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Analysis of a Three-Phase Uncontrolled Full-Wave Rectifier Under Induction Motor Rotational Conditions: A Technical Investigation

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ABSTRACT

Induction motors are among the most commonly utilized motors in modern engineering applications due to their simple construction, cost-effectiveness, lightweight design, high efficiency, and ease of maintenance compared to DC motors. Despite these advantages, controlling the speed and torque of an induction motor presents significant challenges. With advancements in control system technologies, one approach involves using a single-phase inverter operating at a standard frequency of 50 Hz to regulate the speed of three-phase induction motors. In this study, a three-phase uncontrolled full-wave rectifier is analyzed to evaluate its performance under induction motor rotational conditions. The system utilizes a 220V transformer to supply the rectifier. Simulation and data acquisition are conducted using PSIM software to ensure precise modeling and analysis of the rectifier's operational characteristics. The investigation explores the dynamic interplay between the rectifier and motor system, emphasizing the impact on voltage stability, harmonic distortion, and efficiency.

Key Word: *Induction Motor, Three Phase, Transformer*

I.INTRODUCTION

Power electronics circuits are essential components in electrical engineering, enabling the transformation of electrical power from one form to another [1]. These circuits convert a sinusoidal input waveform into a desired output, such as a non-sinusoidal or direct current (DC) waveform, using power semiconductor devices [2]. Power semiconductors play a pivotal role in these circuits, functioning primarily as switches to regulate and control the circuit's performance in accordance with the desired specifications [3]. Power electronics circuits are widely utilized in high-power applications, including electric power transmission, industrial motor regulation, and various household electrical devices [4][5].

The rapid industrial growth in modern society, both in large-scale and small-scale sectors, has intensified the demand for efficient production equipment to optimize time and cost. Electric motors are fundamental to industrial operations, with induction motors being the most widely used type [7]. This preference is due to their simple construction, affordability, lightweight nature, high efficiency, and ease of maintenance compared to DC motors [8]. However, the regulation of speed and torque in induction motors presents significant challenges, particularly under varying load conditions [5]. Effective control of motor speed is essential to maintain stable operation and optimize performance [9][10].

Speed regulation of induction motors can be achieved through various methods, including changing the number of pole pairs and adjusting the operating frequency. Among these, frequency control using an inverter, managed automatically by a Programmable Logic Controller (PLC), stands out as the most efficient and practical approach, particularly for induction motors in industrial settings [11].

Rectifiers, critical components in power electronics, are designed to convert alternating current (AC) to direct current (DC). Depending on the input voltage source, rectifiers are categorized into single-phase and three-phase types. The performance of a rectifier is typically assessed using key parameters, including the output voltage . The initial output of a rectifier is not a pure DC waveform but exhibits ripples, which can adversely affect the performance and lifespan of connected electronic equipment. To mitigate these effects, filters such as capacitive filters are commonly employed. These filters, installed on the rectifier's output side, reduce ripple effects and ensure a smoother DC output [12].

This research focuses on analyzing the output voltage characteristics of single-phase and three-phase rectifiers equipped with capacitive filters [13]. By varying the capacitor size for each rectifier type while maintaining the same output voltage, the study aims to evaluate the impact of capacitive filtering on the rectifier's performance [5]. Simulations are conducted using Power Simulator (PSIM) software to provide a detailed analysis of the system's behavior under varying conditions [14].

II.METHODOLOGY

1. Material

A. Rectifier

Rectifiers are essential components in power electronics, designed to convert an alternating current (AC) voltage source into a direct current (DC) voltage source. These devices play a pivotal role in applications requiring reliable DC power for various industrial and technological uses[15]. Rectifiers are generally categorized into two main types: uncontrolled rectifiers and controlled rectifiers, each serving specific purposes depending on the nature of the application.

- Uncontrolled Rectifiers

An uncontrolled rectifier converts AC voltage into a fixed DC voltage without the ability to regulate or control the output [16]. This type of rectifier is commonly used in simple applications where constant DC output is sufficient. Uncontrolled rectifier circuits, such as single-phase or three-phase configurations, typically incorporate passive components like diodes, resistors, and capacitors to stabilize the output. For instance, a three-phase uncontrolled rectifier produces a smoother DC output than its single-phase counterpart due to reduced ripple effects [17]. The addition of capacitive filters in these circuits further enhances the quality of the DC output, reducing fluctuations that could otherwise disrupt downstream electronic systems.

- Controlled Rectifiers

Controlled rectifiers, often referred to as converters, enhance the functionality of rectification by allowing the regulation of the DC output voltage. These circuits employ power electronic switches, such as thyristors or IGBTs, alongside control mechanisms to achieve adjustable output characteristics. One effective method to regulate a controlled rectifier is through the implementation of Proportional-Integral (PI) controllers[18].

A PI controller introduces voltage feedback to dynamically adjust the output based on the desired setpoint. The application of a PI controller in single-phase and three-phase rectifiers enables precise regulation of load voltage and current. However, without feedback, the controller's impact is minimal, as it cannot significantly influence the amplitude of the output. When feedback is introduced, and the PI values are adjusted, the amplitude of the load voltage and current increases proportionally.

B. Motor induction

A three-phase induction motor shares fundamental structural similarities with other types of electric motors but stands out due to its efficient and robust design[19]. The motor consists of two primary components:

- The Stator: The stationary part of the motor responsible for generating the rotating magnetic field.
- The Rotor: The rotating part that interacts with the stator's magnetic field to produce motion.

These two parts are separated by a narrow air gap, typically ranging from 0.4 mm to 4 mm, which plays a critical role in the motor's performance by influencing electromagnetic coupling. Figure 1 illustrates the internal structure of a three-phase induction motor, highlighting the key components and their spatial relationship.

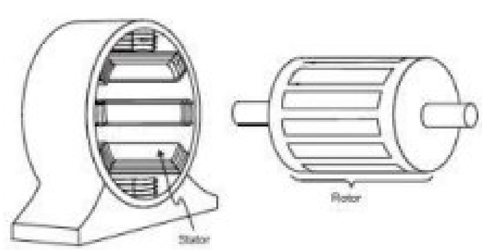


Figure 1. illustrates the internal structure of a three-phase induction motor

The flux lines generated by the stator coil will intersect the rotor coil, inducing an electromotive force (EMF) or voltage. Since the rotor coil is a closed circuit, this results in a flow of current through the rotor coil. [1]

C. Travo

A travo is an essential electrical device that facilitates the transfer and conversion of electrical energy between circuits through magnetic coupling, leveraging the principle of electromagnetic induction. This process occurs without altering the frequency of the electrical signals, making transformers indispensable for voltage regulation in various power systems. Transformers are widely used in applications such as voltage step-up or step-down, impedance matching, and isolation between different sections of electrical networks [20].

In this research, the transformer used operates at a reference voltage of 220V, which serves as a baseline for testing the behavior of the power electronics system. The specific focus is on how the system interacts with a three-phase uncontrolled full-wave rectifier, a common configuration in power electronics. The transformer's 220V output is fed directly into the rectifier, providing the necessary AC voltage for subsequent conversion.

The rectifier plays a key role in converting the AC voltage from the transformer into a DC voltage, which is then used to power a three-phase induction motor[21]. This setup allows for detailed analysis of the motor's behavior and performance under varying electrical conditions, particularly as influenced by changes in input voltage and load.

The configuration is critical for understanding the dynamics of motor speed control[22].

This research aims to explore how the power electronics system, including the transformer and rectifier, contributes to controlling the speed of the induction motor. By varying load conditions, the study seeks to gain insights into the motor's performance and efficiency, providing valuable data for optimizing motor control strategies and enhancing the design of electrical systems for industrial applications [8].

D. Full-wave Three-Phase Uncontrolled Rectifier

In technical research involving rectifier circuits, particularly for three-phase systems, a rectifier from a three-phase network is commonly employed when high direct current (DC) power is required, as it offers superior efficiency and stability compared to other configurations [9]. A typical three-phase rectifier utilizes a three-pulse configuration, where three branches are arranged, each containing a single diode. These branches are connected in a star configuration, a widely adopted setup in electrical engineering applications due to its ability to distribute voltage evenly and provide reliable performance. This setup is often preferred for industrial power systems, as it efficiently converts alternating current (AC) to direct current (DC), ensuring a stable and continuous power supply for demanding applications.

Compared to a single-phase alternating current (AC) rectifier, the three-phase system exhibits a significantly lower ripple factor, which results in a smoother and more stable DC output. This is particularly important in applications where a constant and reliable power source is required, such as in motor control and other sensitive electronic systems. The reduced ripple factor minimizes fluctuations in the DC voltage, contributing to improved performance and longevity of the connected devices, like three-phase induction motors, which rely on stable voltage for smooth operation.

Throughout a single period of the AC supply voltage, the three-phase rectifier generates three distinct pulses of forward current, typically referred to as M3. Within this configuration, two diodes are activated simultaneously for a duration of 60 degrees of the AC cycle. This simultaneous conduction is crucial for optimizing the rectification process and ensures that the DC output is as smooth as possible. As the AC supply voltage oscillates, six diode pairs sequentially conduct throughout the period, following a specific order: D6-D1, D1-D2, D2-D3, D3-D4, D4-D5, and D5-D6. The sequential activation of the diodes ensures that the rectifier continuously produces a stable DC voltage, minimizing the impact of fluctuations in the AC input.

This configuration of sequential diode activation not only optimizes the rectification process but also ensures more efficient conversion of AC to DC. This efficiency is particularly critical in applications such as induction motor control, where consistent and reliable power supply is essential for maintaining operational stability. By minimizing voltage ripple and ensuring a steady DC output, the three-phase rectifier supports the efficient operation of induction motors, which are commonly used in industrial settings requiring high-performance and continuous operation. The ability to achieve a stable and reliable DC output, with minimal ripple, is a fundamental requirement for the optimal performance of motor control systems.

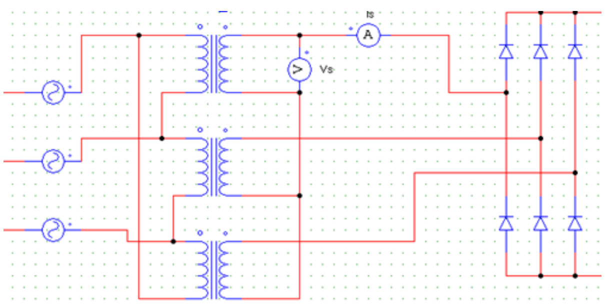


Figure 2. Simulation in psim

In one cycle, there are 6 pairs of diodes that are activated, resulting in an output voltage with 6 waves (pulses), each having a 60° duration. The DC output voltage is:

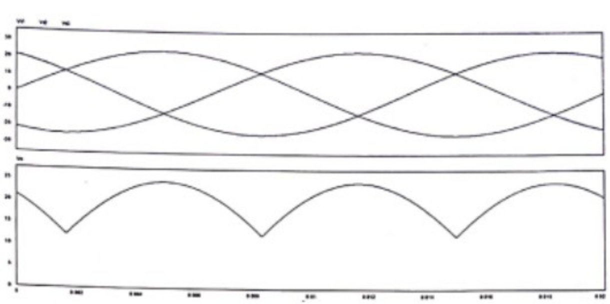
$$V_{o(dc)}=\frac{3V_{m.L-L}}{\pi}=0{,}955V_{m.L-L}=1{,}654V$$

And the rms output voltage is:

$$V_{o(rms)}=V_{m.L-N}\,x\sqrt{\left(\frac{3}{2}+\frac{9\sqrt{3}}{4\pi}\right)}=1.6554\,x\,V_{m.L-N}$$

$$V_{o(rms)}=\frac{V_{m.L-N}}{\sqrt{3}}\,x\sqrt{\left(\frac{3}{2}+\frac{9\sqrt{3}}{4\pi}\right)}=0.95575\,x\,V_{m.L-L}$$

Figure 3. output voltage of a three-phase



full-wave rectifier with a resistor load

In the figure 3 above, the output voltage of a three-phase full-wave rectifier with a resistive load is nearly a pure DC. To achieve a completely pure DC voltage, a relatively small filter is added in parallel[10].

Output voltage ripple:

$$V_{o(rms)}=\sqrt{V_{o_{(dc)}}^2+\sqrt{V_{ac}^2}}$$

$$\Delta V_o=\frac{Vm}{6fRC}=\frac{V_{s(max)(L-L)}}{6fRC} \qquad \text{Dimana :}$$

$$V_{ac}=\frac{\Delta V_o}{2\sqrt{2}}$$

The DC output voltage is :

$$V_{o(dc)}=V_m-\frac{\Delta V_o}{2}$$

III.RESULT & DISCUSION

This experimental study investigates the behavior of a three-phase rectifier system and its application to power a single-phase AC motor. The input voltage from the source consists of three-phase AC with the following voltage ratings: R-phase, S-phase, and T-phase, each at 220V. To adapt the voltage to the required levels for the subsequent stages, a step-down transformer is employed, reducing the voltage to two specific levels: 110V and 50V.

Following the voltage conversion, the AC current is processed by a three-diode rectifier, which rectifies the alternating current into direct current (DC). The rectified current is then supplied to a single-phase AC motor. This system, commonly used in electrical engineering applications, allows for the efficient conversion of three-phase AC power to the appropriate form to drive the motor, ensuring consistent and reliable operation.

The analysis of the system's performance in such configurations is critical for applications requiring precise motor control, as the quality of rectification directly impacts the efficiency of motor operation. The study contributes to understanding the dynamics of voltage transformations, rectification processes, and motor performance under varying electrical conditions, thus offering valuable insights into the design and optimization of power systems in industrial and engineering contexts

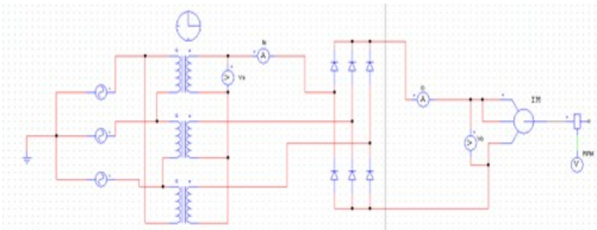


Figure 4.circuit simulation PSIM

Then, taking the data from the PSIM software, the results are as follows: The simulation provided key insights into the system's performance under the specified conditions, offering valuable data that can be analyzed for further optimization.

Table 1. Result simulation

Primer Travo Voltage (V)	**Second Travo Voltage (V)**	**Is**	**Io**	**RPM**
220	50	7,0040e-011	1,3884e-011	1,0020e-031
220	110	3,1791e-011	1,1702e-010	1,8134e-031
220	220	6,6055e-011	1,1728e-010	9,1971e-032

Based on the data from the table above, where the transformer's output voltage was changed to 220V, 110V, and 50V, it was observed that a decrease in current and a reduction in rpm were directly proportional to the decrease in the transformer's secondary voltage. As the secondary voltage of the transformer was reduced, the motor received less power, which led to a corresponding decrease in both the current supplied to the motor and the rotational speed (rpm). This behavior is consistent with the relationship between voltage and current in electrical circuits, where a reduction in voltage typically results in lower current flow and, consequently, less motor speed.

Below are the simulation results that further illustrate this trend. The data show how the motor's performance varies with changes in the transformer's secondary voltage, emphasizing the impact of voltage reduction on the overall system efficiency. The results underscore the importance of maintaining a stable voltage supply to ensure optimal motor performance, particularly in systems where consistent speed control is critical. These findings can help inform the design and operation of power systems, especially in applications requiring precise control over motor speed.

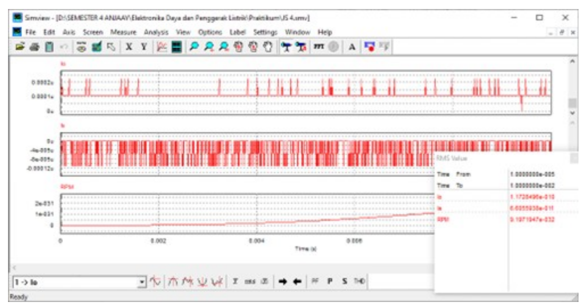


Figure 5. Results of the 1st simulation with a transformer secondary voltage of 50V

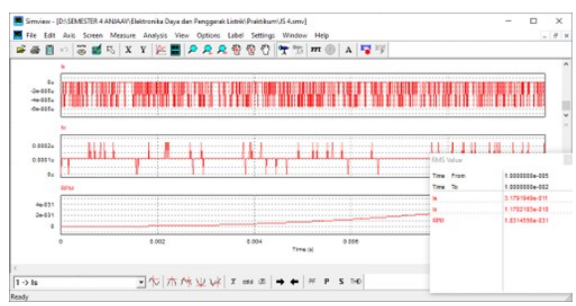


Figure 6. Results of the 2st simulation with a transformer secondary voltage of 110V

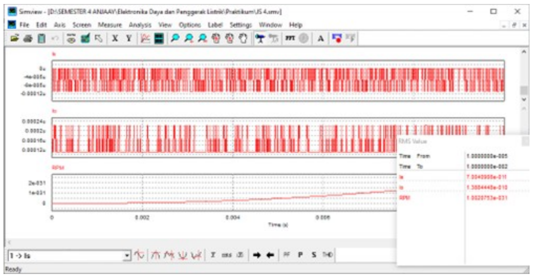


Figure 7. Results of the 3st simulation with a transformer secondary voltage of 220V

IV.CONCLUSION

- Impact of Voltage Reduction on Motor Speed: The simulations show that a decrease in input voltage leads to a proportional reduction in the motor's rotational speed, in line with Ohm's Law. Lower voltage reduces the current supplied to the motor, which in turn decreases the available power, resulting in a drop in the motor's RPM.
- Application of Ohm's Law in Motor Behavior: The observed behavior aligns with the fundamental principles of Ohm's Law, where the current is directly proportional to the applied voltage, assuming constant resistance. This relationship explains the reduction in motor speed as the input voltage is lowered.
- Implications for Power System Design: These findings highlight the importance of understanding voltage fluctuations in the design and optimization of power systems for induction motors. By considering voltage reduction effects, engineers can improve rectifier circuits and control strategies, ensuring efficient motor operation even in variable supply conditions.

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