International Journal of Academic and Applied Research (IJAAR)
ISSN: 2643-9603
Vol. 9 Issue 12 December - 2025, Pages: 291-298

A PLC-Based DC Motor Speed Control System Using Model Reference Adaptive Control Schemes (MRACS)

Oyindinipre Bioko1, Damfebo Franklin Ayebagbalinyo2, Jenny Ebitonere Fawei3, Inanumo Emmanuel 4

1Department of Electrical and Electronic Engineering, Faculty of Engineering, Niger Delta University, Amassoma, Wilberforce Island, Bayelsa State, Nigeria.
oyins.bioko@ndu.edu.ng

2Department of Electrical and Electronic Engineering, Faculty of Engineering, Niger Delta University, Amassoma, Wilberforce Island, Bayelsa State, Nigeria.
damfebofranklin@ndu.edu.ng

3Department of Electrical and Electronic Engineering, Faculty of Engineering, Niger Delta University, Amassoma, Wilberforce Island, Bayelsa State, Nigeria.
faweijenny@ndu.edu.ng

4Department of Electrical and Electronic Engineering, Faculty of Engineering, Niger Delta University, Amassoma, Wilberforce Island, Bayelsa State, Nigeria.
bennicy92@gmail.com

***Abstract**: This paper presents the design and implementation of a programmable logic controller (PLC)-based DC motor speed control system using a Model Reference Adaptive Control Scheme (MRACS). DC motors are widely used in industrial applications due to their simplicity and high torque characteristics; however, achieving precise speed regulation under varying load conditions remains a significant challenge for conventional fixed-gain controllers. The primary problem addressed in this study is the degradation of control performance caused by parameter variations and external disturbances when using traditional PID-based PLC controllers. The objective of the research is to develop a robust, adaptive control strategy that can be practically implemented on an industrial PLC to ensure accurate and stable speed control. The proposed method employs MRACS, in which a reference model defines the desired dynamic response while adaptive laws continuously adjust controller parameters in real time. The system was modeled mathematically, implemented on a PLC platform, and evaluated through simulation and experimental analysis. Results demonstrate fast rise time, zero overshoot, negligible steady-state error, and rapid recovery from load disturbances. The study concludes that PLC-based MRACS offers a reliable and effective solution for real-time industrial DC motor speed control.*

Keywords—component; DC motor, PLC, adaptive control, MRACS, speed control.

1. INTRODUCTION

DC motors have remained essential in industry and automated systems due to their numerous advantages, including high starting torque, a wide range of operation, a linear relationship between torque and current, and ease of control [1], [2]. Nonetheless, the increasing use of other motor technologies, such as AC motors, has not reduced their significance in various applications requiring efficient control functions. DC motors have continued to retain their relevance despite the growing adoption of brushless motor technologies, particularly in applications demanding precise speed and torque regulation [3]. They are also widely used in conveyor systems, rolling mills, electric traction systems, robotic manipulator systems, automated manufacturing systems, and laboratory-scale test rigs [4], [5]. In these applications, the ability to maintain controlled speed is critically important for the effectiveness of the process. This is because speed regulation directly influences product quality, mechanical coordination, and operational efficiency in industrial environments

The efficiency of a DC motor-driven system relies largely on the functionality of the speed control system employed. A system with high accuracy in speed regulation enables smooth material handling, reduced vibration, improved mechanical performance, and minimized stress on system components, all of which are essential requirements in modern industrial automation [7]. However, achieving and sustaining precise speed control in real-world applications is complex due to the dynamic nature of industrial operations. DC motors are frequently subjected to variations in load torque caused by fluctuating production demands, mechanical dynamics, friction, and environmental uncertainties [8]. These disturbances significantly affect the system's dynamic response and stability.

The electrical and mechanical parameters of DC motors are directly influenced by load variations. Changes in load torque led to variations in armature current demand, while prolonged operation results in thermal effects that alter armature resistance [9]. Additionally, component aging and supply voltage fluctuations further complicate accurate speed regulation over extended operational periods [10].

To address these challenges, conventional control methods such as Proportional–Integral–Derivative (PID) controllers have been widely employed. PID controllers are extensively used in motor control systems due to their simple structure, ease of implementation, and availability of established tuning techniques [11]. The PID speed control system is illustrated in Figure 1 as follows:

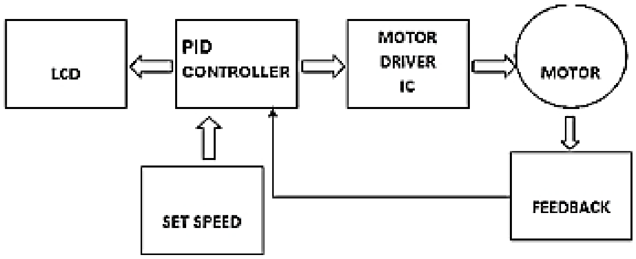

Figure 1: Speed Control of DC motor using PID Method

PLC-based motor control systems favor PID controllers because of their compatibility with industrial automation infrastructures. PLCs offer high reliability, support for standard industrial communication protocols, and real-time processing capabilities, making them suitable for closed-loop motor control applications [12]. Consequently, PID-based speed control of DC motors using PLCs has become well established in industrial practice. Despite their widespread use, fixed-gain PID controllers exhibit limitations when dealing with systems experiencing parameter variations and external disturbances. The controller gains are typically tuned for a specific operating point, and deviations due to load changes, temperature effects, or supply variations often result in degraded transient and steady-state performance [13].

In practical applications, the performance of fixed-gain controllers deteriorates in the form of increased overshoot, longer settling times, and persistent steady-state errors in motor speed [14]. Compensating for these effects generally requires manual retuning of controller parameters, which often necessitates system downtime and reduces overall productivity, leading to the development of adaptive control strategies capable of automatically adjusting controller parameters in real time. Adaptive control systems are designed to handle uncertainties and time-varying characteristics by continuously modifying control parameters to maintain desired performance [15].

Several adaptive control approaches have been proposed, including self-tuning regulators, gain scheduling techniques, fuzzy adaptive controllers, and neural network-based controllers [16], [17]. While these methods demonstrate improved performance under varying conditions, their practical implementation is often hindered by computational complexity, tuning difficulty, and lack of transparency

Industrial control systems require solutions that are transparent, predictable, and easy to maintain. Many intelligent adaptive control schemes lack clearly defined optimal design procedures, limiting their adoption in industrial environments. This creates a strong need for adaptive control methods that balance theoretical robustness with practical implementable.

Model Reference Adaptive Control Schemes (MRACS) have emerged as a promising solution that addresses these requirements and have attracted significant attention in recent control system research. In MRACS, the desired closed-loop behavior is specified through a reference model, and the controller is designed to force the actual system output to follow this model. MRACS continuously adjusts controller parameters based on the error between the plant output and the reference model output. The adaptation law is commonly derived using Lyapunov stability theory, ensuring closed-loop stability under defined conditions [18]. This theoretical guarantee makes MRACS particularly attractive for safety-critical and industrial applications.

The application of MRACS to DC motor speed control offers advantages such as fast transient response, improved steady-state accuracy, and enhanced resilience against parameter variations. By enforcing model-following behavior, stable performance is maintained even when motor parameters deviate from nominal values.

The primary objective of this research is to develop and validate a PLC-based DC motor speed control system using a Model Reference Adaptive Control Scheme. This is achieved by developing an accurate mathematical model of the DC motor, designing a stable MRACS controller, implementing the MRACS algorithm on a PLC, and comparing its performance with conventional control methods.

2. LITERATURE REVIEW

2.1 Adaptive and Intelligent Control Techniques for DC Motor Speed Regulation

Adaptive and intelligent control techniques have gained significant attention in DC motor speed regulation because of their ability to address nonlinear dynamics, parameter uncertainties, and external disturbances that degrade the performance of fixed-gain controllers. Classical PID controllers assume constant motor parameters and operating conditions, which is rarely the case in practical industrial environments. As a result, adaptive strategies that update control parameters online have become an important research focus [19].

Among the earliest intelligent adaptive approaches, fuzzy logic and neural network controllers have been widely investigated for DC motor applications. Hameed presented a comparative study of fuzzy logic and artificial neural network (ANN) controllers for DC motor speed control and showed that intelligent controllers significantly reduce rise time and steady-state error compared to classical PID control [20]. This work demonstrated the potential of intelligent control techniques for improving motor drive performance under varying operating conditions.

Model Reference Adaptive Control (MRAC) has also attracted considerable interest due to its solid theoretical foundation and guaranteed stability properties. Nguyen et al. applied MRAC to DC motor speed regulation under parameter uncertainties and reported superior transient performance and robustness compared to conventional PID controllers [21]. Their results confirmed that MRAC is well suited for applications involving load and parameter variations.

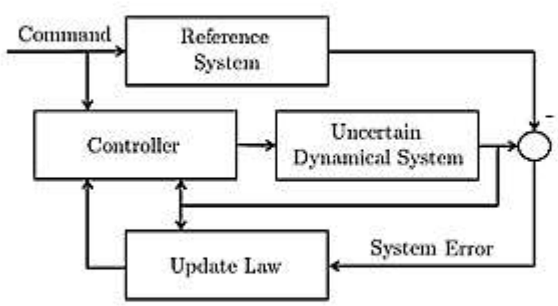

Figure 2: The Model Reference Adaptive Control System.

To enhance robustness, modified MRAC structures have been proposed. [22] developed a robust modified MRAC scheme for DC motor drives that combines adaptive laws with classical feedback control. Their approach achieved improved overshoot reduction and disturbance rejection, particularly in the presence of unmodeled dynamics. This work highlighted the practical relevance of MRAC variants in real motor drive systems.

Beyond simulation studies, experimental validation of adaptive controllers has gained attention. Reference [23], implemented an MRAC-based DC motor speed controller using a hardware-in-the-loop platform, demonstrating accurate reference tracking and strong robustness to parameter variations. However, their implementation relied on dedicated real-time hardware rather than industrial PLC platforms

2.2 Gaps in PLC-Based Motor Control Systems

Programmable Logic Controllers (PLCs) are the backbone of industrial automation due to their reliability, deterministic execution, and compatibility with industrial communication standards. In recent years, researchers have explored PLC-based motor control solutions to leverage these advantages in electric drive systems. Mahmoud et al. implemented a real-time neural network adaptive speed controller for DC motors directly on a PLC, demonstrating improved speed regulation under load disturbances [24]. However, most PLC-based DC motor control systems still rely on classical PID control. Saputra et al. developed a PLC-based DC motor speed controller using a PID algorithm with MATLAB-assisted tuning and showed that acceptable dynamic performance can be achieved for industrial applications [25].

Some researchers have attempted to improve PLC-based PID control through fuzzy logic extensions. Reference [26], implemented a fuzzy-PID speed controller for a DC motor on a PLC and demonstrated enhanced transient response and disturbance rejection compared to conventional PID control. While effective, such approaches remain semi-adaptive and do not offer continuous parameter adaptation.

Generally, PLC-based motor control studies emphasize simplicity, reliability, and ease of maintenance, but they rarely integrate fully adaptive control schemes such as MRAC, thus requires further research into PLC-compatible adaptive controllers that preserve industrial reliability while improving performance.

2.3 Review on related work

- Recent literature has begun to focus specifically on PLC-based intelligent motor control systems. Performance comparisons between adaptive and classical PID controllers performed by authors in reference [27], further highlight the limitations of fixed-gain PLC-based control. They compared the adaptive PID and classical PID controllers for DC motor drives and showed that adaptive controllers significantly outperform classical PID in terms of steady-state error and robustness. However, their adaptive implementation was not PLC-based.
- Reference [28], reviewed PLC-based implementations of intelligent motor control schemes and concluded that, although PLC hardware has evolved significantly, most industrial applications still underutilize advanced adaptive control techniques.
- Industry-oriented publications also reflect growing interest in adaptive motor drive technologies. Reference [29] has highlighted recent developments in industrial motor control and adaptive drive systems, emphasizing the need for robust, reliable, and intelligent control solutions that are compatible with industrial automation platforms.
- These articles reveal a clear gap between adaptive control theory and its implementation on PLCs. Most adaptive and intelligent controllers are validated using simulations or high-performance processors rather than PLC hardware. Consequently, there remains a strong need for research that demonstrates practical, real-time implementation of adaptive control schemes such as MRACS on industrial PLC platforms.

3. METHODOLOGY

3.1 SYSTEM ARCHITECTURE

The system is designed as a closed-loop control arrangement in which all components interact to achieve accurate and robust motor speed regulation. The control system consists of four main components: the DC motor, motor controller, programmable logic controller (PLC), and rotary (incremental) encoder. The PLC functions as the central control unit, coordinating system operation by generating control signals based on the desired speed reference and processing feedback information from the encoder. Figure 3.1 shows the overall architecture of the PLC-based DC motor speed control system.

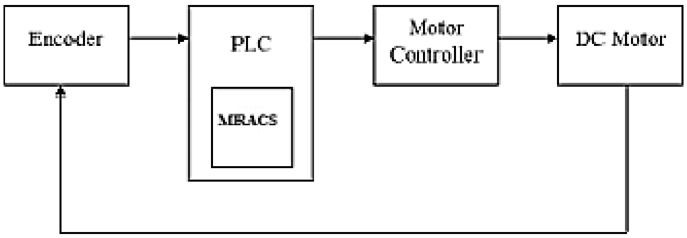

Figure 3.1: Overall System Architecture

When the system is energized and a start command is issued, the PLC executes the MRACS algorithm to generate an appropriate control signal corresponding to the reference speed. This signal is sent to the motor controller, which serves as a power interface by converting the low-level PLC output into a suitable armature voltage for driving the DC motor. The internal structure of the Model Reference Adaptive Control Scheme (MRACS) implemented within the PLC is presented Figure 3.2 as shown

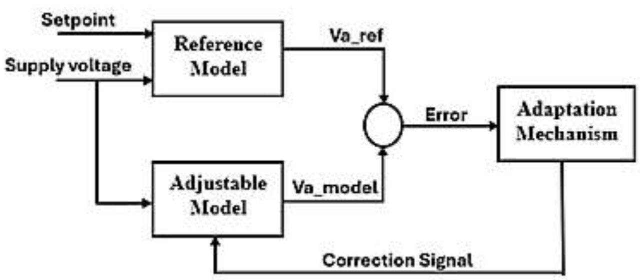

Figure 3.2: MRAC Control Structure

As the motor operates, the encoder mounted on the motor shaft continuously measures the rotational speed and converts it into digital pulse signals. These pulses are fed back to the PLC, where the actual motor speed is calculated in real time and compared with the desired speed obtained from the reference model. Within the MRACS framework, the reference model defines the desired dynamic response of the motor, while the adjustable model represents the actual motor dynamics subject to uncertainties and load variations. The difference between their outputs generates an error signal, which is processed by the adaptation mechanism to update the controller parameters continuously. This adaptive process ensures that the motor speed closely follows the reference trajectory, effectively rejecting disturbances and maintaining accurate speed control throughout operation.

3.2 Materials

- *Description of Hardware Used*

The heart of the system is the Siemens Simatic S7-1200 PLC (CPU 1215C DC/DC/DC), which handles all control logic for the DC motor. It receives inputs from the incremental encoder and start/stop push buttons, executes the programmed logic including PID control, and sends analog output signals to the motor controller. With a 24V DC supply, 14 digital inputs, 4 analog outputs, and support for high-speed counters and PID blocks, the PLC provides an ideal platform for precise speed regulation. Programming and configuration were carried out using Siemens TIA Portal V17.

The DC motor (CM 82869012) is the primary actuator, operating at 5–24V with a nominal maximum speed of 5000 RPM. However, an integrated gearbox with a ratio of 80 reduces the output speed to 62.5 RPM. The motor speed varies directly with the supply voltage, enabling control through voltage modulation. A 600 PPR incremental rotary encoder (E38S6G5-600B-G24N) measures motor speed and direction using channels A and B, which are connected to the PLC. The encoder operates up to 5000 RPM with a 100 kHz frequency and is powered directly from the PLC.

The motor controller (RS 313-2122) acts as the actuator, converting the PLC's analog control signal into a suitable voltage and current to drive the motor. It can provide up to 24V and 60W to achieve the desired speed. Additional components include pull-up resistors (4.7kΩ for each encoder channel, 10kΩ for the motor controller) to ensure proper logic levels, and push buttons for system start (green) and stop (red). These components together create a complete and functional PLC-based DC motor speed control setup.

- *DC Motor Parameters*

The parameters of the DC motor are shown in table 1

Table 1: DC Motor Parameters

Parameters	Value
Armature resistance (Ra)	26Ω
Armature inductance (La)	0.104H
Rotor moment of inertia (J)	1.0e-4 kg.m^2
Friction Constant (B)	0 Nms
Torque constant	0.2765Nm/A
Back emf constant	0.2765Vs
Maximum mechanical speed	5000RPM
Gear Box Ratio	80
Maximum output speed	62.5RPM

3.3 DC Motor Speed Control

A DC motor is an electrical machine that operates using direct current (DC) and converts electrical energy into mechanical energy through the interaction of magnetic fields [30]. Due to the widespread adoption of DC motors in industrial applications, controlling their speed has become a key area of research, leading to the development of numerous control strategies based on different theoretical principles. In this work, the voltage control method is employed, which relies on the principle that the speed of a DC motor is directly proportional to the armature voltage, assuming the field flux remains constant.

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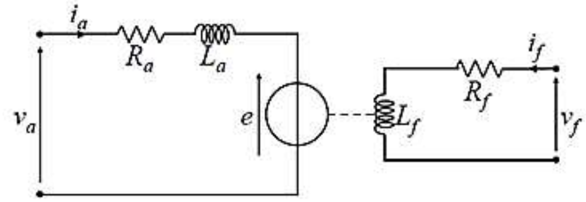

Figure 3.6: DC motor Equiv. Circuit with field winding [31]

Figure 3.6 illustrates the equivalent circuit of a separately excited DC motor with a field winding, and the corresponding armature voltage equation (applying KVL) is given as:

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + e \quad (1)$$

where e = back emf = $K_e \omega_m$;

where K_e is the back-emf coefficient of the machine and ω_m is the speed of the motor. Also, at steady state, the armature current is constant and thus, equation 1 reduces to:

$$V_a = R_a I_a + K_e \omega_m$$

Hence, the Dc motor speed can be expressed as:

$$\omega_m = \frac{V_a - R_a I_a}{K_e} \quad (2)$$

This means that increasing the armature voltage increases motor speed and decreasing the voltage decreases the motor speed, provided that the back-emf coefficient, or rather, the field flux, is kept constant. This paper uses an MRACS controller to achieve this voltage variation, which in turn controls the motor.

3.4 Model Reference Adaptive Control Scheme

Reference Model

A first-order reference model defines the desired speed response:

$$\frac{\omega_m(s)}{r(s)} = \frac{\omega_n}{s + \omega_n} \quad (3)$$

where ω_n determines system bandwidth.

- *Control Law:* The adaptive control input is given by:

$$u(t) = \theta_1(t)\omega(t) + \theta_2(t)r(t) \quad (4)$$

where $\theta_1$and θ_2 are adaptive parameters.

- *Adaptation Law:* Using the Lyapunov stability approach, the parameter update laws are:

$$\dot{\theta} = -\gamma e(t)\phi(t) \quad (5)$$

where

$e(t) = \omega(t) - \omega_m(t)$ is tracking error,

γ is adaptation gain,

$\phi(t)$ is the regression vector.

3.5 Wiring and Configuration

- *PLC Power Supply:* The PLC is energized using a 24 V DC power source. The positive and negative terminals of the supply are connected directly to the corresponding L+ and M terminals of the PLC to ensure stable operation.

- *Start and Stop Push Buttons:* The start and stop push buttons are directly interfaced with the PLC. The negative terminals of both buttons are connected to the PLC ground, while their positive terminals are wired to digital input channels I5 and I6, respectively, enabling operator control of system operation.

- *DC Motor Speed Measurement:* As illustrated in Figure 3.3, the DC motor is mechanically coupled to the rotary encoder using a rigid, non-slip belt to ensure that the encoder rotates at the same angular speed as the motor shaft.

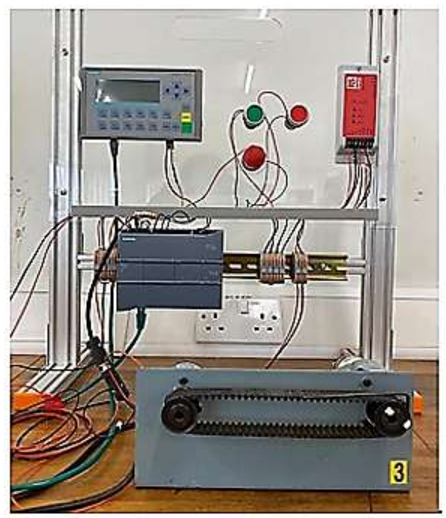

Figure 3.3: Complete Setup

The encoder is powered directly from the PLC, and its four connecting cables are interfaced as shown in Figure 3.4. Channels A and B are connected to digital input ports I0 and I1, respectively. Each channel is pulled up to the PLC's L+ terminal through 4.7 kΩ resistors to guarantee proper logic levels in the absence of pulse signals. Within the TIA Portal environment, input ports I0 and I1 are configured for high-speed counting, with a sampling cycle time set to 1 µs. This value is deliberately selected to be lower than the encoder pulse period of 10 µs, thereby ensuring accurate and reliable speed measurement.

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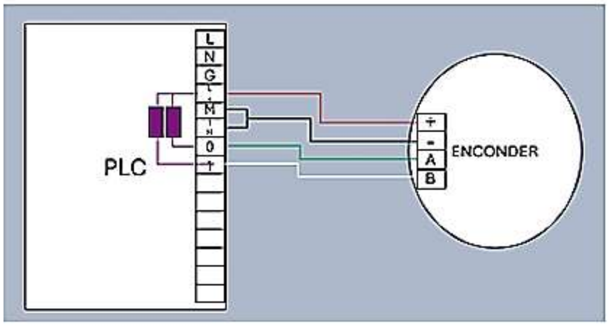

Figure 3.4: Wring of Encoder to PLC

- *Motor Controller Interface:*

The motor controller is connected as shown in Figure 3.5. It is supplied directly from an external 24 V DC source through its positive and negative power terminals. The PLC's analog output channel AO1, which delivers the control signal, is connected to the controller's Vset terminal, while the Vref terminal is linked to the PLC common terminal (M). The controller's M+ and M− output terminals are then connected to the DC motor, allowing the controller to regulate motor speed based on the PLC-generated control signal.

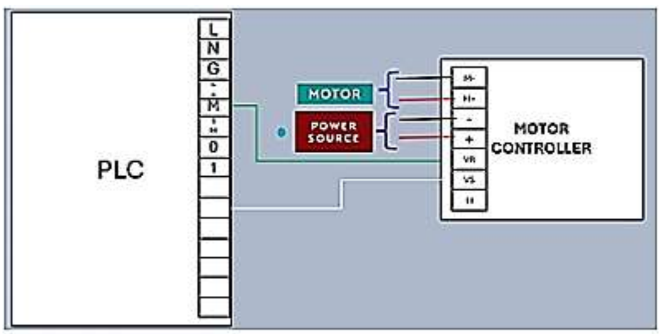

Figure 3.5: Wiring of PLC to Motor Controller

4. Result and Discussion

At startup, the motor speed increases smoothly from zero and closely follows the reference speed of 10 rpm. The response exhibits a fast rise time of approximately 2 seconds and reaches steady state at about 2.6 seconds. Notably, the speed response shows no overshoot or oscillatory behavior, indicating a well-damped closed-loop system and effective adaptive parameter tuning within the MRACS framework.

Figure 4.1 illustrates the dynamic speed response of the DC motor under the proposed PLC-based MRACS, showing the reference speed (setpoint), actual motor speed, and the corresponding tracking error over time.

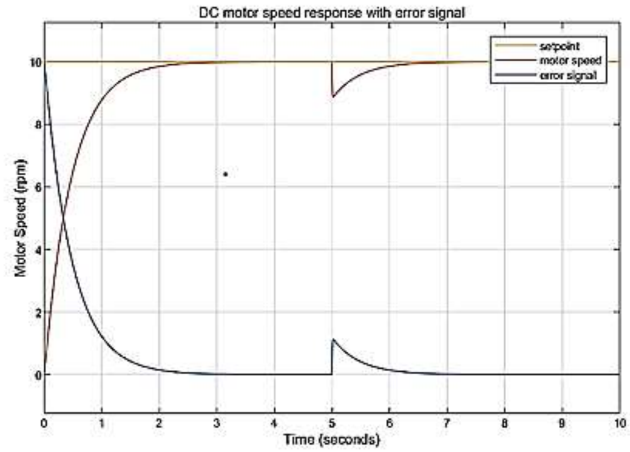

Figure 4.1: DC Motor Speed Response using Model Reference Adaptive Control Method

The error signal decreases rapidly during the transient period and converges asymptotically to zero as the motor speed approaches the reference model output. This behavior confirms that the adaptive mechanism successfully minimizes the tracking error by continuously updating the controller parameters, forcing the actual plant dynamics to match the desired reference model. The monotonic decay of the error signal further demonstrates the stability of the adaptive law and the absence of sustained oscillations or instability during normal operation.

At (t = 5) seconds, a sudden disturbance in the form of an external load torque (0.05 Nm) is applied, causing a temporary drop in motor speed and a corresponding spike in the error signal. However, the controller reacts immediately by adjusting the control voltage through the adaptive gains, allowing the motor speed to recover rapidly.

The system retains the reference speed within approximately 1.5 seconds, and the error signal again converges to zero without overshoot. This disturbance rejection capability highlights the reliability and resilience of the MRACS against load variations and confirms its superiority over fixed-gain controllers in handling parameter uncertainties and external disturbances.

5. Conclusions

This research has presented the design, implementation, and evaluation of a PLC-based DC motor speed control system using a Model Reference Adaptive Control Scheme (MRACS) aimed at overcoming the inherent limitations of conventional fixed-gain controllers in industrial environments. A detailed mathematical model of the DC motor was developed, and an MRACS controller was formulated using Lyapunov-based adaptation laws to guarantee closed-loop stability while ensuring accurate model-following behavior.

The design was implemented on an industrial PLC platform, demonstrating that advanced adaptive control algorithms can be practically realized within the constraints of standard industrial automation hardware. Unlike traditional PID-based PLC controllers, which often suffer performance degradation under parameter variations and load disturbances, the MRACS continuously adjusted its control parameters in real-time to maintain desired performance.

Simulation and experimental results confirmed the effectiveness of the proposed approach. The system achieved a fast rise time of approximately 2 seconds, a settling time of about 2.6 seconds, and zero overshoot under nominal conditions. More importantly, when subjected to a sudden load disturbance of 0.05 Nm, the controller rapidly rejected the disturbance and restored the motor speed to the reference value within approximately 1.5 seconds. The tracking error converged asymptotically to zero in all operating conditions, validating the stability and robustness of the adaptive law.

Finally, the results clearly demonstrate that the PLC-based MRACS provides superior transient response, excellent disturbance rejection, and strong robustness against parameter uncertainties compared to conventional fixed-gain control methods. The transparency of the MRACS structure and its compatibility with industrial PLC platforms make it particularly attractive for real-time industrial motor control applications.

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