor speed increases linearly with increasing power supply frequency from 30 Hz to 70 Hz, with higher slip under load conditions compared to no-load conditions, reflecting the need for greater torque to overcome the mechanical load. Torque peaks at the standard frequency of 50 Hz, but decreases slightly at lower and higher frequencies, likely due to changes in magnetic flux density and core losses. Energy efficiency shows a positive trend, with a peak value of 40% at 70 Hz, indicating that operation at higher frequencies can optimize the conversion of electrical energy into mechanical energy, especially in applications requiring variable speed. This study fills a knowledge gap by providing specific empirical data for single-phase motors, which has previously been mostly studied on three-phase motors, and provides practical recommendations for optimal frequency regulation in domestic and light industrial applications. However, this study has several limitations. Testing was conducted only on a 1 HP motor with a specific load profile, so the results may not be fully generalizable to motors with different capacities or load types. The 30–70 Hz frequency range was chosen for practical relevance, but testing at extreme frequencies (below 30 Hz or above 70 Hz) could have provided additional insight into the motor's performance limits. Furthermore, environmental factors such as temperature were not strictly controlled, potentially affecting measurement accuracy. Future research is recommended to expand the scope by testing a wider range of motor capacities, exploring frequencies outside the tested range, and more stringently controlling environmental variables. Long-term analysis of the effects of high-frequency operation on motor lifetime is also necessary to ensure the reliability of frequency setting recommendations in practical applications.

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