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HARDWARE IMPLEMENTATION OF A DC MOTOR SPEED, DIRECTION CONTROL&REGENERATIVE BRAKING

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***Abstract*— Direct Current (DC) motors are extensively used in applications such as electric vehicles, industrial systems, and robotics due to their simple speed control and reliable performance. This project focuses on the design and implementation of a DC motor control system capable of regulating speed, changing direction, and incorporating regenerative braking. A potentiometer is used to vary the input voltage for speed control, while an L298N motor driver enables bidirectional operation of the motor. The proposed system also implements regenerative braking, where the kinetic energy of the motor during deceleration is converted into electrical energy instead of being dissipated as heat. The recovered energy can be utilized to power auxiliary loads or stored for future use, thereby improving overall system efficiency. The developed system is simple, cost-effective, and suitable for educational and experimental applications, providing a practical understanding of motor control and energy recovery techniques.**

***Index Terms* — DC motor, speed control, direction control, regenerative braking, L298N driver, energy recovery, embedded system.**

I. INTRODUCTION

Control of speed and direction is a fundamental requirement in DC motor-based systems used across various engineering applications. Speed control enables the motor to operate at different levels depending on system requirements, while direction control allows rotation in both forward and reverse directions. In this project, motor speed is regulated using a potentiometer, which varies the input voltage supplied to the motor. The direction of rotation is controlled using an L298N motor driver module by changing the polarity of the applied voltage.

In addition to basic motor control, this project incorporates the concept of regenerative braking. In conventional braking systems, the kinetic energy of a rotating motor is dissipated as heat, resulting in energy loss. Regenerative braking overcomes this limitation by allowing the motor to act as a generator during deceleration, converting mechanical energy into electrical energy. This recovered energy can be reused or stored, thereby improving system efficiency and reducing energy wastage.

The increasing advancement of technology has led to a growing demand for efficient and reliable motor control systems in applications such as electric vehicles, robotics, industrial automation, and household equipment. DC motors are widely used in these applications due to their simple construction, high starting torque, and ease of control. Therefore, understanding DC motor speed and direction control is essential for modern engineering systems.

Another key motivation for this work is the need for energy conservation. In conventional motor systems, a significant portion of energy is lost as heat during braking. Regenerative braking provides an effective solution by converting mechanical energy into electrical energy, which can be reused. This concept is widely adopted in electric vehicles and advanced motor drive systems, making it an important area of study.

Early research on DC motor control primarily focused on simple voltage regulation techniques to control motor speed. Chen and Bhattacharya (2016) highlighted the importance of microcontroller-based control and power electronic circuits for stable motor operation. Later, Khan et al. (2017) introduced Pulse Width Modulation (PWM) techniques, which enable efficient speed control while reducing power losses.

Further developments by Rana et al. (2018) demonstrated the use of H-bridge circuits for controlling both speed and direction of DC motors. Around the same time, Kumar and Singh (2018) explored regenerative braking and explained how motors can operate as generators during braking to recover energy.

Subsequent studies focused on improving performance and efficiency. Patel and Shah (2019) developed enhanced motor control systems using power electronic converters, while Sharma et al. (2019) emphasized the benefits of regenerative braking in electric vehicles. Verma and Gupta (2020) introduced advanced PWM-based control methods for improved accuracy, and Li et al. (2020) worked on optimizing energy recovery in regenerative braking systems.

Recent research has explored advanced control strategies and intelligent techniques. Ahmed and Khan (2021) improved motor driver circuits for better direction control, while Wang et al. (2021) investigated intelligent algorithms to enhance motor efficiency and braking performance. Chaithanakulwat et al. (2021) proposed a four-quadrant DC motor drive using a PI controller, achieving precise speed regulation, although regenerative braking was not extensively addressed.

Further studies by Singh and Patel (2022) focused on integrating regenerative braking with motor control systems to reduce energy loss. Zhang et al. (2023) introduced digital control techniques for improved stability and accuracy. More recent works by Kumar et al. (2024) and Santhosh et al. (2024) developed advanced drive systems incorporating closed-loop control and sensors, improving overall performance, though regenerative braking analysis was limited in some cases.

Abdelfatah et al. (2025) proposed a four-quadrant chopper-based DC motor drive system for electric vehicle applications, emphasizing regenerative braking and energy recovery using PWM techniques. Their results demonstrated improved efficiency, although detailed monitoring mechanisms were limited.

From the literature, it is evident that significant progress has been made in DC motor control and regenerative braking technologies. The integration of speed control, direction control, and energy recovery plays a crucial role in enhancing system efficiency and performance. Therefore, this project focuses on implementing these concepts using simple components such as a potentiometer, L298N motor driver, and DC motor to develop an effective and practical motor control system with regenerative braking capability.

II. Speed And Direction Control of DC Motor.

DC motor control mainly involves regulating speed and direction. Speed control is achieved by adjusting the input voltage, commonly using methods like armature voltage control and Pulse Width Modulation (PWM), where the duty cycle determines the motor speed. Direction control is based on reversing the polarity of the applied voltage, which can be effectively implemented using an H-bridge circuit.

These control techniques are widely used in practical applications such as robotics, electric vehicles, and industrial automation, where precise and efficient motor operation is essential.

A. Speed Control of DC Motor:

Speed control of a DC motor is essential for ensuring efficient and flexible operation in various applications such as electric vehicles, robotics, and industrial machinery. The speed of a DC motor mainly depends on the applied voltage, armature resistance, and magnetic flux. By controlling these parameters, the motor speed can be varied according to load requirements.

In this project, speed control is achieved using a potentiometer and an L298N motor driver. The potentiometer provides a variable voltage signal, and the motor driver regulates the power supplied to the motor, enabling smooth speed variation.

Different methods of speed control include armature voltage control, armature resistance control, and field flux control. Among these, armature voltage control is widely used due to its high efficiency and smooth operation, while armature resistance control is less efficient due to power losses. Field flux control is useful for achieving higher speeds but has a limited control range.

The L298N motor driver plays an important role by supplying sufficient current, controlling speed and direction, and protecting the circuit. Overall, DC motor speed control improves system efficiency, reduces energy loss, ensures smooth operation, and enhances the performance and lifespan of the motor.

B. Direction Control of DC Motor:

Direction control of a DC motor is essential for applications that require both forward and reverse motion, such as robotics, electric vehicles, and industrial systems. The direction of rotation depends on the direction of current flowing through the armature. When the current is reversed, the motor rotates in the opposite direction, which is explained by Fleming's Left-Hand Rule.

The simplest method of direction control is reversing the polarity of the supply voltage. A more efficient and commonly used method is the H-bridge circuit is shown in Fig.1. which allows safe and electronic control of current direction using switching devices.

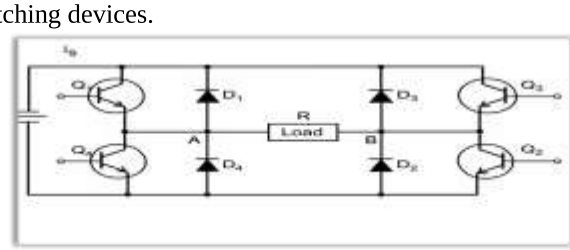

Fig.1. H-Bridge Method

In this project, direction control is implemented using an L298N motor driver, which contains an internal H-bridge circuit. By applying different logic signals to its input pins, the motor can rotate forward, reverse, or stop.

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Overall, direction control provides flexibility, improves system performance, and is widely used in modern applications where bidirectional motor operation is required.

III. Regenerative Braking System

Regenerative braking is an advanced technique used to improve energy efficiency by converting the kinetic energy of a motor into electrical energy during braking. Unlike conventional braking, where energy is lost as heat, regenerative braking allows the motor to operate as a generator and feed energy back into the system. This reduces energy consumption, improves efficiency, and minimizes mechanical wear is shown in Fig.2.

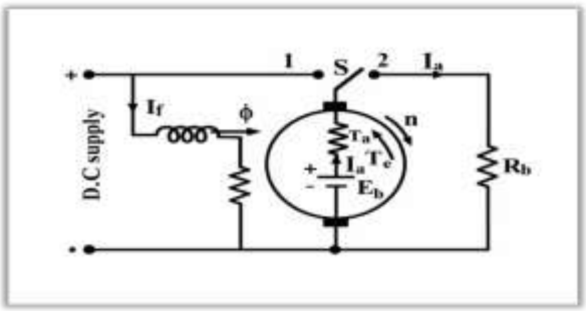

Fig.2. Regenerative Braking

In this project, regenerative braking is implemented using an Arduino, L298N motor driver, potentiometer, and DC motor. During normal operation, the motor runs using PWM control. When braking is applied, the motor switches to generator mode, and the generated energy is redirected back into the circuit, resulting in smooth and controlled deceleration.

The concept of four-quadrant operation explains how a DC motor can operate in different modes based on the direction of voltage and current is shown in Fig 3. The four quadrants include forward motoring, forward regenerative braking, reverse motoring, and reverse regenerative braking. This enables complete control over motor speed, direction, and braking in both forward and reverse directions.

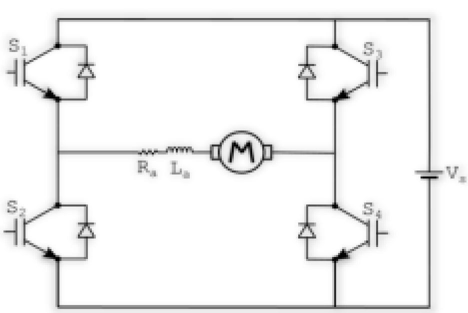

Fig.3. Four-quadrant chopper schematic diagram

Overall, regenerative braking combined with four-quadrant operation enhances system performance, improves energy utilization, reduces losses, and is widely used in applications such as electric vehicles, industrial drives, and automation systems.

IV. Hardware Implementation

This project, focuses on advanced speed control of DC motors using a four-quadrant chopper combined with regenerative braking.The block diagram in Fig.4 illustrates an Arduino-based DC motor control system. At the core of the system is the Arduino microcontroller, which serves as the central processing unit. It receives input from various components such as switches, a potentiometer, a voltage sensor, and a current sensor, enabling it to monitor and adjust the motor's operation

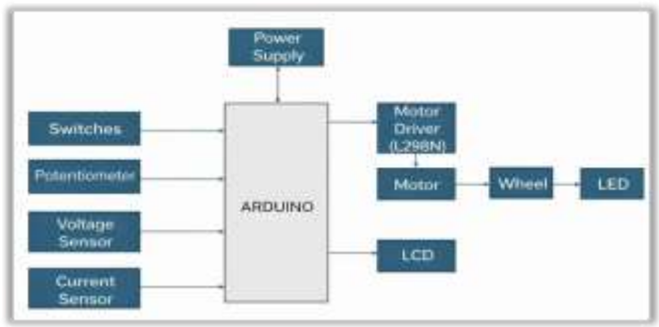

Fig.4. Block Diagram of the Proposed Prototype

A dedicated power supply ensures stable functioning of the controller and peripherals. On the output side, the Arduino communicates with an L298N motor driver that powers the motor, which in turn drives a wheel. Additional outputs include an LED for status indication and an LCD display for real-time feedback of system parameters. Together, these elements form an integrated control system that allows precise monitoring and regulation of motor performance. The system is developed using the following components.

A. *Arduino Uno:*

The Arduino Uno is a widely used microcontroller board based on the ATmega328P microcontroller, as shown in Fig. 5. It is commonly used in embedded systems and automation applications due to its simplicity and versatility.

The Arduino Uno can read input signals from sensors and providing output control to devices such as motors, displays, and relays. It processes the input data and executes programmed instructions to control connected components effectively, making it suitable for real-time control applications.

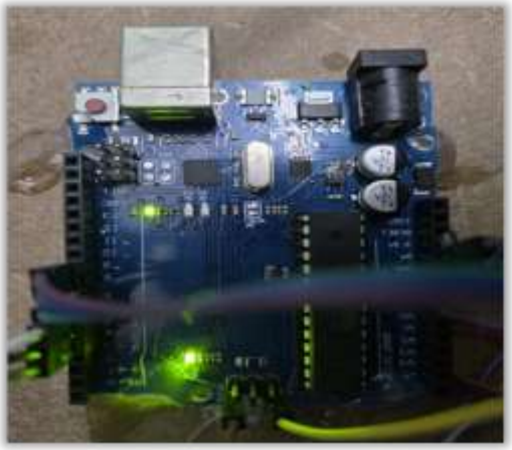

Fig.5 Arduino UNO

Specifications:

- Microcontroller: ATmega328P
- Operating Voltage: 5V
- Input Voltage (Recommended): 7–12V
- Digital I/O Pins: 14 (including 6 PWM outputs)
- Analog Input Pins: 6
- Clock Speed: 16 MHz

B. Motor Driver(L298N):

The L298N motor driver module, as shown in Fig. 6, is a high-power motor driver used for controlling the speed and direction of DC motors. It acts as an interface between the microcontroller and the motor, enabling safe and efficient operation.

The module contains a dual H-bridge circuit, which allows control of two DC motors or a single motor with bidirectional rotation. It enables the microcontroller to drive motors that require higher voltage and current than it can supply directly. The L298N receives control signals from the microcontroller and accordingly regulates the current flow through the motor to control its speed and direction.

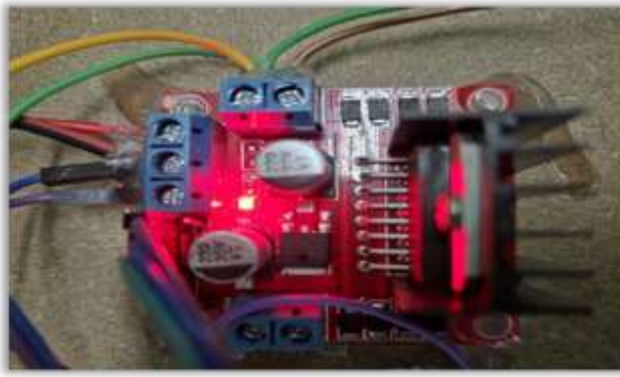

Fig.6 L298N Motor Driver

Specifications:

- Operating Voltage: 5–35V
- Maximum Peak Current: 2A per channel (up to 4A total)
- Continuous Current: 2A per channel
- Logic Voltage: 5V
- Built-in 5V Regulator

C. DC Motor:

A DC Motor converts electrical energy into mechanical energy. It is commonly used in robotics and automation systems to create rotational movement. In this project, the DC motor's are used to provide motion for the mechanical system as shown in Fig.7.

Fig.7 DC Motor

Specifications:

- Operating Voltage: 6–12V
- Rated Speed: 2000–5000 RPM
- Continuous Current: 1–2A

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- Torque: 0.5–1 kg/cm

D. Voltage Sensor:

The 0–25V Voltage Sensor Module shown in Fig.8 is used to measure voltage levels in the circuit. It converts higher voltage signals into a safe analog voltage that can be read by the Arduino.

Fig.8 Voltage Sensor

Specifications:

- Voltage Range: 0–25V
- Analog Output: 0–5V

Compatible with Arduino analog input.

E. Switches:

A Push Button Switch is a simple input device used to control the system manually as shown in Fig.9. When pressed, it completes the circuit and sends a signal to the microcontroller.

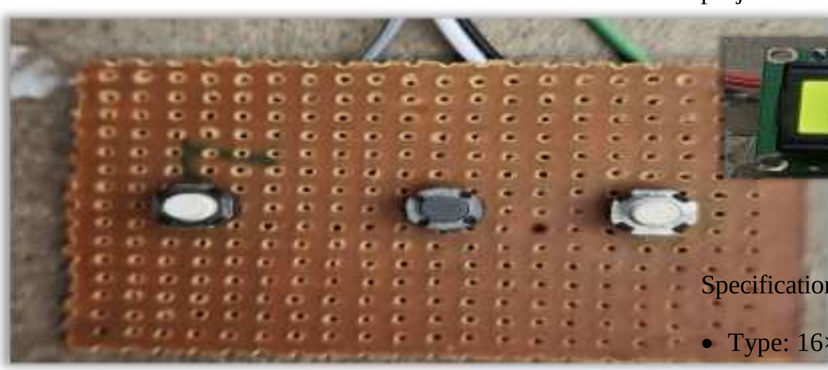

Fig.9 Switches

Specifications:

Operating Voltage: 5V

Compact and easy to interface

Switches

F. Potentiometer:

The Rotary Potentiometer shown in Fig.10 is a variable resistor used to adjust voltage levels manually. It is often used for controlling parameters like speed, brightness, or contrast.

Fig.10 Potentiometer

Specifications:

Type: Rotary Potentiometer

Adjustable Output: 0–5V Used for analog input control

G. 16×2 LCD display:

The 16x2 LCD Display Module is used to display information such as voltage, current, and system status. It can show 16 characters in 2 rows and is widely used in microcontroller projects for user interface as shown in Fig.11.

Fig.11 16*2 LCD Display

Specifications:

- Type: 16×2 Alphanumeric
- LCD Interface: Parallel (HD44780 controller)
- Operating Voltage: 5V
- Backlight: Green/Blue with adjustable contrast

V. HARDWARE SETUP

The practical hardware implementation of the DC motor system, as shown in Fig. 12, is designed to control speed and direction along with regenerative braking. The entire setup is built around an Arduino microcontroller, which is mounted on a wooden base and interconnected with various components using jumper wires.

A motor driver module (L298N) is used to interface the Arduino with a DC motor connected to a wheel, enabling controlled rotation and braking. A breadboard is utilized to assemble resistors and supporting circuitry for proper signal conditioning and connections. An LCD display is incorporated to show real-time parameters such as motor speed or system status.

Additionally, a mechanical arrangement consisting of a metallic arm structure supports another motor and wheel assembly, which acts as a load. This setup demonstrates the interaction between electrical control, sensing, and mechanical motion. The overall system effectively illustrates precise motor control and energy recovery through regenerative braking.

Circuit Connections

1) Arduino to L298N Motor Driver:

- PWM pin (e.g., D5/D6) → ENA pin (controls motor speed using PWM)
- Digital pins D7 and D8 → IN1 and IN2 (controls motor direction)
- 5V and GND → Logic power supply of L298N

2) L298N to Main DC Motor:

- OUT1 and OUT2 → Motor terminals
- 12V input → External power supply

3)Potentiometer to Arduino:

- Middle pin (wiper) → A0 (analog input for speed control)
- Outer pins → 5V and GND

4)LCD to Arduino:

- Connected using either 4-bit parallel interface or I2C module
- VSS and VDD → GND and 5V
- RS, EN, D4–D7 → Arduino digital pins

Regenerative Braking Setup

- A secondary DC motor is used as a generator
- During deceleration, back EMF is generated and captured
- The generated energy is fed back through flyback diodes in the L298N module or through a rectifier circuit

This hardware setup demonstrates the integration of microcontroller-based control, power electronics, and mechanical systems to achieve efficient DC motor operation with speed control, direction control, and regenerative braking.

Fig.12 Hardware Setup

VI. RESULTS AND DISCUSSION

The hardware implementation for DC motor speed, direction control and regenerative braking was successfully designed and tested. The system performance was evaluated under different operating conditions.

Speed Control Results:

The speed of the DC motor was regulated by using the PWM technique. By controlling the duty cycle from 10% to 100%, the speed of the motor was increased in proportion. Smooth and steady speed changes were observed without any fluctuations. Table I and II represent the relationship between speed percentage and the average voltage applied to the DC motor in both forward and reverse directions. It is observed that as the speed percentage increases, the applied average voltage also increases gradually.

TABLE I
PERFORMANCE OF SPEED AND VOLTAGE UNDER FORWARD MOTORING

S.No	Speed %	Average Voltage (V)
1.	25	7

2.	40	8.5
3.	60	9.5
4.	80	10
5.	90	11.21

TABLE II
PERFORMANCE OF SPEED AND VOLTAGE UNDER REVERSE MOTORING

S.No	Speed %	Average Voltage(Volts)
1.	25	7
2.	40	8
3.	60	9
4.	80	9.5
5.	90	11.30

At lower speeds (25%), the voltage is approximately 7V, indicating minimal power input. As the speed increases, the voltage rises gradually, confirming effective control. Minor variations between forward and reverse voltages are due to practical factors such as switching losses and internal resistance.

Overall, the results show that motor speed is directly proportional to the applied voltage.

Regenerative Braking Results:

During braking, the motor operated in generator mode and fed energy back into the system. A reduction in speed along with measurable voltage at the supply terminals was observed.

Voltage generated during braking ≈ 2V – 5V (depending on speed). Motor deceleration was faster compared to normal stopping. During regenerative braking, the motor acts as a generator and feeds energy back to the supply. The regenerative braking Table III and IV shows the behavior of the motor when braking is applied in both forward and reverse directions.

TABLE III
PERFORMANCE OF SPEED AND VOLTAGE UNDER FORWARD BRAKING

SPEED IN %	VOLTAGE(V)	LED STATUS
BEFORE 85	11	LED DOES NOT GLOW
AFTER 87	11.18	LED FLICKERS
AFTER 90	11.21	LED GLOWS

TABLE IV
PERFORMANCE OF SPEED AND VOLTAGE UNDER REVERSE BRAKING

SPEED IN %	VOLTAGE(V)	LED STATUS
BEFORE 83	11.08	LED DOES NOT GLOW
AFTER 87	11.11	LED FLICKERS
AFTER 90	11.30	LED GLOWS

Similarly, in reverse direction, below 83% speed, the voltage is around 11.08V and no LED glow is observed. After 87%, the voltage increases slightly and the LED glows dimly. At 90%, the voltage reaches around 11.30V and the LED glows brightly, confirming efficient energy regeneration.

These observations clearly indicate that regenerative braking becomes more effective at higher speeds, as more kinetic energy is converted back into electrical energy.

Performance Analysis:

In order to better understand the performance of the DC motor under different operating conditions, graphical analysis is carried out. The experimental readings obtained during speed control, direction control, and regenerative braking are represented using graphs. The graph titled Speed vs Average Voltage in Fig.13 shows the variation of average voltage with respect to speed percentage for both forward and reverse motoring conditions.

From the graph, it is observed that as the speed increases from 25% to 90%, the average voltage also increases in a nearly linear manner for both forward and reverse directions. In forward motoring, the voltage increases from 7V to approximately 11.21V, while in reverse motoring it increases from 7V to around 11.30V.

The forward motoring curve is slightly higher than the reverse motoring curve at intermediate speeds (40% to 80%), which indicates minor system losses and asymmetry in switching or circuit components. However, at higher speeds (around 90%), both curves converge, showing similar voltage values and stable motor performance.

This graph clearly demonstrates that motor speed is directly proportional to the applied average voltage, confirming effective speed control using voltage variation.

The Forward Regenerative Braking graph in Fig.14 represents the variation of generated voltage during braking in the forward direction. It is observed that at 85% speed, the voltage is around 11V, indicating low energy recovery. As the speed increases to 87%, the voltage rises to approximately 11.18V, showing the beginning of regenerative action. At 90% speed, the voltage further increases to around 11.21V, indicating efficient energy regeneration.

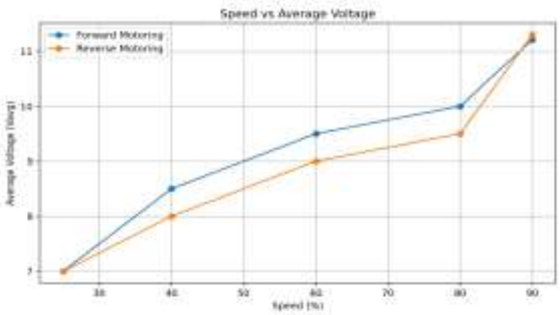

Fig. 13 Graphical Representation of Forward & Reverse Motoring

The gradual increase in voltage with speed shows that higher kinetic energy at higher speeds results in greater energy conversion back into electrical form. This confirms that regenerative braking is more effective at higher speeds in forward direction.

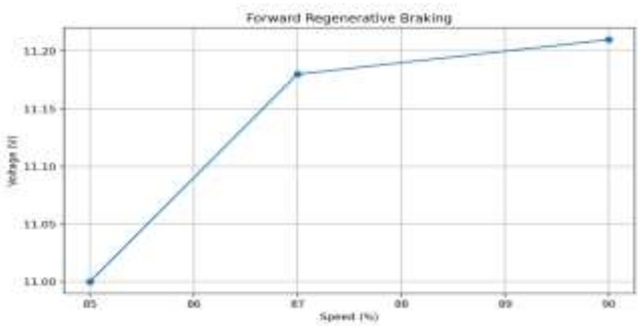

Fig.14 Graphical Representation of Forward Regenerative Braking

The Reverse Regenerative Braking graph in Fig.15 shows a similar trend in the reverse direction. At 83% speed, the voltage is about 11.05V, indicating minimal regeneration. As the speed increases to 87%, the voltage slightly increases to around 11.11V. At 90% speed, the voltage reaches approximately 11.30V, which represents maximum energy recovery. Compared to forward braking, the reverse braking shows a slightly higher voltage at maximum speed. This may be due to variations in load conditions or changing characteristics of the circuit**.**

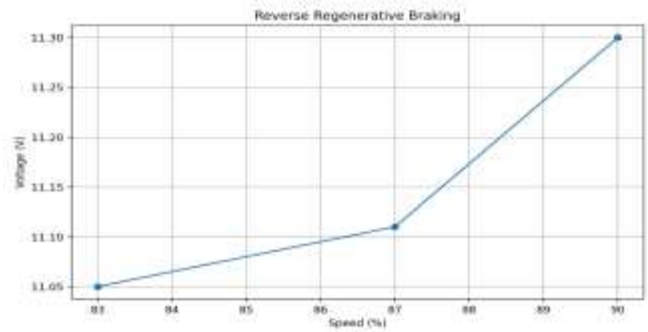

Fig.15 Graphical Representation of Reverse Regenerative Braking

VII. CONCLUSION

The hardware implementation of DC motor speed control, direction control, and regenerative braking has been successfully designed and developed. The primary objective of this project was to achieve efficient control of motor speed and direction while incorporating a regenerative braking mechanism to enhance energy utilization.

The developed system effectively controls motor speed using suitable control techniques, and the direction of rotation can be easily changed as per requirements. The integration of the motor driver and control circuitry ensures smooth operation and reliable performance under different conditions.

A key highlight of this project is the implementation of regenerative braking. Unlike conventional braking methods, where energy is lost as heat, the proposed system converts the motor's kinetic energy into electrical energy during braking. This recovered energy can be reused, thereby improving overall system efficiency and reducing energy losses.

The experimental results confirm that the motor operates smoothly with accurate speed control and quick directional response. The regenerative braking mechanism also demonstrates effective energy recovery, especially at higher speeds.

Overall, the system provides a simple, efficient, and cost-effective solution for DC motor control. The concepts implemented in this project have wide applications in electric vehicles, robotics, industrial automation, and other motor-driven systems, where efficiency and energy conservation are important.

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