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Controlled Single-Phase Full-Wave Rectifier Experiment for DC Shunt Motor Control

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Abstract

A DC shunt motor is a type of direct current motor that allows for speed regulation, making it essential for applications requiring steady-state speed control and transient response optimization, particularly under load conditions. Accurate speed control is crucial in industrial automation, robotics, and precision engineering systems that demand fast response and stability. This study aims to analyze the relationship between motor speed and reference speed, as well as its correlation with voltage and current variations. The research is conducted using PSIM software, a widely used simulation tool in power electronics and motor control studies. The methodology involves designing a controlled single-phase full-wave rectifier circuit within PSIM, incorporating gating block angle variations to observe their effects on motor performance. The data obtained are analyzed using descriptive analytical methods to assess system behavior. The experimental results indicate that motor speed increases as the firing angle decreases, and conversely, the speed reduces when the firing angle is increased, particularly under zero torque conditions (0 Nm). When a load torque of 5 Nm is applied, the relationship becomes inversely proportional, demonstrating a dependency between torque, voltage control, and motor speed stability. These findings provide valuable insights into DC shunt motor control optimization, highlighting the effectiveness of phase-controlled rectification in improving motor performance under variable load conditions.

Keywords: DC Shunt Motor, PSIM Software, Controlled Rectifier, DC Motor Speed Control

1. Introduction

A DC shunt motor is a type of direct current motor that features an easily adjustable speed characteristic (Winardi, 2021). Speed control is essential to achieve a steady-state speed and an optimized transient response, particularly when the motor operates in precision-demanding applications requiring fast response and load adaptation. Speed regulation in DC shunt motors is primarily achieved by adjusting the armature terminal voltage (Vt) (Hartono & Nurcahyo, 2017). The terminal voltage control method can be applied both during the starting phase and while the motor is in continuous operation (running phase) (Evalina, Azis, & Zulfikar, 2018) (Ambabunga, 2020).

DC shunt motors continue to be widely used in industrial applications where precise speed control is critical, particularly in paper manufacturing industries (Usman et al., 2017). In such industries, proper speed regulation is essential to ensure consistent paper production quality and to meet production targets (Nugraha et al., 2023a). If speed control is inadequate, defects in the paper output may occur, leading to substantial material waste and financial losses for the industry(Yuniza, Agna, & Nugraha, 2022). Despite advancements in induction motor technology, DC shunt motors remain irreplaceable in applications that demand precise and smooth speed adjustments(As'ad, Yuniza, & Nugraha, 2022).

A controlled rectifier is a power electronic circuit that utilizes thyristors as rectifying elements to regulate DC output voltage (Bintari, Mudjiono, & Nugraha, 2022). Controlled rectifiers are classified into single-phase or three-phase configurations and can operate in half-wave or full-wave rectification modes. A half-wave controlled rectifier uses two diodes and a bridge rectifier, serving as an input voltage regulator for the motor field winding. In contrast, a full-wave controlled rectifier is designed to efficiently convert AC to DC using diodes and thyristors as key components(Jamil et al., 2021).

One of the main challenges in controlled rectifier systems is the presence of ripple in the DC output voltage (Pambudi et al., 2021) (Nugraha et al., 2023b). Ripples are undesirable AC components superimposed on the DC waveform due to rectification imperfections and the nature of electrical loads (Nugraha, 2023). In power electronics and motor drive applications, excessive ripple can lead to low efficiency and poor power quality(Nugraha et al., 2024). When controlling DC motors using power electronic devices, ripple formation occurs due to non-ideal rectifier output characteristics, causing fluctuations in motor performance(Agna, Sobhita,

& Nugraha, 2023). Proper filtering and firing angle control techniques are essential to minimize ripple effects and enhance the stability of the DC motor speed control system(Mehar, 2013).

The DC shunt motor speed control system based on a controlled rectifier can be effectively simulated using PSIM software(Kamiriski, Wejrzanowski, & Koczara, 2004) (Hermawan, Aripriharta, & Homggowiyono, 2014). PSIM, developed by Powersim Inc., is a specialized simulation tool widely used in power electronics and motor control analysis. The primary purpose of using PSIM simulations is to evaluate the performance of electronic circuits before real-world implementation. Engineers frequently utilize PSIM to simulate power systems, motor drives, and electronic circuit characteristics to optimize system behavior(Sufyani et al., 2019).

In this study, a DC motor control model is developed in PSIM, integrating the rectifier circuit and gating angle variations to analyze the dynamic response of the system. The simulation results provide insights into the speed-torque relationship, allowing engineers to identify necessary control optimizations before practical application. By employing PSIM, potential system inefficiencies and design flaws can be identified and mitigated in advance, ensuring optimal motor performance in industrial applications.

2. Material and methods

Research on designing DC motor systems using controlled systems has been done a lot before, but in this study the author designed a program for controlling the speed of a DC shunt motor based on a controlled rectifier using Matlab Simulink. Research on controlling the speed of a DC motor using a controlled system can be seen as follows.

Basuki, Sumardi and Setiawan (2004) "Real Time DC Motor Speed Control Using the LRQ Optimal Control Technique" revealed that in the test results with variations in rotational speed between 700 - 1000 rpm with the same Q value of 0.01, the system time constant value T = 0.36 seconds and the closed loop pole value of the system s = - 2.7778 for all speeds.

Hidayat (2004) "Simulation of DC motor speed control with a semi-converter controlled rectifier based on Matlab/Simulink" Reveals that controlling the speed of a DC motor with a semi-converter full-wave controlled rectifier with semi-closed loop control can be used for systems that require constant speed.

Husein and Haryudo (2019) “Design and Construction of a Monitoring System Using Arduino-Based Matlab‘“‘ Reveals that the monitoring system for rotational speed, excess current, and temperature of DC motors can transmit data as far as 50 meters indoors and 120 meters outdoors. Pathoni and Suni (2016) Design of Direct Current Motor Speed Control Using the Root Locus Method” reveals that the design of DC PID motor speed control using the root locus method has been successfully carried out and simulated through simulink matlab so that the transient and steady state responses of the system are as desired.

2.1. DC Motor

A DC motor is an electric motor that requires a direct current voltage supply to the field coil to be converted into mechanical motion energy. A DC motor is an electronic device that converts electrical energy into mechanical energy in the form of rotational motion(Mutiar, 2017). In a DC motor, there is an anchor with one or more separate coils. Each coil ends in a split ring (commutator). With the insulator between the commutator, the split ring can act as a double pole switch (double pole and double throw switch) (Rosdianto & Toifur, 2017).

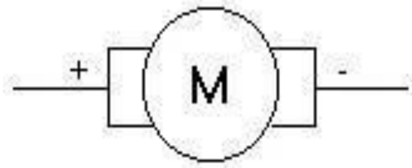

Figure 1. DC Motor Symbol (B.L Thereja 1959)

Based on its physical structure, a DC motor generally consists of a stationary part and a rotating part. The stationary part (stator) houses the field winding, which functions to generate magnetic flux, while the rotating part (rotor) contains the armature circuit, including the armature winding, commutator, and brushes.

A DC motor operates based on the principle of interaction between two magnetic fluxes(Jatmika, Syakur, & Afrisal, 2021). The field winding generates a magnetic flux that flows from the north pole to the south pole, while

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the armature winding produces a circular magnetic flux. The interaction between these two magnetic fluxes creates a force, which in turn generates torque(Abidin, Priangkoso, & Darmanto, 2013).

DC motors come in various sizes and power capacities, each designed for different applications but generally serving the same basic function: converting electrical energy into mechanical energy(Nurfaizah, Istardi, & Toar, 2015). A simple DC motor is built with a wire loop placed between two permanent magnets. When current flows through the wire, it generates its own magnetic field, which continuously changes direction relative to the permanent magnet's field, resulting in rotation.

One of the advantages of using a DC motor lies in its various performance characteristics, made possible by different configurations such as shunt, series, and compound connections. Additional possibilities arise when an extra set of brushes is introduced, allowing different voltages to be obtained from the commutator. This versatility in DC machine systems and the ease of implementing control systems—whether manual or automatic—make DC motors widely applicable. The load torque magnitude can be expressed as:

$$T \approx \emptyset o.Ia \quad (1)$$

2.2. Counter EMF in DC Motors

When the motor armature rotates, its conductor also moves and cuts through the main magnetic flux. According to Faraday's Law, the motion of a conductor within a magnetic field induces an electromotive force (EMF) in the conductor. This induced voltage is generated due to the interaction between the rotating conductor and the magnetic field surrounding it. The magnitude of this induced EMF depends on factors such as the rotational speed of the motor, the strength of the magnetic field, and the number of conductors within the armature.

Since this induced EMF acts in the opposite direction to the externally applied voltage that powers the motor, it is referred to as an opposing EMF or back EMF. The presence of this opposing EMF plays a crucial role in regulating the motor's performance. As the motor speed increases, the back EMF also increases, thereby reducing the net voltage across the armature and consequently limiting the armature current. This phenomenon helps protect the motor from excessive current draw and ensures stable operation (Nurfaizah, Istardi, & Toar, 2015).

The opposing EMF, also known as counter EMF, directly influences the efficiency and speed control of the motor. In practical applications, this relationship is utilized to design speed controllers and feedback mechanisms for ensuring smooth motor operation. The equilibrium between the applied voltage and back EMF determines the steady-state speed of the motor, making this concept fundamental in DC motor theory and control systems.

Based on this principle, the general voltage equation of a DC motor can be expressed mathematically as follows:

$$Eb = Kn.\emptyset \quad (2)$$

2.3. Shunt DC Motor

In both shunt and separately excited DC motors, the field flux remains nearly constant in magnitude (Rosdianto & Toifur, 2017). This is because the field winding in these motors is either directly connected to a constant voltage source (in shunt motors) or powered separately (in separately excited motors), ensuring a steady magnetic field. Consequently, any increase in torque must be accompanied by a corresponding increase in armature current. This relationship follows the fundamental torque equation of a DC motor, where torque is directly proportional to both the field flux and the armature current. Since the field flux remains constant, the armature current plays a key role in torque regulation.

As the armature current increases, there is a slight decrease in the counter-electromotive force (back EMF), which is generated due to the motor's rotation. This reduction in back EMF allows additional current to flow through the small armature resistance, enabling the motor to produce more torque. However, excessive armature current can lead to overheating and increased energy losses due to the resistive properties of the armature winding. To mitigate these effects, proper current regulation techniques, such as field weakening or external resistances, are employed in industrial applications where precise speed and torque control are necessary.

The equivalent circuit of a shunt-excited DC motor consists of an armature circuit and a field circuit connected in parallel. The armature circuit includes the applied voltage, armature resistance, and back EMF, while the field circuit consists of a separate field winding supplied with constant voltage. The performance of the motor can be analyzed using Kirchhoff's Voltage Law (KVL), which states that the sum of voltages in a closed loop must equal zero. By applying this principle, engineers can calculate the motor's efficiency, power output, and

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torque characteristics, ensuring optimal operation in various applications, such as industrial drives, electric vehicles, and robotics.

With advancements in motor control technology, modern DC motors are often equipped with electronic controllers that precisely regulate armature current and field flux. These improvements have led to more efficient and reliable motor performance, reducing power losses and extending motor lifespan. Additionally, shunt-excited DC motors continue to be widely used in applications requiring stable speed control and smooth operation, making them a preferred choice in automation, transportation, and power generation systems.

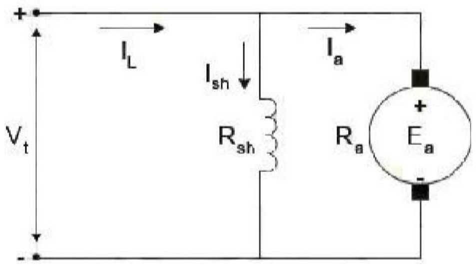

Figure 2. DC Shunt Motor Equivalent Circuit (B.L Thereja 1959)

General equation of shunt-excited direct current motor

$$Vt = Ea + Ia.\,Ra \quad (3)$$

$$Vsh = Vt = Ish.\,Rsh \quad (4)$$

$$IL = Ia + Ish \quad (5)$$

2.4. Thyristor

The term thyristor originates from the Latin word meaning "door," reflecting its function as a switch that controls the flow of electric current. This semiconductor component was developed by Bell Laboratories in the 1950s and was later commercialized by General Electric in the 1960s. Due to its ability to handle high voltages and currents, the thyristor, also known as a Silicon Controlled Rectifier (SCR), has become a crucial component in various industrial electrical applications. It is widely used in power control systems, motor drives, and AC-DC conversion circuits, where efficient and reliable switching is essential.

A thyristor consists of three terminals: the Anode (A), Cathode (K), and Gate (G). The anode and cathode function similarly to a diode, allowing current to flow in only one direction. However, the gate terminal serves as a control switch, determining when the thyristor turns on or off. Unlike standard diodes, a thyristor remains in its conducting state even after the gate signal is removed, requiring the circuit to turn off the current flow for deactivation. This characteristic makes thyristors highly effective for controlling power in high-voltage applications.

There are two types of thyristors, categorized based on their gate structure: P-Gate Thyristors and N-Gate Thyristors. These classifications refer to the material composition of the gate region, which influences the triggering characteristics of the component. The gate terminal functions similarly to the base of a transistor, allowing precise control over the thyristor's operation. By regulating the gate current (IG), engineers can control the power delivered to a circuit, making thyristors a fundamental component in phase-controlled rectifiers and variable-speed motor drives.

The gate current (IG) typically ranges from 1 mA to a maximum of 100 mA, enabling control over the thyristor's output voltage. The voltage that can be regulated starts from 50 volts, making thyristors suitable for applications requiring fine-tuned voltage adjustments. Because of their robustness and efficiency, thyristors continue to play a critical role in modern electrical and power electronics systems, including industrial automation, renewable energy systems, and high-power switching circuits.

2.5. Controlled Rectifier

Phase-controlled thyristor rectifiers are simple and cost-effective rectifiers, with rectification efficiencies generally above 95%. Since these rectifiers convert alternating current (AC) to direct current (DC) voltage, they are commonly referred to as AC-DC converters. Due to their high efficiency and reliability, they are widely used in industrial applications such as motor drives, power supplies, and battery charging systems. The ability to control the phase angle of the thyristor firing enables precise regulation of the output voltage, making these rectifiers highly versatile for various power control applications.

Phase-controlled converters are classified into two types based on the input supply: single-phase converters and three-phase converters. Single-phase converters are used in low-power applications and typically consist of half-wave or full-wave rectifiers controlled by thyristors. These converters are suitable for household appliances, small power tools, and laboratory equipment where moderate power conversion is required. On the other hand, three-phase converters are designed for high-power applications, providing smoother DC output with reduced ripple content. These are commonly used in industrial motor control, electrochemical processes, and high-power heating systems.

The primary advantage of phase-controlled rectifiers is their ability to regulate the output voltage by adjusting the firing angle of the thyristors. By delaying the conduction angle, the effective DC output voltage can be controlled, allowing for efficient power management. However, phase-controlled rectifiers also introduce harmonic distortions in the power system, which may require additional filtering techniques to maintain power quality. Engineers often incorporate filters and advanced control techniques to minimize harmonic interference and improve system efficiency.

With advancements in power electronics, modern phase-controlled rectifiers are integrated with digital control systems for enhanced precision and automation. These rectifiers play a crucial role in renewable energy systems, electric vehicle charging stations, and industrial automation, where controlled DC power is essential. As technology evolves, improvements in thyristor design and control algorithms continue to enhance the performance, efficiency, and reliability of phase-controlled rectifiers, making them a fundamental component in modern electrical and electronic systems.

2.6. Single Phase Full Wave Controlled Rectifier

A single-phase fully controlled rectifier consists of four thyristors (Q1, Q2, Q3, and Q4) arranged in a bridge configuration, as shown in Figure 3. The thyristors operate in pairs Q1-Q4 and Q2-Q3 each receiving a firing pulse at a specific firing angle α during the positive and negative cycles of the AC source voltage. The controlled switching of these thyristors enables the rectifier to regulate the output DC voltage by adjusting the firing angle. This allows for efficient power conversion and control, making single-phase fully controlled rectifiers ideal for applications that require precise DC voltage regulation.

When a resistive load RL is connected to the rectifier, the behavior of the circuit follows a predictable conduction pattern. During the first half-cycle of the AC input voltage, thyristors Q1 and Q4 are triggered at the firing angle α, allowing current to flow through the load. In the next half-cycle, thyristors Q2 and Q3 are triggered, conducting current in the same direction through the load. Because the load is purely resistive, the voltage and current remain in phase, ensuring smooth and efficient energy transfer. The output DC voltage depends on the firing angle, with higher values of α reducing the average DC voltage output.

One of the key advantages of a fully controlled rectifier is its ability to provide variable DC output voltage, which is crucial in motor speed control, battery charging, and industrial power supplies. However, phase-controlled rectifiers introduce harmonics into the power system, which can affect power quality. Additional filtering components, such as inductors and capacitors, are often required to smooth the output voltage and reduce harmonic distortions. The efficiency of the rectifier also depends on the conduction and switching characteristics of the thyristors, which must be properly synchronized to ensure reliable operation.

With advancements in power electronics, modern single-phase fully controlled rectifiers are often integrated with microcontroller-based or digital signal processing (DSP) systems for precise control and automation. These systems enable dynamic adjustment of the firing angle to optimize efficiency and minimize power losses. As industries move towards energy-efficient solutions, fully controlled rectifiers continue to play a vital role in power conversion and regulation, ensuring reliable operation in applications such as heating systems, power tools, and renewable energy systems.

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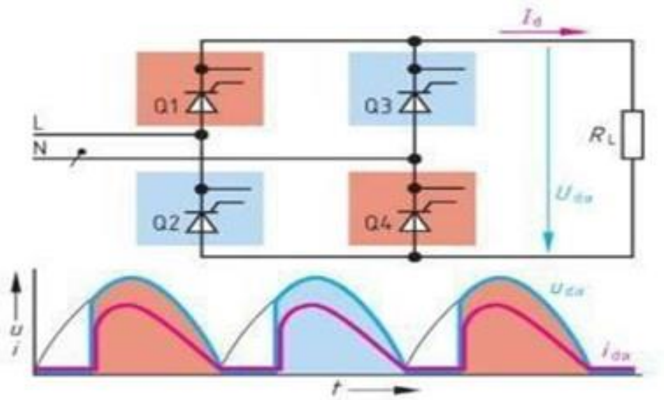

Figure 3. Single Phase Full Wave Controlled Rectifier Circuit

3. Results and discussion

3.1. Simulation

Conducting practical work in PSIM software allows users to simulate and analyze various power electronics and electrical circuit designs efficiently. The practical work carried out in the software is visually represented in Figure 4, demonstrating the configuration and behavior of the simulated circuit. PSIM is widely used in academic and industrial settings due to its user-friendly interface and ability to accurately model electrical components, making it an essential tool for engineers and researchers working on power systems, motor drives, and renewable energy applications.

In the simulation environment, users can design circuits, apply different input parameters, and observe the corresponding output waveforms in real time. The software provides valuable insights into circuit behavior under various conditions, such as changes in load, voltage variations, and switching operations. By using PSIM, students and engineers can conduct virtual experiments that closely mimic real-world scenarios, allowing for better understanding and optimization of circuit performance before physical implementation. The ability to analyze waveforms, measure electrical parameters, and troubleshoot potential issues makes PSIM an invaluable tool in power electronics education and research.

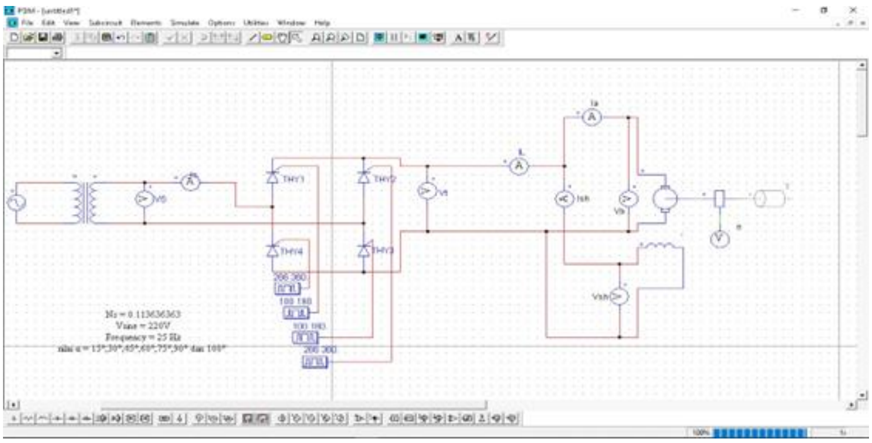

Figure 4. Simulation PSIM

In this simulation, two types of experiments were conducted to observe the effects of different torque values on system performance. The experiments were carried out using torque values of 0 Nm and 5 Nm, allowing a clear comparison of the system's response under varying load conditions. By analyzing the results, the impact of torque on parameters such as speed, current, and efficiency can be better understood. This approach helps in evaluating the performance characteristics of electric motors and power systems in different operating scenarios.

When the applied torque is 0 Nm, the motor operates in a no-load condition, meaning it runs freely without any external resistance. Under this condition, the current drawn by the motor is minimal, and the speed remains close to its rated value. However, when the torque is increased to 5 Nm, the motor experiences a load that requires additional power to maintain its operation. This leads to an increase in current consumption, a slight decrease in speed, and changes in power efficiency. The ability to analyze these variations is crucial for designing motors and controllers that can adapt to changing load conditions efficiently.

By conducting these experiments in a simulation environment, engineers and researchers can study motor behavior without the need for physical prototypes, reducing costs and time. The data obtained from these simulations can be used to optimize motor performance, improve energy efficiency, and develop better control strategies for real-world applications such as industrial automation, robotics, and electric vehicles. Additionally, these experiments help in identifying potential issues such as overheating, excessive current draw, or unstable operation, allowing for necessary design improvements before implementation.

3.2. Result

The following table presents the simulation results, providing a detailed analysis of the relationship between the thyristor firing angle (α), torque (Nm), terminal voltage (V), motor armature current (Ia), and motor rotational speed (RPM). These parameters play a crucial role in determining the performance characteristics of a DC shunt motor, particularly in applications where precise speed control is required.

By varying the firing angle (α), the amount of power supplied to the motor can be adjusted, which in turn affects the terminal voltage and armature current. This variation influences the rotational speed of the motor, demonstrating how thyristor-based control systems can effectively regulate motor performance under different load conditions.

The data presented in the table helps in understanding the dynamic behavior of the motor when subjected to different torque values. By comparing the results, it becomes possible to observe trends in motor speed and current consumption, which are essential for optimizing motor efficiency, improving energy usage, and ensuring stable operation.

This analysis is particularly useful in industrial and automation applications, where controlled speed variations and load-handling capabilities are critical factors in maintaining smooth and efficient system performance. The insights gained from these simulation results can aid in designing better motor control strategies for various real-world applications.

Table 1. Simulation Result 0 (Nm)

Trigger angel (a)	**Torque (Nm)**	**Terminal voltage (V)**	**Motor Anchor current (Ia)**	**Rotation (Rpm)**
15	0	17.67	6.55	706
30	0	17.61	6.28	666
45	0	17.45	5.91	601
60	0	17.16	5.40	516
75	0	16.68	4.77	418
90	0	15.98	4.05	316
100	0	15.39	3.53	250

Table 2. Simulation Result 5 (Nm)

Trigger angel (a)	Torque (Nm)	Terminal voltage (V)	Motor Anchor current (Ia)	Rotation (Rpm)
15	5	17.65	6.56	626
30	5	17.60	6.30	630
45	5	17.42	5.91	637
60	5	17.15	5.42	645
75	5	16.67	4.78	654
90	5	15.96	4.07	664
100	5	15.38	3.54	670

The measurement data observed in this study include armature voltage (Va), armature current (Ia), and the rotational speed of a DC shunt motor. When the DC motor operates without a torque load (0 Nm), the test results indicate that the firing angle (α) has an inverse relationship with the motor's rotational speed. This means that as the thyristor firing angle increases, the rotational speed of the DC shunt motor decreases. This behavior occurs because a larger firing angle delays the conduction period of the thyristors, reducing the average voltage supplied to the motor and subsequently lowering its speed.

Additionally, the relationship between armature voltage and rotational speed is direct—when the armature voltage increases, the rotational speed of a self-excited series DC motor also increases. Similarly, the armature current (Ia) also follows a direct relationship with rotational speed, where an increase in armature current results in a corresponding increase in motor speed. This is due to the motor's fundamental principle, where higher current flow strengthens the electromagnetic field interaction, generating greater torque and higher rotational speed. These findings align with theoretical expectations and validate the operational characteristics of a DC motor under no-load conditions.

However, when the DC motor is subjected to a torque load of 5 Nm, the behavior of the system changes. Under these conditions, the firing angle (α) exhibits a direct relationship with the rotational speed, meaning that as the thyristor firing angle increases, the rotational speed of the DC motor also increases. This is in contrast to the no-load condition, where an increase in the firing angle reduces speed. Additionally, the relationship between armature voltage and rotational speed becomes inverse—an increase in armature voltage results in a decrease in the rotational speed of the DC shunt motor. Similarly, the relationship between armature current and rotational speed is also inverse, where an increase in armature current (Ia) leads to a decrease in motor speed. This occurs because the additional torque load increases mechanical resistance, requiring greater current to maintain operation, ultimately affecting overall speed dynamics.

The experimental results confirm variations in rotational speed corresponding to changes in the thyristor firing angle and torque load. The calculations demonstrate similar trends, validating the observed behavior. For instance, when the firing angle (α) is set to 100° with a torque load of 0 Nm, the measured rotational speed is 250 RPM. These findings provide valuable insights into the complex interactions between electrical parameters and mechanical performance in DC motors. By understanding these relationships, engineers can optimize motor control strategies for applications requiring precise speed regulation, such as industrial automation, electric vehicles, and robotics.

4. Conclusion

From the results of this study, the following conclusions can be drawn:

1. Speed Control Mechanism

   The speed control of a DC shunt motor with torque loads of 0 Nm and 5 Nm can be effectively regulated using a single-phase fully controlled full-wave rectifier. This is achieved by adjusting the thyristor firing angle (α) between 0° and 180°, which directly influences the armature voltage and armature current, thereby controlling the motor's rotational speed.

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2. Effect of Firing Angle on Motor Speed (0 Nm Load)
   When operating under no-load conditions (0 Nm), the motor's rotational speed is highly dependent on the firing angle. The measurement results indicate that at a firing angle of 100°, the motor rotates at 250 RPM, while at a firing angle of 15°, the speed significantly increases to 706 RPM. This confirms the inverse relationship between the firing angle and motor speed in a no-load condition.

3. Effect of Firing Angle on Motor Speed (5 Nm Load)
   Under a torque load of 5 Nm, the motor exhibits a different behavior. The calculation results show that when the firing angle is 15°, the motor reaches a speed of 626 RPM. However, as the firing angle increases to 100°, the rotational speed also increases to 670 RPM. This demonstrates that under load conditions, the relationship between the firing angle and speed is direct, meaning that increasing the firing angle results in a higher motor speed.

Overall, these findings highlight the impact of the thyristor firing angle on DC shunt motor performance, providing valuable insights into speed regulation techniques. By carefully adjusting the firing angle, armature voltage, and armature current, the motor’s speed can be precisely controlled for different torque loads, making this method suitable for various industrial and automation applications.

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