Design and Development of Gain Scheduling PID and Fuzzy-PID Control for DC Motor Speed Based on MATLAB Simulink

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Abstract—*Speed control of DC motors plays an important role in industrial applications because it directly affects system performance and efficiency. Conventional PID controllers are widely used; however, they have limitations in handling setpoint changes and varying system dynamics. Previous studies have shown that adaptive methods such as Gain Scheduling PID and Fuzzy-PID can improve control performance, but comparative studies under varying setpoints remain limited. Therefore, this research aims to design and analyze the performance of Gain Scheduling PID and Mamdani-based Fuzzy-PID controllers for DC motor speed control using MATLAB Simulink. The research method includes DC motor modeling, controller design, simulation under setpoint variations from 2000 to 8000 RPM, and performance analysis based on rise time, overshoot, settling time, and steady-state error. The results indicate that both controllers are capable of regulating DC motor speed effectively; however, the Fuzzy-PID controller provides a more adaptive transient response with lower overshoot and steady-state error at certain operating conditions compared to the Gain Scheduling PID controller.*

Index Terms—DC motor, speed control, Gain Scheduling PID, Fuzzy-PID, MATLAB Simulink.

1. Introduction

A Direct Current (DC) motor is a device that converts direct electrical energy into mechanical energy. DC motors are widely used in various industrial, automotive, and electronic applications, particularly in systems that require variable speed operation [1]. Speed control of DC motors is a critical aspect, as inadequate speed regulation can adversely affect the overall performance and efficiency of the system. Various control schemes are employed in industrial applications, with the Proportional–Integral–Derivative (PID) controller being one of the most commonly used and effective methods. The conventional PID controller remains widely applied in industrial systems compared to more advanced control techniques [2].

However, conventional PID controllers often exhibit limitations when applied to complex systems, such as high-order systems, systems with time delays, systems with varying parameters, nonlinear systems, or systems with uncertainties. These limitations arise because the linear structure of the PID controller is unable to adapt to varying system dynamics. To address these challenges, modern control theory highlights the importance of the gain scheduling approach as an effective technique for improving control performance under changing operating conditions [3]. In addition to this approach, artificial intelligence–based control methods have also been developed, such as the Fuzzy-PID controller, which combines conventional PID control with fuzzy logic systems.

The design of a Fuzzy-PID controller essentially involves adjusting PID parameters using fuzzy logic principles. The main advantage of this controller lies in its ability to perform adaptive parameter tuning (online tuning), making the control system more flexible and capable of adapting to variations in system conditions in real time [4]. In this study, the Gain Scheduling PID and Fuzzy-PID methods are compared to determine which approach provides the best performance for DC motor speed control under varying load conditions.

Through this research, it is expected that a deeper understanding of the advantages and limitations of each method can be obtained, as well as the potential for their integration to develop a more adaptive, efficient, and stable control system capable of handling dynamic operating conditions.

2. Literatur Riview

A review of previous studies aims to identify the development of control methods that have been implemented, including aspects such as the use of microcontrollers, input sensors, system outputs, software platforms, and applied control processes. Numerous prior studies have discussed the implementation of control systems for DC motors using different approaches and objectives.

Alfano et al. (2019) investigated the modeling and simulation of DC motor speed control using a Fuzzy–PID algorithm to achieve smoother system performance compared to conventional PID control. The results showed that the Fuzzy–PID method was able to reduce overshoot and improve response time [5].

Hammoodi et al. (2020) examined a PID-based DC motor speed control system simulated using MATLAB Simulink, demonstrating that appropriate PID tuning can produce stable motor speed with minimal error [6].

Kristiyono and Wiyono (2021) developed a Fuzzy–PID controller for a BLDC motor using PSIM and MATLAB simulations. Their results indicated that the Fuzzy–PID controller outperformed the conventional PID controller in terms of overshoot reduction and improved system stability [7].

Iradiratu Diah Prahmana Karyatanti et al. (2024) implemented a DC motor speed control system based on ESP32 and IoT technology with wireless monitoring. The system successfully controlled motor speed in real time using a PID controller integrated with the Blynk platform [1].

Rasyid et al. (2024) designed a PID-based DC motor control system using Arduino Uno and Tinkercad simulation. The results showed that the system was able to stabilize the motor speed according to the desired setpoint, although slight deviations were observed during the initial transient response [8].

Subarta et al. (2024) experimentally compared PID and Fuzzy–PID control systems implemented on an Arduino Mega 2560 platform. The study found that the Fuzzy–PID controller provided faster response, lower overshoot, and steady-state error values close to zero compared to the conventional PID controller [9].

Based on the identified research gaps, this study proposes a research entitled “Design and Development of Gain Scheduling PID and Fuzzy-PID Control for DC Motor Speed Based on MATLAB Simulink.” This research focuses on the design, simulation, and comparative performance analysis of Gain Scheduling PID and Fuzzy-PID methods for controlling DC motor speed under various load conditions.

3. Research Methodology

This study adopts an experimental research approach to design, implement, and evaluate a DC motor speed control system using Gain Scheduling PID and Fuzzy-PID methods based on MATLAB Simulink. The research methodology is systematically structured so that each stage, from control model design to system performance testing, can accurately represent real DC motor operating conditions, particularly under varying setpoints and load changes.

The development of the control system is carried out in a gradual and iterative manner, beginning with DC motor system modeling, followed by the design of PID, Gain Scheduling PID, and Fuzzy-PID controllers, and finally performance evaluation of each method. This approach allows for continuous refinement of control parameters based on simulation and testing results, ensuring that the developed control system delivers stable, adaptive, and reliable performance in accordance with the established performance criteria.

3.1 Design Stage

The design stage is the initial step in the research process, which aims to determine the fundamental system concept as well as the components used in the development of the proposed system.

3.1.1 Research Design

The research design is structured to provide a comprehensive overview of the research workflow. Therefore, a research flowchart is developed to illustrate the sequence of activities, starting from the planning stage, control model design, hardware implementation, to system performance evaluation. The preparation of this flowchart is intended to ensure that each research stage is interconnected and effectively directed toward achieving the main research objectives, as shown in Figure 3.1.

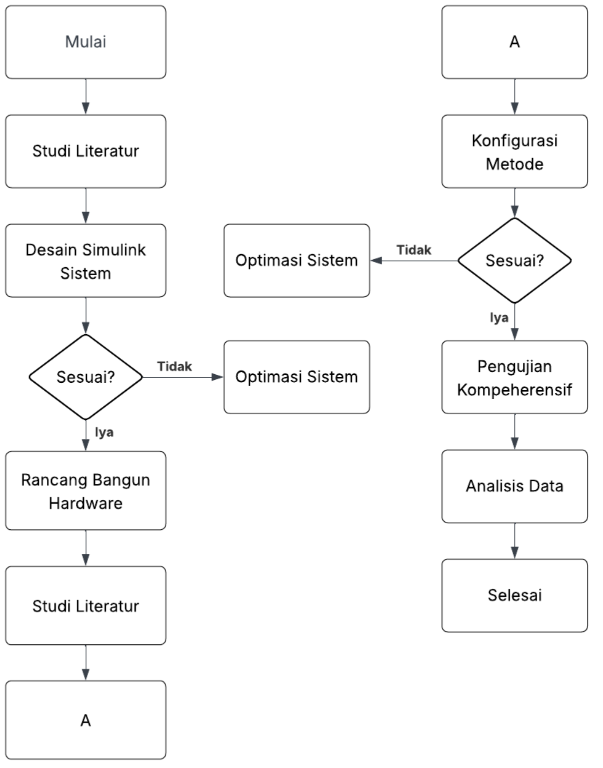

Figure 3.1 Research Design

3.1.2 Block Diagram

The system block diagram in this study illustrates the relationship between the software and hardware components used in the design and implementation of the DC motor speed control system based on PID and Fuzzy controllers, which are developed using the MATLAB Simulink application, as shown in Figure 3.2.

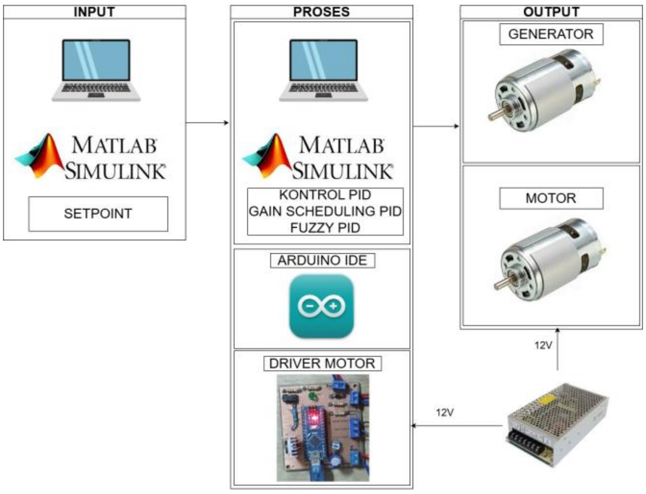

Figure 3.2 Block Diagram of DC Motor Speed Control System

3.1.3 Motor Driver Design

The DC motor driver is designed to control the direction and rotational speed of the motor based on PWM signals generated by the microcontroller. The motor driver is implemented using a PC817 optocoupler circuit, which functions as an electrical isolator between the control and power sections, and a HY1420 MOSFET that acts as an electronic switch to regulate the current supplied to the motor. In addition, a flyback diode is incorporated into the circuit to protect the MOSFET from reverse inductive voltage generated when the motor is suddenly stopped, as shown in Figure 3.3.

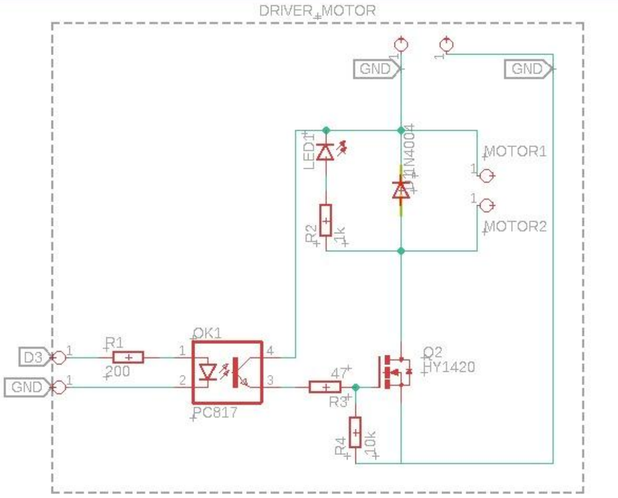

Figure 3.3 Motor Driver Circuit Schematic

In general, the DC motor driver circuit functions as an amplifier of the control signal from the microcontroller, enabling it to drive the motor with an appropriate power level.

3.1.4 Voltage Divider Design

The voltage divider circuit in this system functions to reduce and adjust the output voltage level from the generator so that it can be read by the Arduino microcontroller. The schematic of the voltage divider circuit is shown in Figure 3.4.

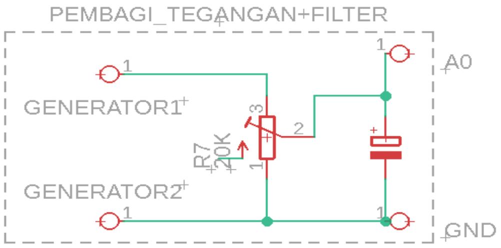

Figure 3.4 Schematic Diagram of the Voltage Divider and Filter Circuit

3.1.5 Motor Module Design

The motor module design stage is conducted to develop the mechanical and electrical systems used for testing the DC motor speed control. This module is designed to ensure stable motor operation, ease of control, and the ability to provide a representative response to the implemented Gain Scheduling PID and Fuzzy–PID control systems.

3.1.6 Gain Scheduling PID Program Design

At this stage, the Gain Scheduling PID program is designed and implemented using MATLAB Simulink. The Gain Scheduling method is selected to address variations in the dynamic characteristics of the DC motor under different operating conditions, allowing the PID gain parameters to vary adaptively rather than remain constant, according to the setpoint value or system conditions. The Simulink diagrams of the Gain Scheduling PID are shown in Figures 3.5 and 3.6.

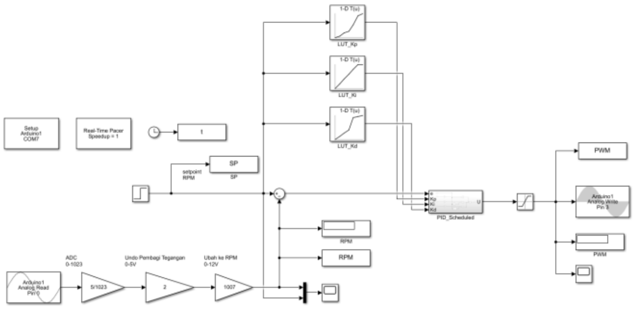

Figure 3.5 Gain Scheduling PID Simulink Diagram

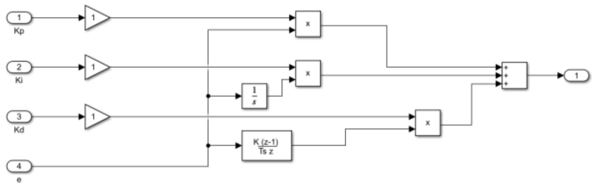

Figure 3.6 PID Controller Simulink Diagram

3.1.7 Fuzzy-PID Program Design

At this stage, the Fuzzy-PID program is designed and implemented using MATLAB Simulink as one of the control methods to be compared with the Gain Scheduling PID approach. The Simulink diagrams of the Fuzzy-PID controller are shown in Figures 3.7 and 3.6.

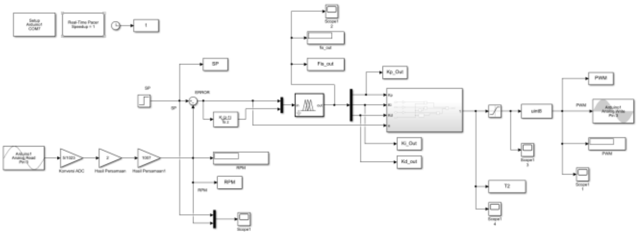

Figure 3.7 Fuzzy-PID Simulink Diagram

3.1.8 Fuzzy Inference System (FIS) Program Design

At this stage, a Fuzzy Inference System (FIS) is designed to adaptively generate the PID parameters Kp, Ki, and Kd in order to regulate the PID controller response. The FIS design is carried out by defining two input variables, namely error (e) and change of error (de), each consisting of five fuzzy sets: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). The input and output configurations of the Fuzzy controller are illustrated in Figures 3.9, 3.10, and 3.11.

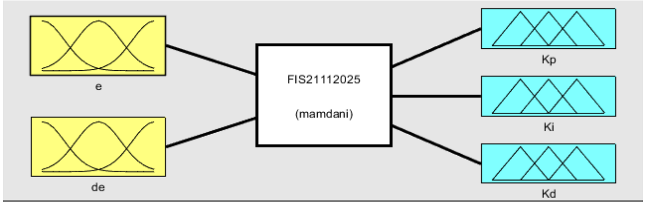

Figure 3.9 Input and Output of the Fuzzy-PID Controller

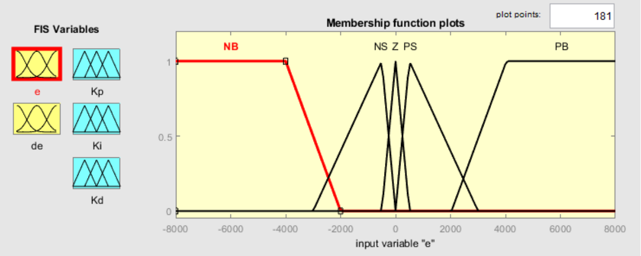

Figure 3.10 Error Membership Function

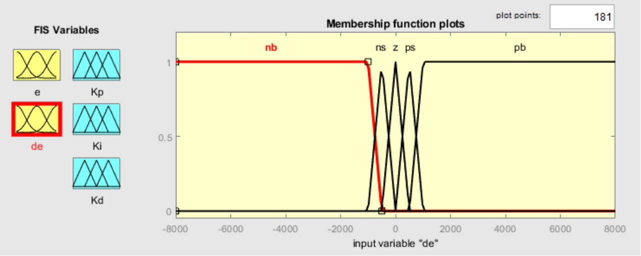

Figure 3.11 Delta Error Membership Function

The membership functions of the three output variables are presented in Figures 3.12, 3.13, and 3.14, which illustrate the distribution of fuzzy sets in triangular (trimf) and trapezoidal forms. For the Kp parameter, the value range is defined from the Very Low to Very High categories based on the minimum and maximum limits obtained from system testing. Meanwhile, the membership functions for Ki and Kd are designed with narrower ranges to maintain the stability of the integrator and the derivative action in the PID control.

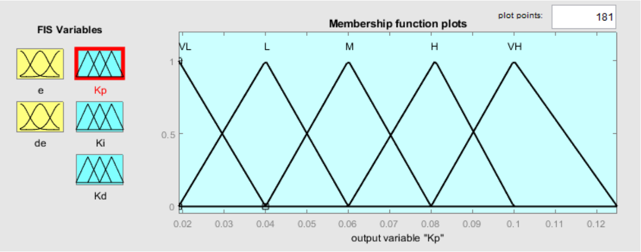

Figure 3.12 Membership Function of Gain Kp

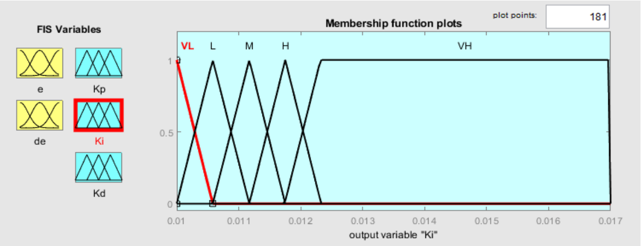

Figure 3.13 Membership Function of Gain Ki

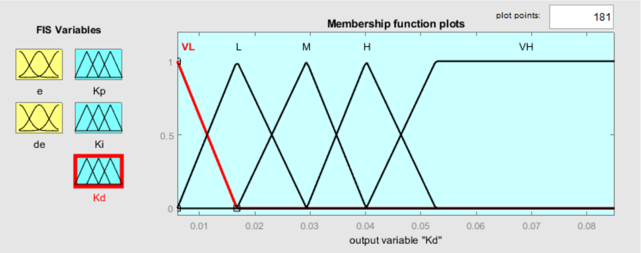

Figure 3.14 Membership Function of Gain Kd

The fuzzy rule structure (rule base) is presented in Tables 3.1, 3.2, and 3.3, which describe the relationship between the error and change of error with respect to the values of Kp, Ki, and Kd. The rule table for Kp is designed to enhance the proportional action when large errors or rapid changes in error occur. Meanwhile, the Ki rule table is primarily aimed at reducing steady-state error so that the system can reach the setpoint without excessive overshoot. The Kd rules focus on increasing the derivative action when the error changes rapidly, thereby damping oscillations in the system.

Each rule is formulated based on the previously tested dynamic response characteristics of the DC motor, ensuring that the overall fuzzy rule base produces adaptive and consistent behavior under varying operating conditions.

Table 3.1 Kp Rules in the PID Controller

e/de	**NB**	**NS**	**Z**	**PS**	**PB**
NB	VH	H	VL	H	VH
NS	VH	H	VL	H	VH
Z	VH	H	M	L	M
PS	VH	H	L	M	VH
PB	VH	VH	L	L	VH

Table 3.2 Ki Rules in the PID Controller

e/de	**NB**	**NS**	**Z**	**PS**	**PB**
NB	M	L	L	L	VH
NS	L	L	H	L	M
Z	L	L	H	VH	M
PS	L	L	L	VH	VH
PB	M	L	M	VH	VH

Table 3.3 Kd Rules in the PID Controller

e/de	**NB**	**NS**	**Z**	**PS**	**PB**
NB	VL	L	M	H	VH
NS	L	H	VH	VH	VH
Z	M	H	H	VH	VH
PS	VH	VH	VH	VH	VH
PB	VH	VH	VH	VH	VH

With this FIS design, the fuzzy system is capable of automatically generating the Kp, Ki, and Kd values based on the current error conditions. This adaptive parameter adjustment enhances the flexibility of the Fuzzy-PID controller in handling nonlinearities and load dynamics, making it a suitable benchmark for comparison with the Gain Scheduling PID method in this study.

3.1.8 System Flowchart

The development of the system flowchart is intended to facilitate understanding of the data flow and control logic, starting from the initialization stage, sensor data acquisition, control signal computation, to the feedback process to Simulink. All processes involved in motor control can be comprehensively visualized, thereby simplifying the analysis, implementation, and evaluation of the system, as shown in Figure 3.15.

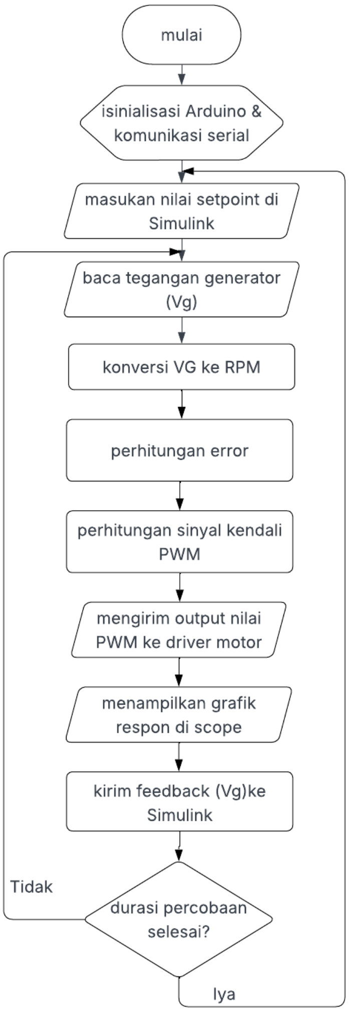

Figure 3.15 Flowchart of the DC Motor Speed Control System

3.2 Hardware Design Stage

The hardware development stage involves realizing the system design into a physical form that can be tested and operated. At this stage, hardware assembly, electronic circuit construction, and software programming for the control system are carried out.

3.2.1 Motor Module Assembly

The motor module assembly stage is conducted to implement the previously designed mechanical and electrical systems. At this stage, the main components such as the DC motor, encoder, and mechanical mounting are assembled into a single unit so that it can be used as a test module for the speed control system. The temporary physical form of the motor module is shown in Figure 3.16.

Figure 3.16 Temporary Motor Module

3.2.2 Electronic Circuit Construction

The circuit design stage is a critical process that determines the quality and success of the developed system. At this stage, thorough preparation and planning are carried out to ensure that all components and assembly requirements are available from the outset, thereby minimizing potential obstacles during the fabrication process. The system schematic diagram is presented in Figure 3.17.

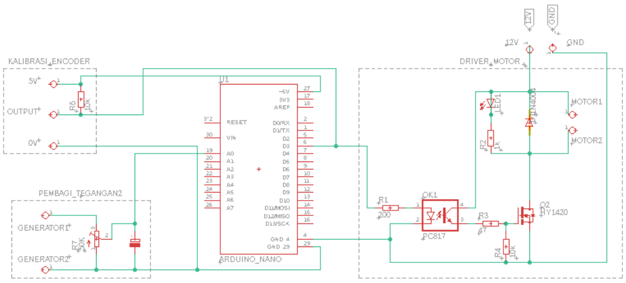

Figure 3.17 System Schematic Diagram

The initial step in the circuit board fabrication process is designing the layout or routing of interconnections between electronic components. This layout is created based on the previously designed and tested circuit schematic. The printed circuit board (PCB) layouts are shown in Figures 3.18 and 3.19.

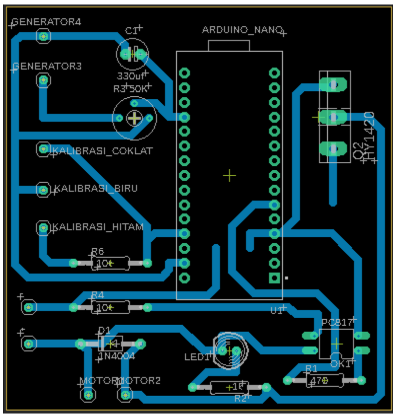

Figure 3.18 PCB Layout Design (Layer 1)

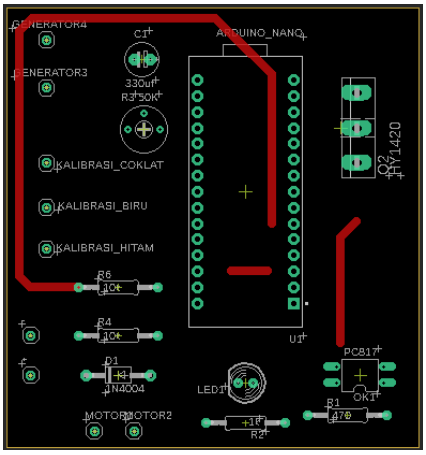

Figure 3.19 PCB Layout Design (Layer 2)

3.3 Measurement Stage

The measurement stage is conducted to ensure that the speed measurement system operates properly and provides accurate results.

3.3.1 System Calibration

The calibration process aims to align the encoder output readings with the actual rotational speed of the DC motor, ensuring that the acquired data can be accurately used in the control system testing process. At this stage, the encoder mounted on the motor shaft functions as a speed sensor that generates pulse signals for each shaft rotation. The number of pulses received within a specific time interval is then processed to obtain the motor speed in revolutions per minute (RPM).

3.3.2 Measurement of Kp, Ki, and Kd in the PID Controller

At this stage, the PID controller parameters, namely proportional gain (Kp), integral gain (Ki), and derivative gain (Kd), are measured for each DC motor speed setpoint. Measurements are conducted sequentially for seven setpoints: 2000 RPM, 3000 RPM, 4000 RPM, 5000 RPM, 6000 RPM, 7000 RPM, and 8000 RPM. After completing the measurements for each setpoint, the resulting Kp, Ki, and Kd values are summarized in Table 3.5.

Table 3.5 PID Gain Measurement Results (Kp, Ki, and Kd)

Setpoint	Kp	Kd	Ki
2000	0.019	0.006	0.01
3000	0.026	0.009	0.011
4000	0.04	0.012	0.012
5000	0.048	0.015	0.013
6000	0.075	0.027	0.014
7000	0.115	0.028	0.015
8000	0.125	0.029	0.016

4. Results And Discussion

4.1 Gain Scheduling PID Results

The speed response graph at the 2000 RPM setpoint is shown in Figure 4.1. The graph illustrates how the system responds to changes in the setpoint. It can be observed that the motor speed increases rapidly from 0 to approximately 2000 RPM, followed by a slight overshoot before stabilizing near the setpoint value. After this initial phase, the motor response becomes smooth with small fluctuations around 2000 RPM, indicating that the system has reached a stable condition with a very small steady-state error. Overall, the graph demonstrates that the control system performs well and is able to track the setpoint stably.

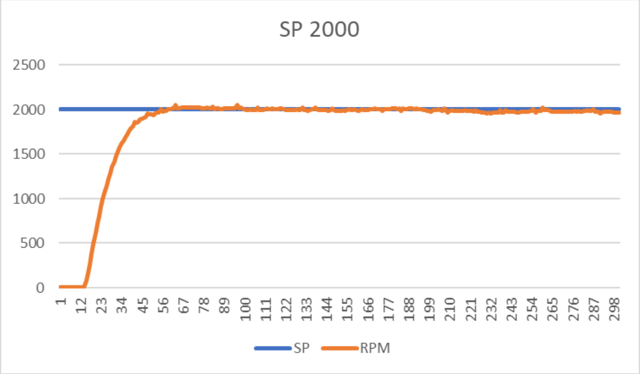

Figure 4.1 Gain Scheduling PID Response at 2000 RPM Setpoint

The speed response graph at the 8000 RPM setpoint is shown in Figure 4.2. The graph shows that the motor speed increases very rapidly from 0 to nearly 8000 RPM, with a small overshoot occurring at the initial stage before the response stabilizes close to the setpoint value. After the transient phase, the motor response appears smooth with minor fluctuations around 8000 RPM, indicating that the system has reached a stable condition with a very small steady-state error.

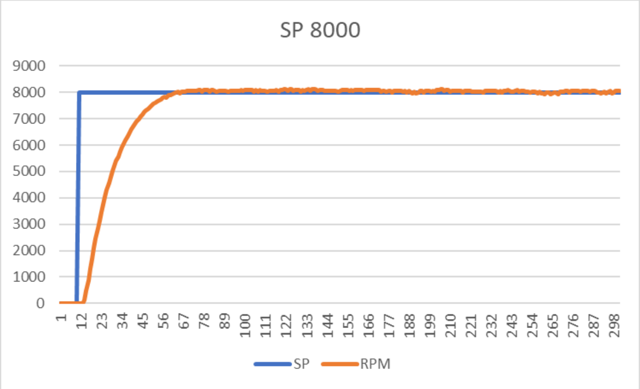

Figure 4.2 Gain Scheduling PID Response at 8000 RPM Setpoint

4.2 Fuzzy-PID Results

The speed response graph at the 2000 RPM setpoint is shown in Figure 4.3. The graph indicates that the Fuzzy-PID method is able to increase the motor speed rapidly toward the 2000 RPM setpoint without any overshoot during the initial response. The RPM value remains stable and follows the setpoint with minimal fluctuations. This result demonstrates that the Fuzzy-PID controller can produce a fast response while maintaining stability at the setpoint value.

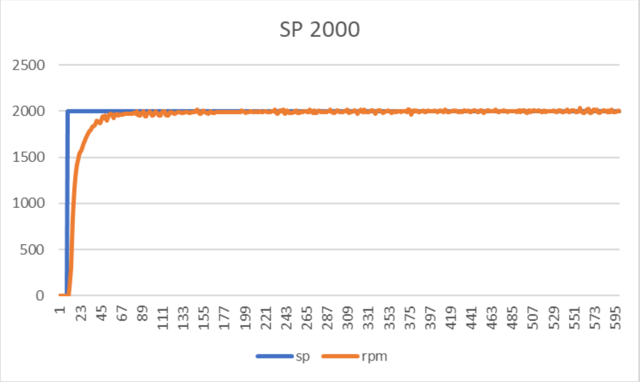

Figure 4.3 Fuzzy-PID Response at 2000 RPM Setpoint

The speed response graph at the 8000 RPM setpoint is shown in Figure 4.4. The graph shows that the Fuzzy-PID method can drive the motor speed quickly toward the 8000 RPM setpoint without overshoot during the initial response. The RPM value remains stable and closely follows the setpoint with small fluctuations. This indicates that the Fuzzy-PID controller provides a fast and stable response across different operating conditions.

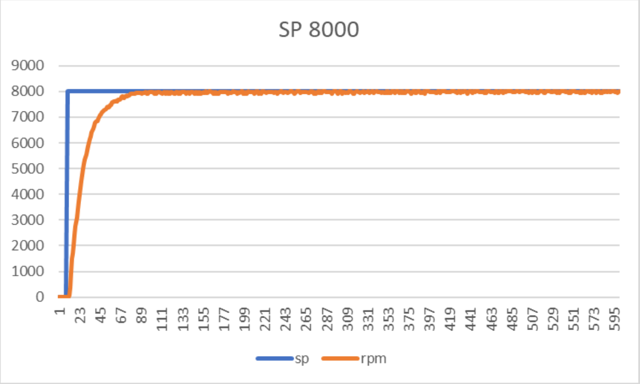

Figure 4.4 Fuzzy-PID Response at 8000 RPM Setpoint

4.2 Discussion

4.2.1 Overshoot (%)

This section presents a detailed analysis of the performance of the Gain Scheduling PID controller based on the experimental results, including the calculation of overshoot, settling time, and steady-state error for each tested setpoint.

Overshoot is defined as the condition in which the system output exceeds the setpoint value during the transient response. The overshoot percentage is calculated using Equation (4.1)

$$Overshoot\ (\%) = \frac{RPMmax - RPMSetpoint}{RPMSetpoint} \times\ 100\% \quad 4.1$$

where:
RPM_{max} = maximum speed achieved by the DC motor
$RPM_{setpoint}$ = desired speed setpoint

4.2.2 Settling Time (t)

Settling time is defined as the time required for the system to reach a stable condition after a change occurs. In simple terms, it represents the duration until the system response stops oscillating and remains within a specified tolerance band around the setpoint. The tolerance range used in this study is defined by Equation (4.2)

$$Tolerance\ Range = \pm 5\% \times RPMsetpoint \qquad 4.2$$

4.2.3 Steady-State Error (SSE)

Steady-state error is the small difference between the system output and the setpoint value after the system has reached a stable condition. Even when the response has settled and exhibits minimal variation, a slight deviation from the setpoint may still occur. The steady-state error is calculated using Equation (4.3)

$$SSE = \frac{SSEmax - SSEmin}{Setpoint} \times 100\% \qquad 4.3$$

Table 4.1 Gain Scheduling PID Test Results

No.	**Setpoint**	**Overshoot (%)**	**Settling Time (s)**	**Steady State Error (%)**
1	2000	2.37	4.5	6.89
2	3000	1.72	3.9	6.56
3	4000	1.39	3.6	5.66
4	5000	1.78	3.6	-5.91
5	6000	1.72	3.8	6.07
6	7000	2.73	4	-6.47
7	8000	1.51	5.1	-6.28

Table 4.2 Fuzzy-PID Test Results

No.	**Setpoint**	**Overshoot (%)**	**Settling Time (s)**	**Steady State Error (%)**
1	2000	1.88	4.6	6.89
2	3000	1.06	4.3	5.24
3	4000	1.39	4	6.15
4	5000	1	4.3	5.91
5	6000	0.9	4.5	5.91
6	7000	0.69	5.1	5.34
7	8000	0.28	6.1	5.17

5. Conclusion

Based on the design, implementation, and testing results of the DC motor speed control system using the Gain Scheduling PID and Fuzzy-PID methods, several conclusions can be drawn as follows:

1. The performance of both control methods indicates that Gain Scheduling PID and Fuzzy-PID are capable of regulating DC motor speed according to the given setpoints under various testing conditions. The Gain Scheduling PID controller provides a relatively fast initial response, particularly at medium setpoints. However, its performance tends to vary as the setpoint increases, as indicated by the occurrence of overshoot and small oscillations before reaching steady-state conditions.

   In contrast, the Mamdani-based Fuzzy-PID controller demonstrates more stable and consistent performance, characterized by lower overshoot, smoother settling time, and smaller steady-state error across the entire range of setpoints. This indicates that the Fuzzy-PID controller is more adaptive to changes in system dynamics compared to the Gain Scheduling PID method.

2. The optimal performance of the Gain Scheduling PID method is determined by evaluating transient response parameters, namely rise time, overshoot, and settling time at each setpoint. Based on the experimental results, the best transient response of the Gain Scheduling PID controller is achieved at medium setpoints

(approximately 4000–5000 RPM), where the system produces the fastest rise time with acceptable overshoot.

However, at higher setpoints, the performance of the Gain Scheduling PID controller degrades due to limitations in gain region partitioning, which is not fully adaptive to changes in motor characteristics. Therefore, this method is optimal only under specific operating conditions and is less effective over a wide speed range.

3. The optimal performance of the Mamdani Fuzzy-PID method is determined by the system's ability to produce stable and consistent transient responses, as indicated by low overshoot, smooth settling time, and small steady-state error across all setpoint variations.

The optimal performance of the Mamdani Fuzzy-PID method is determined by the system's ability to produce stable and consistent transient responses, as indicated by low overshoot, smooth settling time, and small steady-state error across all setpoint variations.

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