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Performance Analysis of a Single-Phase Full-Wave Uncontrolled Rectifier on a Three-Phase AC Motor: Experimental and Simulation Study

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Abstract

Electric motors are essential electromechanical devices that convert electrical energy into mechanical energy, widely used in both household appliances (e.g., mixers, electric drills, and fans) and industrial applications (e.g., pumps, compressors, and conveyors). In industrial settings, three-phase AC motors are considered the "workhorses" of the industry, accounting for approximately 70% of total electrical energy consumption. This study focuses on the performance analysis of a three-phase AC motor driven by a single-phase full-wave uncontrolled rectifier, emphasizing key parameters such as power, torque, and efficiency curves. The experiment utilizes a three-phase AC motor connected to a 2500-watt lamp load on a generator, regulated incrementally from 0 to 250 watts to observe variations in torque, power, and speed. The experimental procedure includes preparing the test setup, warming up the motor for five minutes, applying incremental loads, recording performance data, and conducting comprehensive data analysis. The results indicate that the maximum power output of 1032.08 watts is achieved at 2846 RPM, while the maximum torque of 3.464 Nm is recorded at the same speed. Additionally, the highest efficiency of 72.68% occurs at 2941 RPM. To optimize efficiency and performance, it is crucial to ensure that the input voltage remains within the motor's maximum rated voltage capacity. The findings provide valuable insights into the impact of uncontrolled rectification on three-phase AC motor performance, offering potential applications in power conversion, industrial automation, and energy-efficient motor control systems.

Keywords: Performance, Three-phase AC Motor, Power, Torque, Efficiency.

1. Introduction

Electricity plays a fundamental role in modern life, powering nearly all household and industrial devices (Winardi, 2021). The dependence on electrical energy is so significant that even a short power outage can disrupt daily activities and reduce work efficiency (Hartono & Nurcahyo, 2017) (Evalina, Azis, & Zulfikar, 2018). Electrical power in residential and industrial settings is typically supplied in alternating current (AC) form, but not all electronic devices operate using AC voltage (Ambabunga, 2020). Many applications, particularly in power electronics and motor drive systems, require direct current (DC) voltage to function efficiently (Usman et al., 2017) (Nugraha et al., 2023a). This necessity has led to the development of rectifier circuits, which serve to convert AC voltage into DC voltage, enabling compatibility with various electrical and electronic systems (Yuniza, Agna, & Nugraha, 2022).

Power electronics is a crucial field of electrical engineering that focuses on the conversion and control of electrical power using semiconductor devices (As'ad, Yuniza, & Nugraha, 2022). One of the essential applications of power electronics is the rectifier circuit, which is widely used in industrial and household applications. Rectifier circuits are generally classified into uncontrolled rectifiers and controlled rectifiers (Bintari, Mudjiono, & Nugraha, 2022). Uncontrolled rectifiers utilize semiconductor diodes and operate without external control signals, allowing the flow of current in only one direction to convert AC voltage into pulsating DC voltage (Jamil et al., 2021) (Pambudi et al., 2021). In contrast, controlled rectifiers employ power electronic switches such as thyristors, MOSFETs, or IGBTs, allowing for variable control over the output voltage and current (Nugraha et al., 2023b).

Rectifiers can also be categorized based on their input voltage configuration into single-phase rectifiers and three-phase rectifiers (Nugraha, 2023). Single-phase rectifiers operate with a single-phase AC supply and are commonly used in low-power applications, while three-phase rectifiers are designed for high-power applications, particularly in industrial motor drives, power supplies, and renewable energy systems (Nugraha et al., 2024).

An uncontrolled rectifier is a power conversion circuit that transforms an AC voltage source into a DC voltage output using only diodes as switching elements (Agna, Sobhita, & Nugraha, 2023) (Mehar, 2013). The term "uncontrolled" stems from the fact that diodes conduct automatically when forward-biased and block current

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in reverse-bias conditions, without requiring an external control signal. A half-wave rectifier represents the simplest form of rectification, utilizing a single diode to allow only positive half-cycles of the AC waveform to pass through while blocking the negative half, resulting in a pulsating DC output, which is often unsuitable for applications requiring a more stable voltage (Kamiriski, Wejrzanowski, & Koczara, 2004). A full-wave rectifier, on the other hand, allows both positive and negative half-cycles of the AC waveform to contribute to the DC output, significantly improving efficiency and reducing ripple (Hermawan, Aripriharta, & Homggowiyono, 2014). Full-wave rectifiers can be implemented using either a center-tapped transformer with two diodes or a bridge rectifier configuration using four diodes. The uncontrolled single-phase full-wave rectifier is widely used in applications such as DC motor drives, battery charging circuits, industrial power supplies, and variable frequency drive (VFD) systems (Sufyani et al., 2019).

In industrial applications, three-phase AC motors serve as the backbone of automation, manufacturing, and heavy-duty machinery. These motors require stable and efficient power conversion systems to operate optimally. When powered by an uncontrolled rectifier, the quality of the DC supply significantly influences motor performance, affecting parameters such as torque, speed, efficiency, and power output (Mutiar, 2017). This study focuses on the performance analysis of a three-phase AC motor driven by a single-phase full-wave uncontrolled rectifier, evaluating the system's efficiency, power characteristics, and operational stability. The research incorporates both experimental and simulation-based approaches to assess the impact of rectification on motor behavior, providing insights into practical applications in industrial power conversion and motor control strategies.

The study aims to contribute to the existing body of knowledge by examining the effects of an uncontrolled rectification system on the performance of a three-phase AC motor. Through rigorous analysis of power losses, waveform distortions, and overall efficiency, this research will offer valuable insights into optimizing rectifier design for industrial applications. Additionally, the findings will provide a foundation for further developments in power electronics, particularly in enhancing the efficiency and reliability of motor drive systems.

2. Material and methods

2.1. 3 Phase Electric Motor

An electric motor is an electromagnetic device that can convert electrical energy into mechanical energy. Mechanical energy is used to rotate the pump impeller, fan or blower, compressor, etc. Electric motors are often used in everyday life such as mixers, fans, electric drills, etc.

3-phase electric motors are also used in industry because they have many advantages (Rosdianto & Toifur, 2017). The advantages of controlling 3-phase electric motors include controlling 3-phase induction motors, namely the structure of a 3-phase electric motor that is lighter, cheaper, and maintenance efficient.

An electric motor is included in the category of an electric machine which is an energy conversion that can rotate, which can convert magnetic energy into electricity. Vice versa. When mechanical energy is converted into electrical energy, the machine can work as a generator (Jatmika, Syakur, & Afrisal, 2021). On the other hand, if electrical energy is converted into mechanical energy, the machine works as a motor.

Basically, electrical or electrical and mechanical energy has different properties. Electrical energy deals with voltage and electric current while mechanics deals with torque and rotational speed.
The formation of the salt provides the basis for the concept of the electric motor. When the conductor forms a coil, which is energized and placed in a magnetic field between the north and south poles, then the sides of the coil experience opposite forces, resulting in a torque that will rotate the coil.

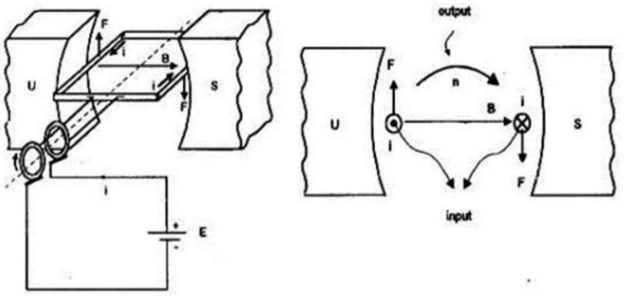

Figure 1. Basic Concept of Electric Motor

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2.2. Induction Motor Working Principle

The working principle of an induction motor is simple, that is when a 3-phase voltage source is mounted on the stator coil. This creates a rotating field with a certain speed. The rotating field of the stator will cut the conductor rods on the rotor, causing a voltage induced by the electromotive force (Abidin, Priangkoso, & Darmanto, 2013).

The closed circuit of the motor coil as a result of the emf will produce an electric current. Later, the electric current will cause a force on the motor (Nurfaizah, Istardi, & Toar, 2015). If the initial coupling produced by the force on the rotor is large, the rotor will rotate in the direction of the stator field. The amount of input power can be calculated using the formula.

$$P_1 = \sqrt{3}\, V\, i\, \cos\varphi \qquad (1)$$

Where :

P1 = input power

V = input voltage

I = Input current

Cos teta = 0,7

The efficiency of an induction motor is the ratio between the input power and the power provided by the motor as a driving medium, which is

$$\eta = \frac{P_2}{P_1} \times 100\% \qquad (2)$$

Where :

P1 = input power

P2 = output power.

In an induction motor, the difference in speed between the rotating magnetic field of the stator and the actual speed of the rotor is known as slip. The presence of slip is crucial for the induction process to occur, as it allows the relative motion needed to induce current in the rotor. If the rotor were to rotate at the same speed as the stator field, no relative motion would exist, and consequently, no emf would be induced (Abidin, Priangkoso, & Darmanto, 2013). Therefore, the slip is an essential factor in determining the performance and efficiency of an induction motor.

Furthermore, the efficiency of an induction motor depends on factors such as rotor resistance, core losses, and mechanical losses. As the rotor accelerates and reaches a steady-state speed, the slip decreases, reducing the induced current and the associated losses. Engineers often optimize motor designs to minimize these losses, improving the overall performance and reducing energy consumption (Nurfaizah, Istardi, & Toar, 2015). By selecting high-quality materials and efficient cooling methods, manufacturers can enhance motor durability and reliability.

Induction motors are widely used in industrial and commercial applications due to their robustness and minimal maintenance requirements. Unlike synchronous motors, they do not require additional external excitation, making them simpler and more cost-effective. Their ability to operate in various load conditions with high reliability has made them a preferred choice for applications ranging from household appliances to large industrial machines (Abidin, Priangkoso, & Darmanto, 2013). With continuous advancements in motor technology, modern induction motors are becoming even more energy-efficient, contributing to sustainable industrial development.

2.3. Uncontrolled rectifier circuit 1 Full-wave phase

The rectifier circuit is a power electronics circuit that is used to convert alternating or alternating voltages into DC (unidirectional) voltages. The AC voltage that is often used is usually one-phase or three-phase AC voltage. The single-phase rectifier consists of half-wave and full-wave rectifiers. The single-phase half-wave rectifier is the simplest type of rectifier but is not often used in industry (Nurfaizah, Istardi, & Toar, 2015). Half wave rectifier is useful as a conscious in understanding the principle of rectifier. A very important component in the rectifier is a circuit that occurs from a semiconductor element (diode) and if needed a transformer. The graphic symbol for a semiconductor is an open triangle.

The rectifier of a single phase source system produces high direct current values (Sufyani et al., 2019). The output voltage of a rectifier depends on the type of rectifier circuit, the ratio. transmission of the transformer, the type and magnitude of the resistance and of the type of load. To make a full-wave rectifier with four diodes using a non-CT Transformator.

- Average Output Voltage
$$Vdc = \frac{2\times Vm}{\pi} \quad (3)$$
- Average Current Load
$$Idc = \frac{Vdc}{R} \quad (4)$$
- Output Voltge (rms)
$$Vrms = \frac{Vm}{\sqrt{2}} \quad (5)$$
- Output Current (rms)
$$Irms = \frac{Vrms}{R} \quad (6)$$
- Output Voltage (rms) on the secondary side of the trafo
$$Vs = \frac{Vrms}{\sqrt{2}} \quad (7)$$
- Output current (rms) on the secondary side of the trafo
$$Is = \frac{Vrms}{R} \quad (8)$$

2.4. Diode

Diodes are electronic components that have two electrodes, including the cathode and anode. Almost all electronic devices require direct current to work, so a rectifier is needed to convert alternating current (AC) into direct current (DC). The voltage and current must be properly aligned to prevent interference with connected equipment. Diodes play a crucial role in rectification by allowing current to flow in only one direction while blocking reverse flow, ensuring a steady DC output. The body of the diode is used in both half-wave and full-wave rectifier circuits.

In a half-wave rectifier circuit, a single diode is used to conduct current only during one half of the AC cycle, effectively blocking the negative half-cycle. This results in a pulsating DC output, which may not be ideal for all applications due to its high ripple content. However, half-wave rectifiers are simple and cost-effective, making them suitable for low-power applications where precise DC voltage is not a critical requirement. To improve efficiency and reduce ripples, additional components such as capacitors can be added to smooth the output voltage.

On the other hand, a full-wave rectifier utilizes multiple diodes to convert both halves of the AC cycle into DC, significantly increasing efficiency and reducing fluctuations in the output voltage. A common configuration for full-wave rectifiers is the bridge rectifier circuit, which consists of four diodes arranged in a bridge structure. This setup ensures that current flows in the same direction during both halves of the AC cycle, producing a more stable and continuous DC voltage. Full-wave rectifiers are widely used in power supplies for electronic devices, as they provide a higher and more consistent output compared to half-wave rectifiers.

Figure 2. diode symbol

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2.5. Resistor

Resistors are passive electronic components that serve as a means of resistance to electric current. Their primary function is to limit or regulate the flow of electrical current in a circuit, ensuring that components receive the appropriate voltage and current levels. Resistors come in two-terminal configurations, meaning they have two electrical connection points. The relationship between the current (I) and resistance (R) follows Ohm's Law, which states that the current passing through a resistor is inversely proportional to its resistance when a constant voltage is applied. This fundamental principle makes resistors essential in electronic circuits.

One of the key functions of resistors is to act as current limiters. By placing a resistor in series with other components, it helps control the amount of current flowing through sensitive devices such as LEDs, transistors, and microcontrollers, preventing potential damage due to excessive current. Additionally, resistors play a crucial role in adjusting signal levels, improving circuit stability, and protecting circuits from short circuits and overloads. Their ability to dissipate power in the form of heat also makes them useful in energy management applications.

Another important application of resistors is as voltage dividers. In a simple voltage divider circuit, two or more resistors are connected in series to produce a lower output voltage from a higher input voltage. This is commonly used in analog circuits, sensor interfacing, and power regulation. For instance, in microcontroller applications, a voltage divider can be used to scale down higher voltages to levels that the microcontroller can safely process. The accuracy and precision of voltage dividers depend on the tolerance and stability of the resistors used.

Figure 3. Resistor

2.6. Capasitor

Capacitors are electronic components that function as energy storage devices, capable of holding an electric charge. They consist of two conductive metal plates separated by a dielectric material, which acts as an insulator to prevent direct current (DC) from passing through. The capacitance of a capacitor, measured in farads (F), determines its ability to store an electric charge. The larger the capacitance, the more charge a capacitor can hold at a given voltage. Capacitors are widely used in electronic circuits for various applications, ranging from energy storage to signal processing.

One of the fundamental properties of capacitors is their ability to temporarily store and release electrical energy. When a voltage is applied across the plates, an electric field is created, causing positive and negative charges to accumulate on opposite plates. This stored energy can then be discharged when needed, making capacitors essential for applications such as power supply stabilization, timing circuits, and pulse generation. In power supply systems, capacitors help smooth voltage fluctuations by filtering out noise and maintaining a steady output voltage.

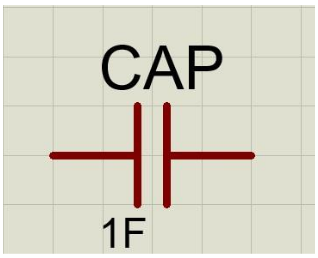

Figure 4. Capacitor Symbol

2.7. Transformator

A transformer is an electrical device that can transfer and modify electrical energy from one or more electrical circuits to another using a magnetic connection. It operates based on the principle of electromagnetic induction, allowing electrical energy to be transmitted without direct electrical contact. One of the key

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characteristics of a transformer is that it does not change the frequency of the input voltage, making it an essential component in power distribution systems. The structure of a transformer consists of a core and two coils: the primary coil, which receives the input voltage, and the secondary coil, which delivers the transformed output voltage. Both coils are made of copper to ensure efficient electrical conductivity and minimal energy loss.

Transformers play a crucial role in adjusting voltage levels to meet specific electrical requirements. Step-up transformers increase the voltage from the primary to the secondary coil, making them useful for power transmission over long distances by reducing energy loss. Conversely, step-down transformers decrease the voltage, making electrical power suitable for household appliances and industrial equipment. The efficiency of a transformer depends on factors such as core material, winding quality, and insulation, which help minimize losses due to resistance and magnetic leakage.

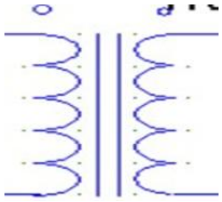

Figure 5. Transformator Symbol

2.8. Oscilloscope

An oscilloscope is a tool used for measuring electrical quantities in the form of waves. These waves have specific properties such as amplitude, frequency, and period, which are displayed in real-time on the oscilloscope screen. The oscilloscope provides a visual representation of electrical signals, making it an essential instrument for diagnosing and analyzing electronic circuits. The voltage and current values are represented along the vertical axis, while the horizontal axis represents time, showing the period of the measured electrical signal. This allows users to observe variations in the waveform and detect abnormalities in electrical signals.

Oscilloscopes are widely used in various fields, including electronics, telecommunications, and medical applications. In electronic circuit testing, oscilloscopes help engineers and technicians analyze signal behavior, detect malfunctions, and ensure proper circuit operation. In telecommunications, they are used to measure signal integrity and analyze transmission quality. Medical professionals also use specialized oscilloscopes, such as electrocardiographs (ECGs), to visualize heart signals and diagnose cardiac conditions. The ability to capture rapid changes in electrical signals makes oscilloscopes a valuable tool in research and development.

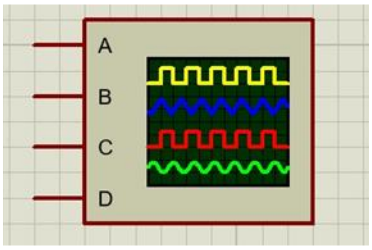

Figure 6. Oscilloscope picture on proteus

2.9. PSIM

PSIM is software created to simulate power electronics and electric drives. Consists of three programs, namely circuit schematic editor – SIMCAD, PSIM simulator, waveform processing- SIMVIEW. In this practicum the PSIM software is used to simulate a single-phase half-wave circuit.

Figure 7. Picture Software PSIM

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2.10. One Phase Full Wave

One full-wave phase consists of four choppers. If the two transistors are turned on together, the output voltage will pass through the load. If the transistors are turned on simultaneously, then what will happen is that the load voltage changes to negative.

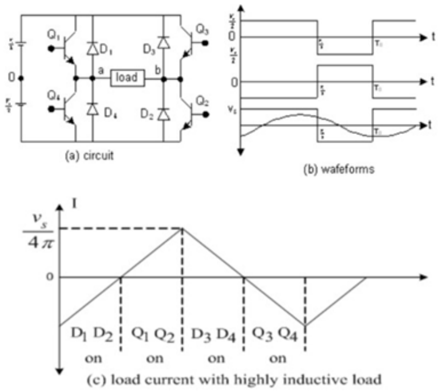

Figure 8. Picture Software PSIM

3. Results and discussion

The results of the simulations that have been carried out, the achievement of maximum power and torque output does not provide maximum efficiency. While the maximum torque and power. The peak torque and power in the AC motor is reached at the same speed. Torque and power initially increase along with the increase in rotation of the electric motor shaft but then it will decrease gradually as the rotation increases.

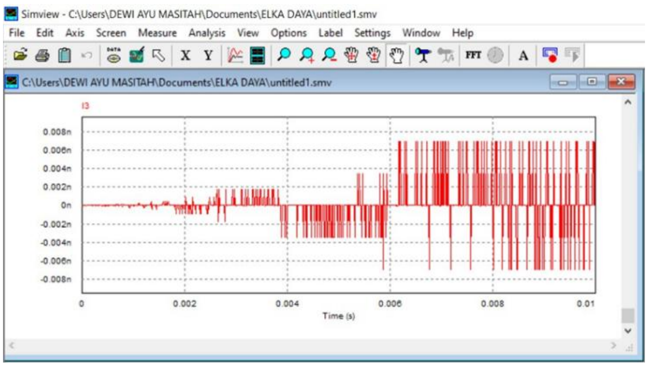

Figure 9. Display after simulation

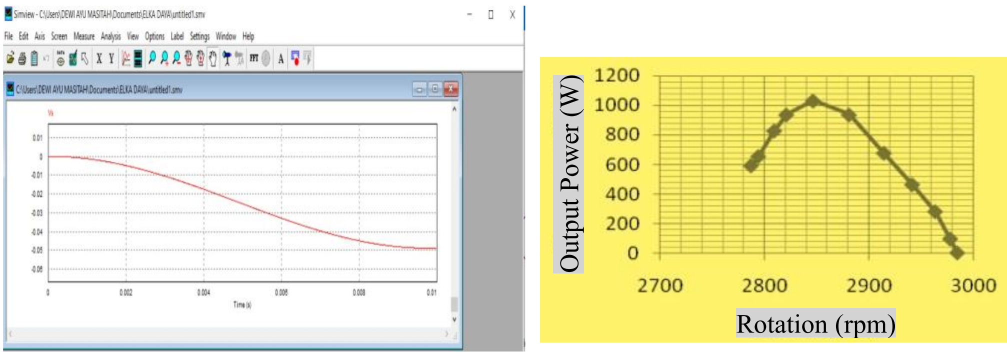

Figure 10. Connection between power and rotation

Figure 10 presents two distinct data visualizations related to system performance analysis. The left side displays a simulation graph generated using Simulink, where the x-axis represents time (seconds) and the y-axis depicts an unspecified variable, potentially voltage or current. The plotted red line indicates a gradual decline over time, suggesting a decaying signal or a transient response in an electrical or mechanical system. This behavior is commonly analyzed in control systems, signal processing, or dynamic system stability studies.

On the right side, the second graph illustrates the relationship between rotational speed (Putaran in rpm) and power output (Daya output in Watts). The x-axis spans from 2700 rpm to 3000 rpm, while the y-axis measures power output, peaking at approximately 1000 watts near 2800 rpm before declining. This trend indicates that the system, possibly a generator or an electric motor, operates most efficiently around 2800 rpm, where it delivers maximum power. Beyond this optimal speed, efficiency decreases due to factors such as increased losses, mechanical inefficiencies, or electrical constraints.

Together, these graphs provide insight into system behavior, with the simulation data potentially validating the experimental results. The findings are relevant to research in power generation, motor efficiency optimization, and dynamic system performance, offering valuable implications for improving energy efficiency and operational stability in rotating machinery.

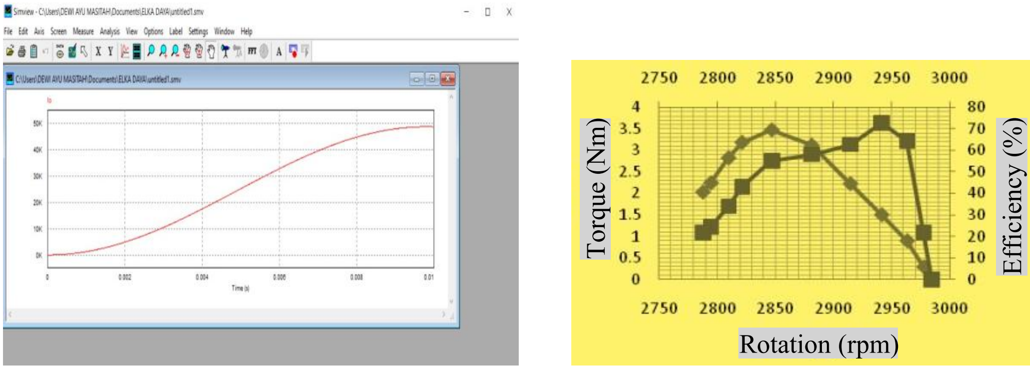

Figure 11. Connection between torque efficiency and rpm

Figure 11 display two different sets of data related to system performance analysis. The first image (left) shows a simulation graph from Simulink, where the x-axis represents time (seconds) and the y-axis represents an increasing variable, possibly torque, speed, or power. The red curve indicates a continuous increase over time, suggesting that the system exhibits acceleration or increasing output behavior, which could be related to motor startup dynamics or load response in an electrical or mechanical system.

The second image (right) presents an experimental performance graph comparing torque (Nm) and efficiency (%) against rotational speed (rpm). The x-axis represents the rotational speed, ranging from 2750 to 3000 rpm. The left y-axis measures torque (Nm), which initially increases, peaks around 2850 rpm, and then declines at higher speeds. The right y-axis represents efficiency (%), showing a similar trend—rising with increasing speed before sharply dropping after 2950 rpm. This suggests that the system operates most efficiently at a certain speed range but experiences reduced performance beyond an optimal operating point.

Together, these graphs highlight the relationship between system dynamics and efficiency, where the Simulink simulation may represent theoretical performance trends, while the experimental data validates real-world behavior. This type of analysis is crucial in optimizing motor efficiency, determining ideal operating conditions, and improving mechanical and electrical system performance.

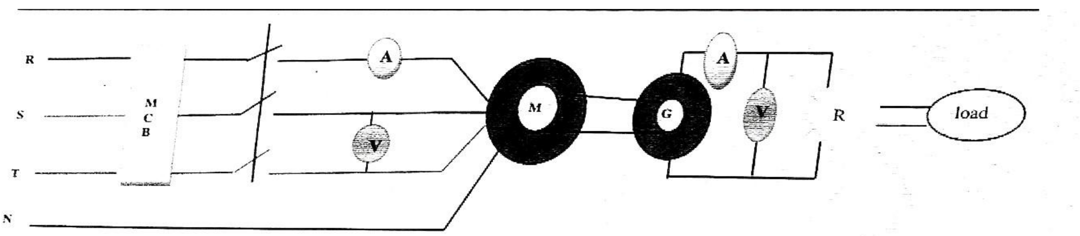

Figure 12. Motor test circuit with a voltage source

4. Conclusion

Based on the test results, data analysis, and discussion regarding the performance of a three-phase AC electric motor in a star circuit, it can be concluded that maximum power and torque occur around 2846 rpm. However, operation at this speed does not result in maximum efficiency. The graph shows that although power and torque increase until they reach their peak, efficiency actually decreases after reaching the optimum point at around 2950 rpm. This is due to increased system losses, sub-optimal energy conversion, and other mechanical factors. Thus, although the motor is capable of producing maximum power and torque at 2846 rpm, for more efficient use, it is recommended to operate the motor at a lower speed range, where efficiency is higher and system losses can be minimized.

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