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Analysis And Optimization Of A Single-Phase Full-Wave Uncontrolled Rectifier For Driving A Three-Phase AC Motor In Engineering Applications

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Abstract

Electric motors, as key electromagnetic devices, play a pivotal role in converting electrical energy into mechanical energy, enabling diverse industrial and domestic applications. They are integral components in powering pump impellers, fans, blowers, compressors, material handling systems, and household appliances such as mixers, electric drills, and fans. In industrial contexts, electric motors are often termed the "workhorse of industry," consuming approximately 70% of total electrical loads. This study focuses on the performance analysis and optimization of a three-phase electric motor to derive power, torque, and efficiency characteristics. The experimental setup includes a three-phase electric motor connected to a lamp-based generator load of up to 2500 watts, regulated incrementally from 0 watts to 250 watts. The primary objective is to evaluate variations in torque, power, and speed under controlled conditions. The methodology involves systematically preparing the testing equipment, conducting a five-minute engine warm-up, gradually increasing the regulator load, recording experimental data, and processing the results for performance analysis. Experimental findings reveal that the maximum power of 1032.08 watts is achieved at 2846 RPM, maximum torque of 3.464 Nm at 2846 RPM, and maximum efficiency of 72.68% at 2941 RPM. Achieving high motor efficiency necessitates ensuring that input voltage aligns with the motor's maximum voltage capacity. These insights contribute significantly to enhancing motor performance and optimizing its operation in both industrial and domestic applications, emphasizing the importance of efficient energy utilization in engineering systems.

Keywords: performance analysis, three-phase AC motor, power optimization, torque, efficiency enhancement

1. Introduction

Electronic devices are integral to modern life, serving as essential tools in both residential and industrial environments. Nearly every daily activity relies on electricity as a primary energy source, and its absence can significantly disrupt workflows and reduce overall efficiency. The presence of alternating current (AC) voltage in every household underscores the importance of understanding and studying electricity, particularly through the field of power electronics.

Power electronics circuits are crucial systems that facilitate the conversion of electrical power sources into specific waveforms. While many electronic devices operate using AC voltage, others require direct current (DC). This discrepancy necessitates the use of rectifier circuits to convert AC voltage into DC voltage efficiently (Krein, 1998; Rashid, 2017).

Rectifiers, broadly categorized into controlled and uncontrolled types, are critical components in electrical engineering. These systems can be further classified based on their voltage sources into single-phase and three-phase rectifiers. For instance, a half-wave rectifier employs a diode to filter the current, allowing only positive pulses to pass. This functionality is due to the diode's ability to conduct forward current when its anode is more positive than the cathode. Such designs are fundamental to rectification processes (Anggara et al., 2020).

Uncontrolled rectifiers, as the name implies, utilize diodes as the sole switching component, converting AC voltage sources into DC voltage outputs. Unlike their controlled counterparts, these rectifiers lack external control mechanisms, relying entirely on the intrinsic properties of diodes. Their typical structure includes an AC voltage source connected in series with a diode and load, forming a simple yet effective rectification system (Hidayat et al., 2021; Nugraha et al., 2022).

The study of these rectifiers is critical for numerous engineering applications, particularly in driving three-phase AC motors. Their efficiency, performance, and reliability make them indispensable in the design and optimization of electrical systems for both industrial and domestic use.

2. Material and methods

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2.1. Material

2.1.1. 3-Phase Electric Motor

An electric motor is an electromagnetic device designed to convert electrical energy into mechanical energy. This mechanical energy is commonly used to rotate components like pump impellers, fans, blowers, and compressors. In industrial settings, electric motors are essential, often used in equipment such as mixers, fans, and electric drills.

Three-phase electric motors are widely adopted in industrial applications due to their many advantages. These include efficient control of 3-phase induction motors, which are lighter, more cost-effective, and require less maintenance than other motor types (Mohanty et al., 2021). Electric motors belong to the category of electric machines, which serve as energy converters capable of transforming mechanical energy into electrical energy and vice versa. This bidirectional functionality allows these machines to operate as either motors or generators.

Electrical energy is associated with voltage and current, while mechanical energy is characterized by torque and rotational speed. The basic concept of electric motor operation is derived from the interaction between a current-carrying conductor and a magnetic field. When a coil of conductor is energized and placed in a magnetic field, the resulting force causes the coil to rotate, generating mechanical work (Tiwari et al., 2020).

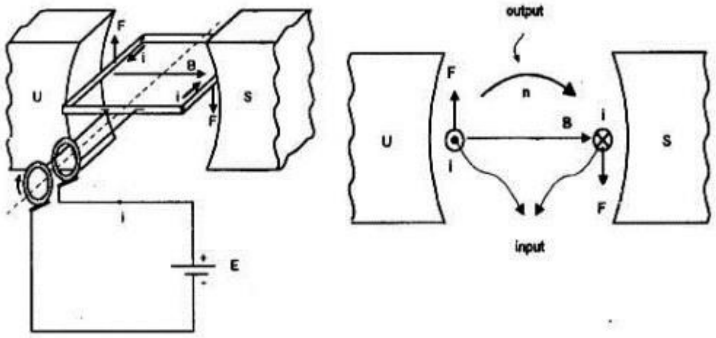

Figure 1. Basic Concept of Electric Motor

2.1.2. Induction Motor Working Principle

The operating principle of an induction motor is straightforward. When a three-phase voltage is applied to the stator coil, it generates a rotating magnetic field. This field induces a voltage in the rotor conductors, producing an electromotive force (emf) and driving current through the rotor. The rotor then experiences a force that causes it to rotate in alignment with the rotating stator field.

The input power to the motor can be calculated using the following equation:

$$P_1 = V \times I \times \cos(\theta) \quad (1)$$

Where:
P1 = input power,
V = input voltage,
I = input current,
cos(θ) = 0.7

The efficiency of the induction motor is the ratio of the output power to the input power, calculated as:

$$\eta = \frac{P_2}{P_1} \quad (2)$$

Where:

P2 = output power,
P1 = input power

2.1.3. Uncontrolled Rectifier Circuit 1 Full-Wave Phase

The rectifier circuit is a fundamental power electronics circuit used to convert alternating current (AC) to direct current (DC). The most common AC voltages are single-phase and three-phase. The single-phase rectifier circuit consists of half-wave and full-wave configurations. The half-wave rectifier, although simple, is rarely used in industrial applications, except as an introductory example for rectifier principles. A full-wave rectifier, using four diodes and a non-center-tapped transformer, is more commonly employed in practical applications (Yuliana et al., 2022).

For a full-wave rectifier, the average output voltage is calculated using the formula:

$$Vdc = \frac{2 \times V_m}{\pi} \tag{1}$$

Where:
Vm = maximum voltage.

The average current through the load can be expressed as:

$$I_{dc} = \frac{Vdc}{R} \tag{2}$$

Where:
R = resistance of the load.

The output voltage in RMS can be calculated by:

$$V_{rms} = \sqrt{\frac{V_m^2}{2}} \tag{3}$$

The corresponding RMS current is:

$$I_{rms} = \frac{V_{rms}}{R} \tag{4}$$

For the transformer secondary side, the output voltage and current are related by the following formulas:

$$V_s = \frac{V_{rms}}{\sqrt{2}}, I_s = \frac{I_{rms}}{\sqrt{2}} \tag{5}$$

Diodes are crucial electronic components with two electrodes, the cathode and anode, used to convert AC into DC. In a rectifier circuit, diodes serve as the key components for current direction control, allowing current to flow in only one direction, making them ideal for use in both half-wave and full-wave rectifier circuits. Diodes also act as filters in rectifier circuits to smooth the output voltage (Narayan et al., 2021). A resistor, a passive component that resists the flow of electric current, creates a voltage drop and plays a role in determining load current and voltage distribution in rectifier circuits, as well as in dividing current and voltage in more complex circuits. Capacitors, which store electric charge, consist of two conductive plates separated by a dielectric material and are used in rectifier circuits to smooth the DC output and reduce ripple, thus improving power conversion efficiency (Kumar et al., 2023). A transformer, essential in rectifier design, transfers and transforms electrical energy from one circuit to another using electromagnetic induction without changing the frequency. It steps up or steps down the AC voltage levels before rectification. An oscilloscope is used in power electronics to visualize and analyze electrical waveforms in real-time, displaying voltage and current waveforms on the vertical and horizontal axes, respectively, to allow engineers to observe the characteristics of AC and DC signals. PSIM is a simulation software for power electronics and electrical drive systems, offering a circuit schematic editor (SIMCAD), a simulator (PSIM), and a waveform viewer (SIMVIEW), which is employed to simulate single-phase rectifier circuits and evaluate their performance. A one-phase full-wave rectifier consists of four switching devices (typically diodes or transistors). When two of the devices are turned on simultaneously, the output voltage passes through the load; however, if all four devices are turned on together, the output voltage reverses, resulting in negative voltage across the load. Finally, the simulation of a full-wave single-phase uncontrolled rectifier circuit using PSIM software demonstrates the performance of the rectifier in driving a three-phase AC motor under various operating conditions.

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3. Results and discussion

The results from the simulations indicate that while the maximum power and torque output in the three-phase AC motor are achieved, these do not correspond to optimal efficiency levels. The peak torque and power in the motor are attained at a specific rotational speed. Initially, torque and power increase as the rotation of the electric motor shaft rises. However, once the rotational speed exceeds a certain threshold, both torque and power begin to gradually decrease. This observation highlights a common trade-off in motor performance, where achieving maximum output does not necessarily translate into the most efficient operation.

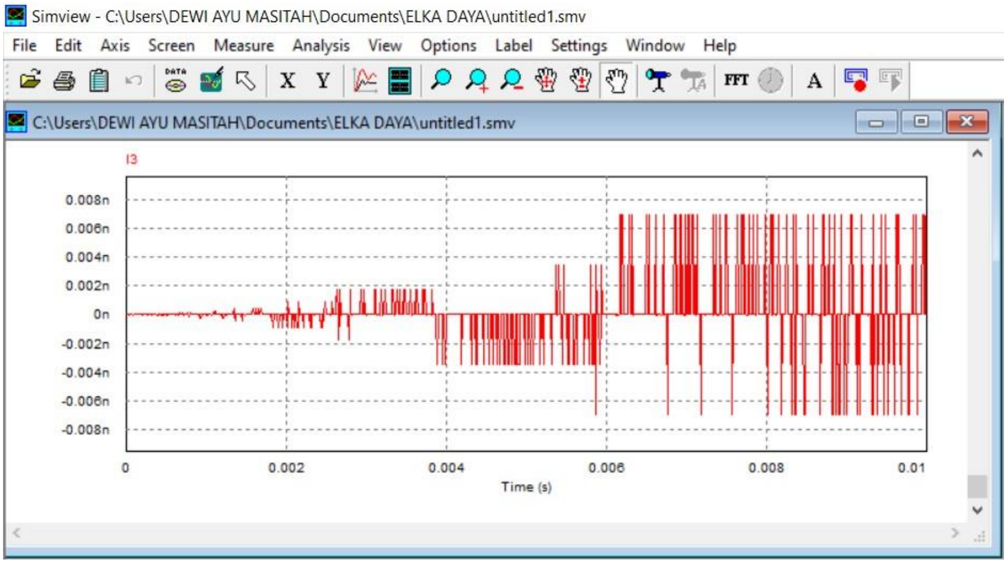

Figure 2. Display after simulation

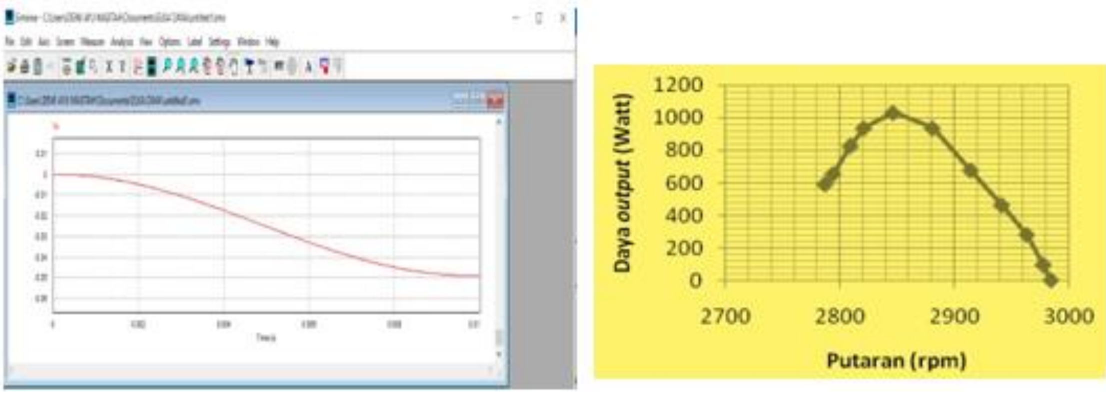

Figure 3. Connection between power and rotation

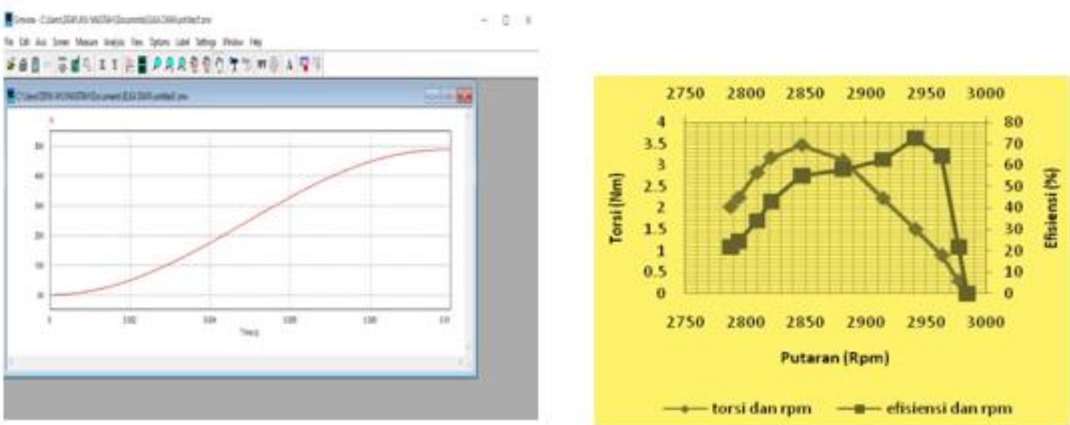

Figure 4. Connection between torque efficiency and rpm

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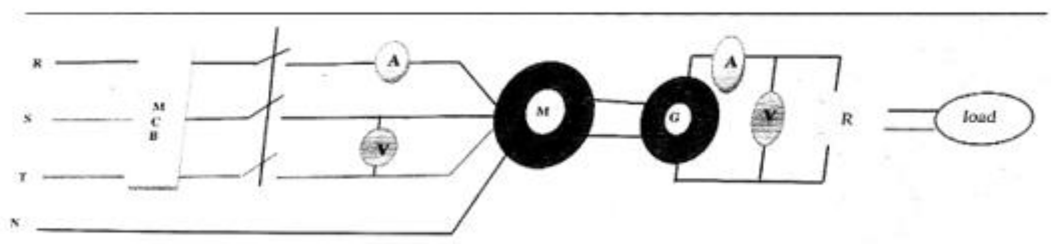

Figure 5. Motor test circuit with a voltage source

The results demonstrate that the relationship between power, torque, and rotational speed is critical in understanding motor performance. The simulation outcomes illustrate how the motor's efficiency is impacted by these factors, especially when operating near peak performance. Further optimization of the rectifier circuit and the control systems could lead to improvements in efficiency, addressing the gap between maximum output and optimal energy utilization.

4. Conclusion

From the research findings, testing, and data analysis, as well as the discussion of the performance of a 3-phase AC motor in a star connection, it can be concluded that the motor achieves maximum power and torque output at 2846 rpm. However, operating the motor at this peak power and torque does not result in the most efficient performance. This suggests that while maximum mechanical output is achieved, energy utilization could be further optimized. Future research and optimization in the rectifier circuit design and motor control strategies can potentially reduce inefficiencies, leading to improved overall performance in engineering applications such as those driving industrial machinery or electric vehicles.

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