

Performance Evaluation of Static Converter Drives in DC Shunt-Wound Motor Applications

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Abstract

This paper presents a detailed evaluation of how static converter drives perform when used with DC shunt-wound motors, focusing on their operation within the first quadrant. The research investigates how controlled full-wave rectifiers enable accurate regulation of speed and torque in forward motor operation. The experimental findings reveal that providing a positive voltage exceeding the motor's back electromotive force (EMF) is essential for sustaining a steady positive current flow. This condition enables efficient conversion of electrical energy into mechanical energy, which is essential in this operational mode. The analysis includes real-time data observations, waveform patterns, and the effects of controlling the phase angle on motor performance. The study suggests future research should explore control across all operational quadrants, advanced modulation techniques, and how these drive systems can integrate with renewable energy sources.

Key Words: *Direct Current Shunt-Wound Motor, Static Power Electronic Drives, Controlled Rectification, First Quadrant Operation, Motor Operating Modes, Unidirectional Power Flow*

1.0 Introduction

Direct Current Shunt-Wound Motor continues to be a fundamental element in various industrial and automation sectors, valued for their natural ability to control speed and their impressive efficiency traits. The use of static converters is essential in contemporary power electronics, allowing for the transformation of AC power into regulated DC power. Within this category, single-phase full-wave rectifiers are especially common due to their affordability and their compatibility with numerous low-power motor uses.

A full-wave rectifier operates by transforming an alternating current (AC) signal into a pulsating direct current (DC), which guarantees a constant flow of current in one direction. This one-way current flow is inherently compatible with the demands of first quadrant motor operation, where both voltage and current are positive, leading to unidirectional power transfer and consistent torque generation in DC shunt-wound motors. This research specifically focuses on experimental investigations within this first quadrant, signifying a critical operational zone suitable for applications demanding consistent, unidirectional power transfer.

This paper thoroughly examines the performance of a full-wave rectifier-based static converter in controlling DC shunt-wound motors. This investigation focus on achieving precise speed control through phase angle modulation, a key technique for regulating the output voltage of the rectifier and, consequently, the motor's speed and torque. Understanding the dynamics of these systems within the first quadrant is crucial for optimizing energy conversion and ensuring reliable motor performance in industrial settings.

2.0 Objectives

The primary aims of this study are as follows:

- i. To design and assemble a one-quadrant static converter circuit integrated with a DC shunt-wound motor.
- ii. To measure the circuit's output voltage and current using a multimeter, and to determine the motor speed by employing a tachometer.
- iii. To examine and analyze the operational characteristics of the DC motor within the first quadrant.

2.1 Relevance of the Study

This research is significant due to its comprehensive examination of static converter drives as applied to DC shunt-wound motors, specifically within the forward motoring (first quadrant) operational mode. It highlights how static converters enable precise speed regulation, stable torque attributes, and improved energy efficiency during standard forward operations. The knowledge derived from this investigation aids in optimizing drive performance and enhancing dependability in diverse industrial environments. Moreover, this inquiry lays the groundwork for future advancements in control methodologies, consequently boosting the efficiency of DC shunt-wound motors in applications requiring smooth and robust forward motion.

2.2 Related Research

Modern power electronics fundamentally relies on static converters, devices instrumental in the effective conversion of electrical energy across various forms, such as alternating current (AC) to direct current (DC) or vice versa, without requiring mechanical rotation. These adaptable circuits are indispensable across a broad spectrum of industrial and consumer applications, spanning from advanced power supplies and emerging renewable energy solutions to standard motor drive systems. In the voltage-current domain, first-quadrant operation is defined by both positive applied voltage and positive resulting current. This inherent characteristic guarantees a unidirectional power flow from the converter to the connected load.

The importance of static converters operating within the first quadrant is particularly evident when power transfer occurs exclusively from the source to the load. A prime illustration of this operational mode is observed in DC shunt-wound motor drive systems. In these setups, the static converter supplies a positive voltage to the motor's armature; when this voltage surpasses the motor's back electromotive force (EMF), a positive current begins to flow. This precisely regulated current ultimately facilitates efficient conversion of electrical energy into mechanical energy and ensures the desired forward rotation of the motor shaft. Sustaining consistent positive voltage and current during this operation is vital for predictable motor performance and effective energy transfer.

For optimal control and performance within a DC shunt-wound motor drive system, deliberate operation of the motor within the first quadrant (characterized by positive voltage and positive current) is indispensable. When the motor receives a positive voltage supply that consistently surpasses its internally generated back EMF ($V > E_b$), a regulated positive current (I_a) enters the armature winding. This current, acting in concert with the motor's magnetic field, produces the necessary electromagnetic torque to overcome both load and inertial forces, thereby enabling the motor to transform the electrical energy from the static converter into useful mechanical energy for driving an attached load. This foundational principle is crucial for the effective operational and control methodologies employed throughout numerous industrial applications.

Furthermore, continuous advancements in power semiconductor devices, including Insulated Gate Bipolar Transistors (IGBTs) and MOSFETs, have significantly enhanced the precision and efficiency of static converters, allowing for improved regulation of motor speed and torque parameters. The inherent advantages of static converters, such as their compact size, reduced maintenance requirements, and heightened reliability compared to rotating alternatives, solidify their position as the preferred choice for modern motor drive systems. This investigation aims to further examine these crucial interactions, specifically exploring how controlled modulation of the static converter, such as phase angle control, improves the operation of DC shunt-wound motors within this vital first quadrant of performance.

3.0 Methodology

This section describes the systematic processes employed to assess the operational attributes of static converter drives when coupled with a DC shunt-wound motor, particularly focusing on their behavior within the first quadrant. The methodology encompasses a description of the experimental configuration, the procedures for collecting data, and the analytical techniques applied to ascertain the system's efficiency and overall performance.

3.1 Test Bench Description

The experimental setup for the direct current (DC) system involved integrating a static converter with a shunt-wound motor. The basic construction of a shunt-wound motor consists of a stator housing the field (excitation) winding and a rotor (armature) equipped with armature windings and a commutator. In this configuration, the DC shunt-wound motor included supplementary windings for both commutation and magnetic field compensation. The armature current flows through these additional windings, which help correct distortions in the magnetic field caused by load variations. The motor was arranged as a separately excited type, connected to an independent voltage source that ensures the excitation current (IE) maintains a stable magnetic flux (Φ E).

Besides its function as a prime mover driving mechanical loads during motor operation, the DC shunt-wound motor can also act as a generator when mechanical energy drives it, allowing power flow back to the source. Moreover, it can rotate in both clockwise and counterclockwise directions.

This investigation focused on evaluating the behaviour of static converter drives coupled with a DC shunt-wound motor functioning within the first quadrant of operation, as illustrated in Figure 1. The system configuration comprised the DC shunt-wound motor, a static converter employing a full-wave controlled rectifier, a control circuit using pulse-width modulation (PWM) techniques to adjust the firing phase angle, and several measurement tools including digital multimeters, oscilloscopes, and tachometers.

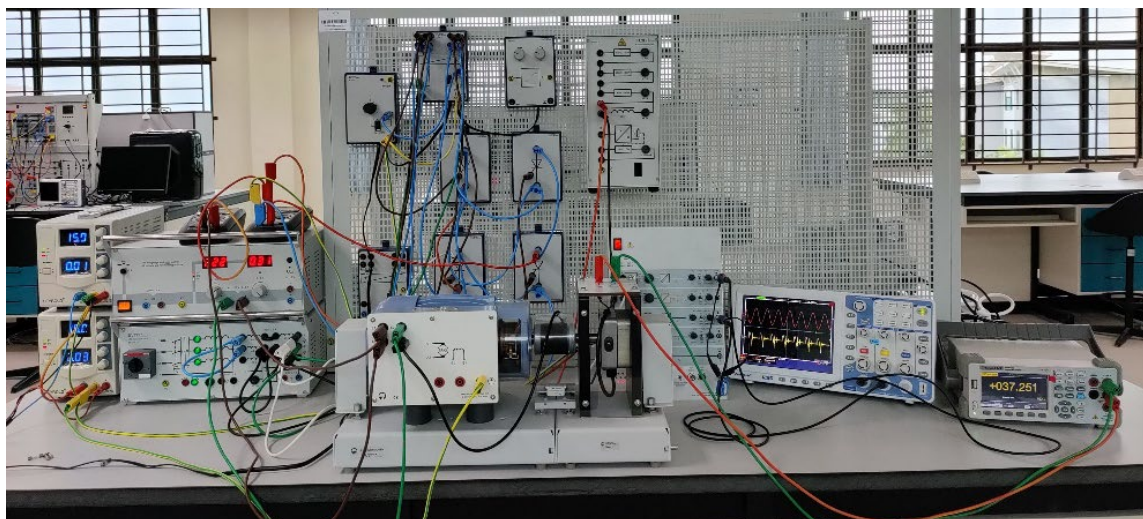


Figure 1: Experiment Setup for Static Converter Drives with DC Shunt-Wound Motor

Significantly, the DC shunt-wound motor's functioning was exclusively concentrated within the first quadrant. During this operational state, the delivered voltage is positive and exceeds the motor's back electromotive force (EMF), which induces a positive current to flow into the motor. As a result, the motor consumes electrical energy from the power source, converting it

into mechanical energy to drive the attached mechanical load. Given that both the current and voltage remain positive, the power produced is also positive. Furthermore, this quadrant is distinguished by positive speed and torque, prompting the motor to rotate in a forward direction

4.0 Analysis of Experimental Data

The information gathered was later processed to pinpoint several key characteristics:

- The observed voltage waveform within the DC shunt-wound motor.
- The controlled adjustment of the rectifier's stability limit, designated as αG .
- The determination of the operational mode.

The methodological approach previously described formed a structured basis for exploring static converter drives that operate DC shunt-wound motors within the first quadrant. The findings derived from this experimental investigation are set to be elaborated upon and scrutinized in the subsequent chapter.

5.0 Interpretation of Results

5.1 Motor Voltage Waveforms

The electrical schematic utilized for this experiment is presented in Figure 2. The generator's adjustable output spanned from 0 to +10V. A single full wave-controlled rectifier employed a phase angle (αG) that was varied between 0 and 180 degrees. An analysis of the resultant waveform showed the voltage generated by the motor armature overlaying the static converter's DC voltage. Upon activation of the thyristors at $\alpha G=90$ degrees, a clipped sinusoidal half-wave was supplied to the DC shunt-wound motor. Due to the intrinsic inductance within DC systems, the DC voltage gradually rose. The current achieved its peak magnitude precisely when the instantaneous value of the clipped sinusoidal half-wave corresponded with the induced voltage (U_0).

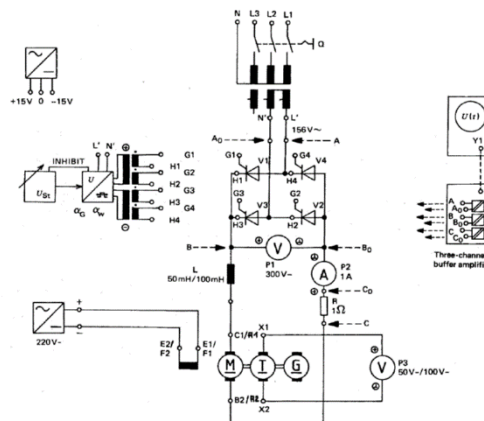


Figure 2: Electrical Schematic of Static Converter Drives Employing a DC Shunt-Wound Motor

If the thyristors remained in a conducting state, the motor's voltage was regulated by the AC voltage, which led to a subsequent gradual decline in current. Once the thyristors ceased conduction, the DC voltage once again climbed to the level of the motor's induced voltage. Further details on this phenomenon are illustrated in Figure 3

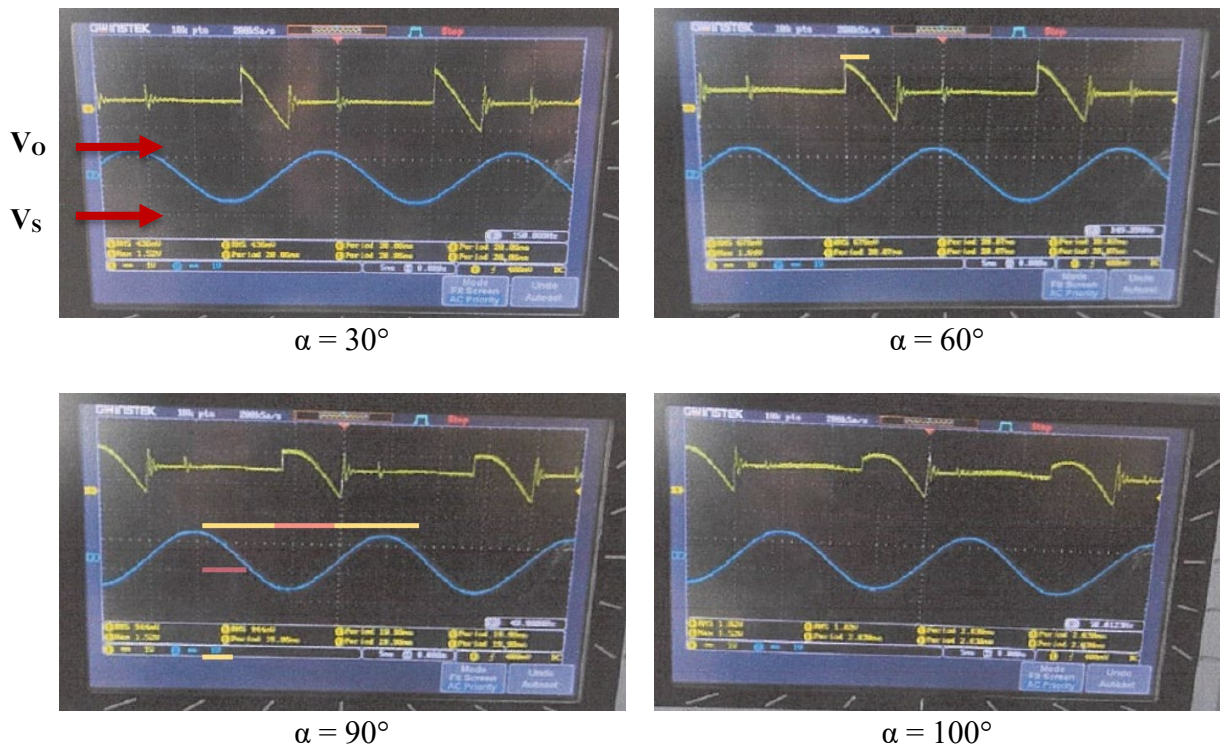


Figure 3: Observed Voltage Waveforms Across Varying Control Angles (α)

5.2 Rectifier Stability Limit Regulation

Within this portion of the experiment, the α_G angle underwent systematic modification, decreasing from 180 degrees to below 90 degrees through an increase in the control voltage (U_{ST}). The highest permissible control voltage for U_{ST} was +10V. The rectifier's stability limit, managed by α_G , was incrementally rotated in a clockwise direction until distinct changes in the current and voltage responses became observable, as detailed in Table 1

Table 1: Outcomes of Rectifier Stability Limit Adjustment

$\alpha_G = 60^\circ$

Lower limit:	$\alpha = 60^\circ$	Corresponding to U_{ST}	+10V
Upper limit:	$\alpha = 180^\circ$	Corresponding to U_{ST}	0V

As indicated by the data in Table 1, thyristors could be triggered when the instantaneous AC voltage surpassed the motor's induced voltage, making the anode potential positive relative to the cathode. Conversely, if the instantaneous AC voltage was equal to or below the induced voltage, the anode's potential was either equal to or negative compared to the cathode, preventing thyristor activation and thus blocking current flow. Consequently, the motor's rotational frequency diminished, resulting in a corresponding reduction in the induced voltage. This condition led to erratic operation of the static converter, manifesting in elevated current levels during periods of current flow. A significant benefit of the static converter, stemming from the revised rectifier stability limit adjustment, is its capacity for operation across the full control range from 0V to +10V, without adverse effects from feedback interference originating in the DC systems.

5.3 Operating Mode Characterization

Experimental setups were configured to vary the DC voltage (U_d) in accordance with Table 2, and the direct current (I_d) along with the tachometer generator voltage (U_{TG}) were recorded.

To obtain the motor's rotational frequency (n), Equation [1] was applied:

$$n = k \cdot U_{TG} \text{ where } k = 33.3 \frac{1}{\text{min.V}} \quad [1]$$

Table 2: Measured Current, Voltage, and Speed Data

U_d in V	0	40	80	120	160
I_d in mA	0	400	450	480	490
U_{TG} in V	0	13.5	27	41.5	56
n in $\frac{1}{\text{min}}$	0	450	900	1380	1860

From Table 2, it is evident that an increase in DC voltage (U_d) corresponds to an increase in motor speed. Both the direct current (I_d) and the tachometer generator voltage (U_{TG}) showed slight increases as U_d rose, influencing the rotational frequency (n) of the motor. Figure 4 visually represents the relationship of U_{TG} (V) versus $n(\text{min}^{-1})$, illustrating the direct proportionality between the tachometer generator voltage and motor speed; as speed increases, so does U_{TG} (V). Furthermore, Table 3 provides a summary of the characteristics for the various operating modes observed during the experiment.

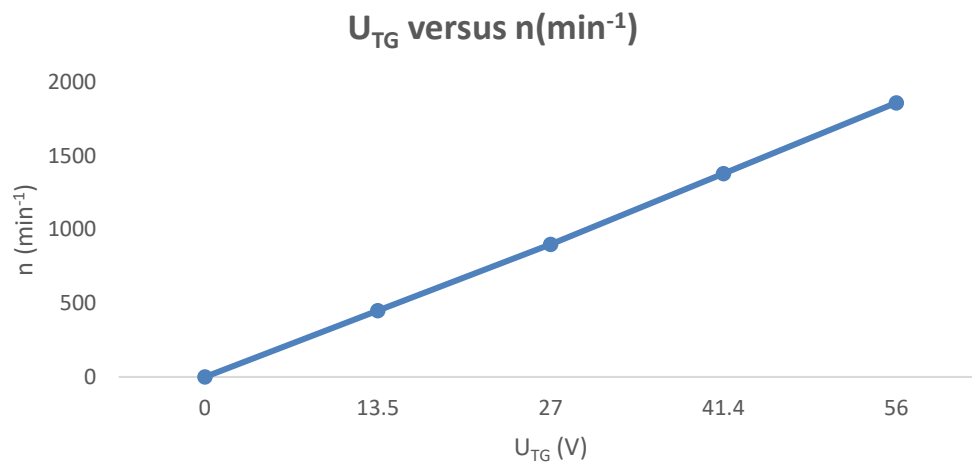


Figure 4: Relationship Between Tachometer Generator Voltage (U_{TG}) and Motor Rotational Frequency (n)

Figure 5 illustrates the operating schematic of a static converter drive derived from this experimental study, aligning with the described features of the different operating modes. In summary, the static converter drive primarily operates within the first quadrant when used with a DC shunt-wound motor.

Table 3: Key Characteristics of Operating Modes

Modes	Key Characteristics of Operating Modes
Clockwise rotation – Anticlockwise rotation	Clockwise rotation: both the tachometer generator voltage and the motor's rotational frequency register as positive.
Motor operation – Generator operation	Motor operation: Voltage, U_d and current I_d are positive, electric power is consumed by the motor
Driving - Braking	Driving: Mechanical power is provided by the motor.
Rectifier operation – Inverter operation	Rectifier operation: energy transfer occurs from the alternating-current system to the direct-current system.

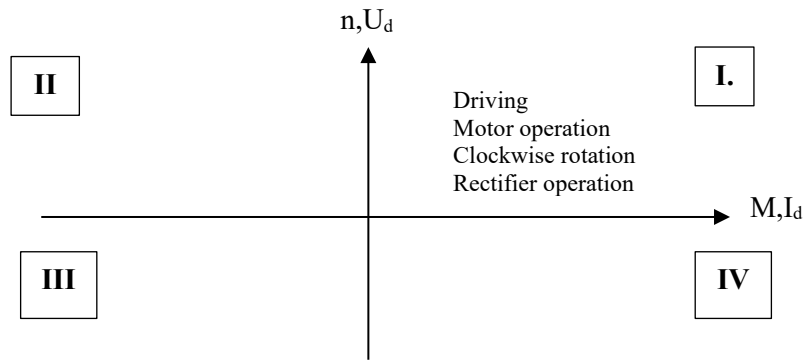


Figure 5: Operational Diagram of the Static Converter Drive System

6.0 Conclusion and Future Work

This study provided an in-depth evaluation of the performance and operational characteristics of static converter drives when paired with DC shunt-wound motors. The results indicate that these drives offer precise and efficient control of motor speed and torque, making them well-suited for various industrial applications where consistent operation is essential. Key benefits of using static converters include improved energy efficiency, smoother speed regulation, and overall better motor responsiveness compared to traditional drive methods. Nevertheless, challenges such as harmonic distortion and thermal management require careful consideration during the design and implementation of these systems.

Looking ahead, future research should focus on enhancing static converter drives to function effectively across all four quadrants of operation—covering forward and reverse motoring, as well as forward and reverse braking. Advances in control strategies, particularly through enhanced Pulse Width Modulation (PWM) techniques, could further boost system performance, while improved filtering methods may help reduce unwanted electrical noise and distortion. Moreover, addressing thermal management issues and exploring the integration of these drive systems with renewable energy sources like solar and wind power could increase their sustainability and applicability. Conducting practical case studies in sectors such as manufacturing and automation will also be valuable for refining and optimizing these technologies in real-world environments.

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