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Comparison of Fuzzy Logic Controllers for Speed Regulation in Separately Excited DC Motors: Field Versus Armature Control

Sri Kurniati, Sudirman Syam*, Nursalim, Wellem F. Galla

Electrical Engineering Department, Faculty of Science and Technology, University of Nusa Cendana, 85228 Kupang-Nusa Tenggara Timur, Indonesia

* Correspondence: Sudirman Syam (sudirman_s@staf.undana.ac.id)

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Abstract: Separately excited direct current (DC) motors, renowned for their linear characteristics and controllability, are extensively employed in various industrial applications. Effective speed control of these motors can be achieved through multiple methods, with fuzzy logic being a particularly robust approach. This study focuses on evaluating the transient responses of current and voltage in relation to the rotational speed of a DC motor under two distinct control schemes: field control and armature control, both subjected to similar load disturbances. A simulation-based methodology was employed using a DC motor speed control system combined with a fuzzy logic controller (FLC) designed with the Mamdani min-max method. The system was implemented in Simulink. In this framework, the FLC processes speed error signals and field current (I_f) errors as inputs to generate a field voltage control signal, which is then utilized by the armature voltage (Va) regulator to modulate the armature voltage. The results demonstrate that the FLC effectively stabilizes motor speed, quickly and accurately following speed references, even under load disturbances. Moreover, the system effectively mitigates speed fluctuations induced by load variations. A comparison between the two control schemes reveals that the field control approach exhibits a slower response time, taking 2.93 seconds to reach a steady state, whereas the armature control achieves this in a significantly faster time of 0.144 seconds. These findings underscore the efficacy of fuzzy logic in maintaining stable and responsive speed control in DC motors, with the armature control method displaying superior transient performance.

Keywords: Simulink; Overshoot; Modelling; Field coil; Fuzzy logic controller; Transient response

1 Introduction

A wide range of industrial applications use separately excited DC motors because of their controllable and linear performance [1]. The field coil and the armature coil are the two coils found in DC motors that are separately energized. Whereas an armature coil generates torque, the field coil generates magnetic flux. An independently stimulated DC motor's speed can be adjusted by varying armature or field voltage [2, 3]. A DC motor's speed can be controlled to a certain extent, offering good performance and ease of handling [4, 5]. Armature voltage speed control, field flux speed control, and armature resistance speed control are the three ways to adjust the speed of an independently excited and shunt DC motor. A Proportional Integral Derivative (PID) controller [6, 7], a FLC [8, 9], or a combination of the two controllers—fuzzy-genetic algorithm, fuzzy neural network [10, 11]—can also be used to regulate the speed of a DC motor. A PID system is a conventional control system, while a FLC is a non-conventional controller widely applied in industry. A comparison of PID and fuzzy logic control systems conducted by Jadmiko et al. [12] concluded that PID control performs better than fuzzy logic control at small time constants when viewed from the response characteristics produced. Conversely, fuzzy logic control shows good performance results when applied to plant characteristics with significant time constant values. For developments related to this, more rule bases can be applied to reduce overshoot during disturbances.

In this regard, speed control of separately excited DC motors has been widely carried out using fuzzy logic control methods [2, 13]. Fuzzy logic is a control method that does not require complex mathematical models and can handle uncertainty in the system. FLCs have several advantages compared to other classical controllers, such as simplicity of control, low cost, and the possibility of designing without knowing the exact mathematical model of the process [14]]. Fuzzy logic incorporates alternative ways of thinking that allow the modelling of complex systems using a higher level of abstraction derived from knowledge and experience [15]. According to Dairoh et al. [16], fuzzy logic works according to rules created based on expert knowledge and experience. The fuzzy logic control system for separately excited DC motor speed control consists of three main parts: fuzzification, inference, and defuzzification [17]. In the fuzzyfication stage, the input variables are converted into fuzzy variables. The input variables in this control system are speed error and field current error. In the inference stage, the fuzzy rules that have been created are used to generate fuzzy control signals. The fuzzy rules in this control system are created based on expert knowledge and experience in controlling separately excited DC motors. The fuzzy control signal is converted into a crisp control signal in the defuzzification stage. The crisp control signal in this control system is the DC motor field voltage.

Furthermore, because their torque and speed can be easily modified without compromising the machine's performance, DC motors—particularly independently excited varieties—are used in high-power applications such as steel mills, conveyors and pumps. The torque is generated when the field winding and armature flux interact. The motor speed constant (k), field current, and voltage generated by the back electromotive force (emf) are all directly related to motor speed. The armature voltage of an independently stimulated motor can be changed to affect the armature current (Ia) or field voltage. When the motor reaches its maximum speed, it functions at its base speed. If the speed is less than the base speed, the armature voltage control can be used. If the speed exceeds the base speed, the field current can be changed. The torque generated during overspeed operation is reduced since the motor's output power cannot exceed its nominal value. As a result, the purpose of this study is to examine the advantages and disadvantages of field control and armature control when controlling the speed of a separately excited DC motor.

2 Methodology

2.1 DC Motor Modelling

Fuzzy logic is defined as "calculating with words rather than numbers" or "controlling with sentences rather than equations." Two types of systems are currently well-known in fuzzy logic: Mamdani fuzzy inference and Sugeno fuzzy inference [18, 19]. In this study, the Mamdami min-max approach was used to simulate the speed control of a separately stimulated DC motor. The comparative materials in analyzing the data are the results of transient response parameter analysis, including:

- Effect of voltage and current on DC motor rotation speed.
- Settling time is the time the system requires from the rise time to reach a steady state.
- Maximum overshoot (Mp) refers to the percentage of peak value at steady state. It is determined using the following formula:

$$\%Mp = \frac{\text{Max.overshoot-reference}}{\text{reference}} \times 100 \tag{1}$$

where, $\%Mp$ equals the maximum percentage overshoot.

The modelling stage is the process of creating a mathematical model of a physical system by examining and analyzing the system's dynamic characteristics, which is then simulated on a computer. A mathematical model of a dynamical system was defined as several equations that describe the system's dynamics correctly or at least reasonably well. The dynamics of the system were explained in the form of differential equations. Then it was transformed in the form of the Laplace transformation and converted into a transfer function. Meanwhile, the equations are related to the system model. The steps that must be taken at this modelling stage are determining the DC motor parameters, as follows:

- Power = 5 HP
- Speed (n) = 1750 RPM
- Armature resistance = 2.581 ohms
- Armature inductance = 0.028 Henry
- Field resistance = 281.3 ohms
- Field inductance = 156 Henry
- Mutual armature field inductance = 0.9483 Henry
- Moment of inertia = 0.02215 J ($\mathrm{Kg} \cdot \mathrm{m}^2$)

2.2 Model of the Uncontrolled DC Motor System

The uncontrolled DC motor circuit can be seen in Figure 1.

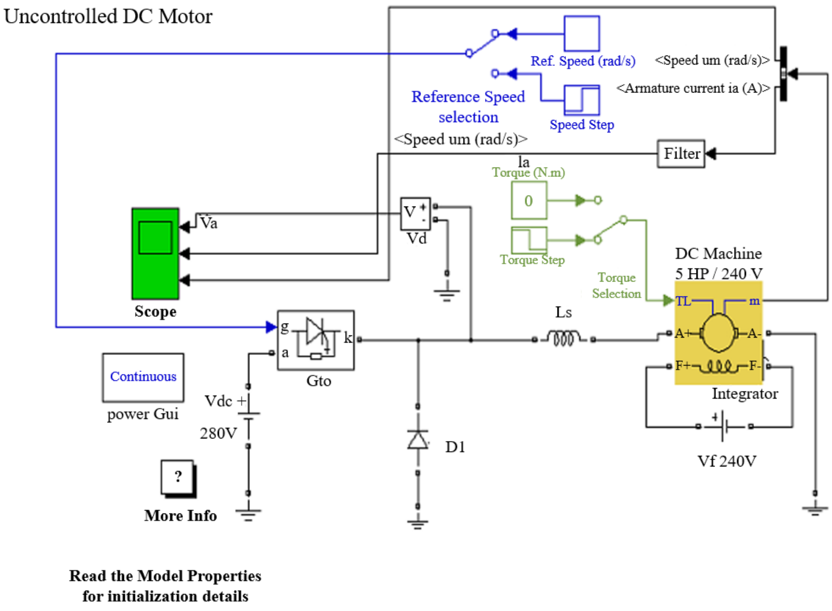


Figure 1. Uncontrolled DC motor circuit

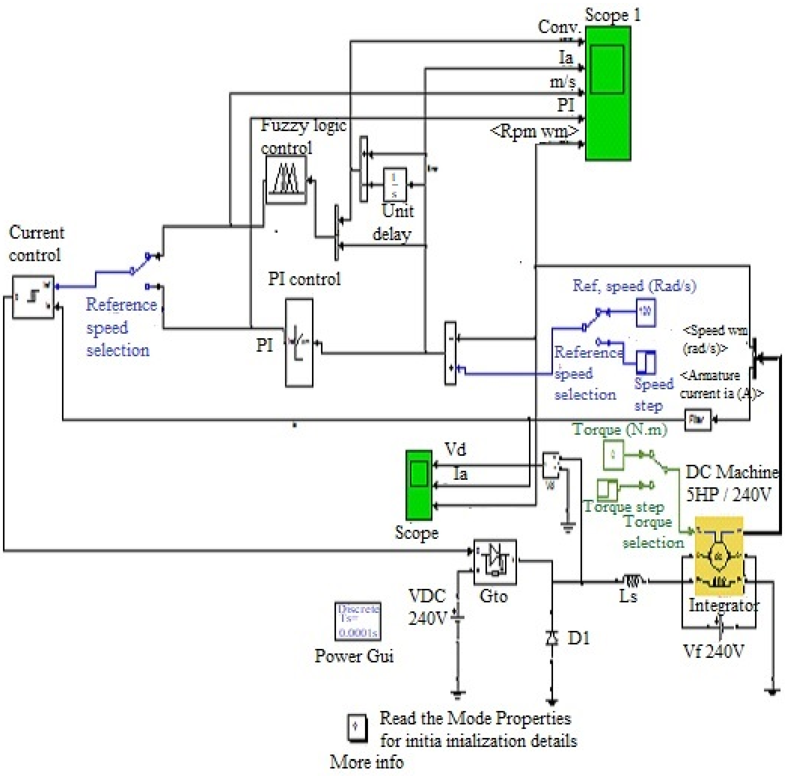


Figure 2. DC motor control modelling

2.3 Model of the DC Motor Control System

The DC motor controller used in this study consists of two controllers, namely, fuzzy logic, which is simulated using MATLAB 10.1 Simulink software, as shown in Figure 2.

In this control system, the central controller is the fuzzy controller, while the Proportional Integral (PI) controller is a reference in determining the range value in the FLC. The control coefficient (Kp and Ki) values were determined in the PI controller using the trial-and-error method. After several tunings, the coefficient values used are $Kp = 2.85, Ki = 7.85$. This is because the Kp and Ki parameters are independent. To obtain good control action, trial-and-error steps are needed with a combination of Proportional (P) and Integral (I) until the desired Kp and Ki values are found.

2.4 FLC Block Diagram

Figure 3 shows the FLC block diagram. In the input section, fuzzy logic controls the controller process, and the output is converted into pulse width modulation (PWM).

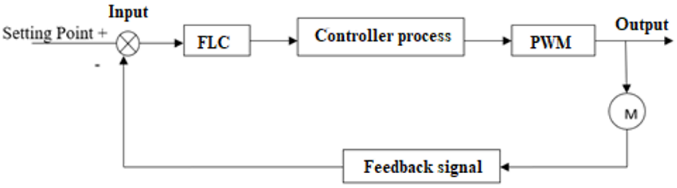


Figure 3. Block diagram of the fuzzy logic control

2.5 FLC Design

Figure 4 shows the design of a FLC. In designing a FLC, three main steps were carried out: the fuzzification process, the rule evaluation process, the defuzzification process, and the FIS integration stage in the FLC.

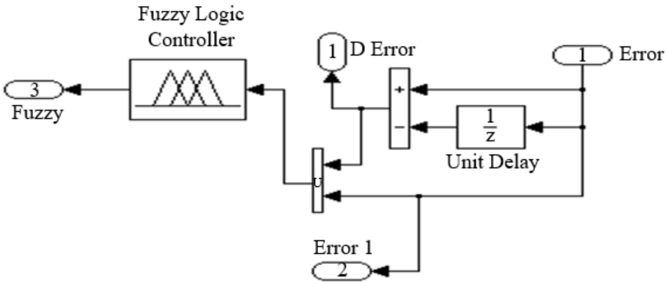


Figure 4. FLC design

2.5.1 Fuzzification

Fuzzification, also known as domain transformation, is the initial step in the FLC process. The conversion of crisp information into fuzzy input is the primary objective of the fuzzification process. Finding the membership function for each crisp input is the first step in converting it from crisp to fuzzy. After deciding the membership function, the fuzzification process takes the crisp input value ($Error$ and $Derror$) and compares it with the existing one to produce the fuzzy input value. The following equations define $Error$ and $Derror$:

$$Error = PV – SP \tag{2}$$

$$Derror = Error(n) – Error(n-1) \tag{3}$$

where, PV is the actual motor speed, SP is the desired motor speed, and Derror is the difference between the current and previous errors.

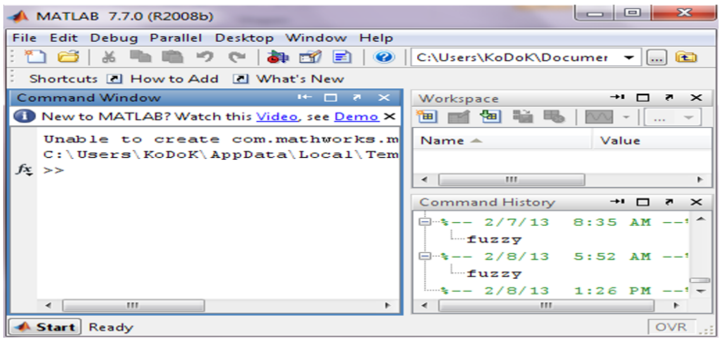
Then the $Error$ and $Derror$ input is processed by fuzzy logic with the following stages:

a) When opening the MATLAB program, there is a front display, as shown in Figure 5.

b) After writing the word fuzzy in the MATLAB command window, the FIZ editor window appears, as shown in Figure 6. In this FIZ editor, input variables and output variables can be determined. The input variables are Error and Derror.

c) To create $Error$ and $Derror$, the FIZ Mamdani type is selected by clicking the file menu, and the "new Mamdani" is selected and clicked. For more than one input, an output can be added by clicking "edit" and then selecting "add input," as shown in Figure 7.

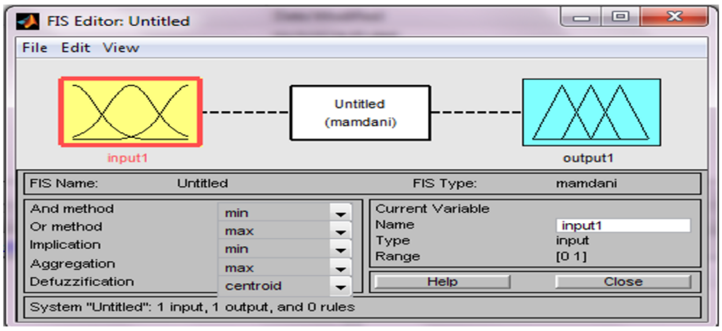
The FLC has five membership functions with a triangular shape for $Derror$, $Error$ and $Output$, as seen in Figure 8.



```
Unable to create com.mathworks.m
C:\Users\KoDoK\AppData\Local\Tem
>>
```

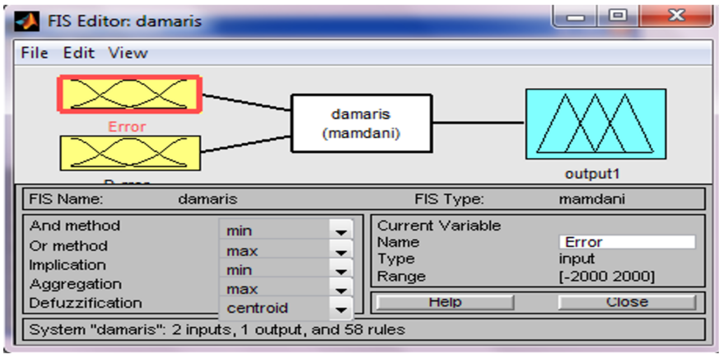
```
%-- 2/7/13   8:35 AM --
  fuzzy
%-- 2/8/13   5:52 AM --
  fuzzy
%-- 2/8/13   1:26 PM --
```

Figure 5. Initial display when opening the MATLAB program



FIS Name: Untitled
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Name: input1
Type: input
Range: [0 1]
System "Untitled": 1 input, 1 output, and 0 rules

Figure 6. FIS editor window



FIS Name: damaris
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Name: Error
Type: input
Range: [-2000 2000]
System "damaris": 2 inputs, 1 output, and 58 rules

Figure 7. Creating input $Error$ and $Derror$

2.5.2 Rule evaluation

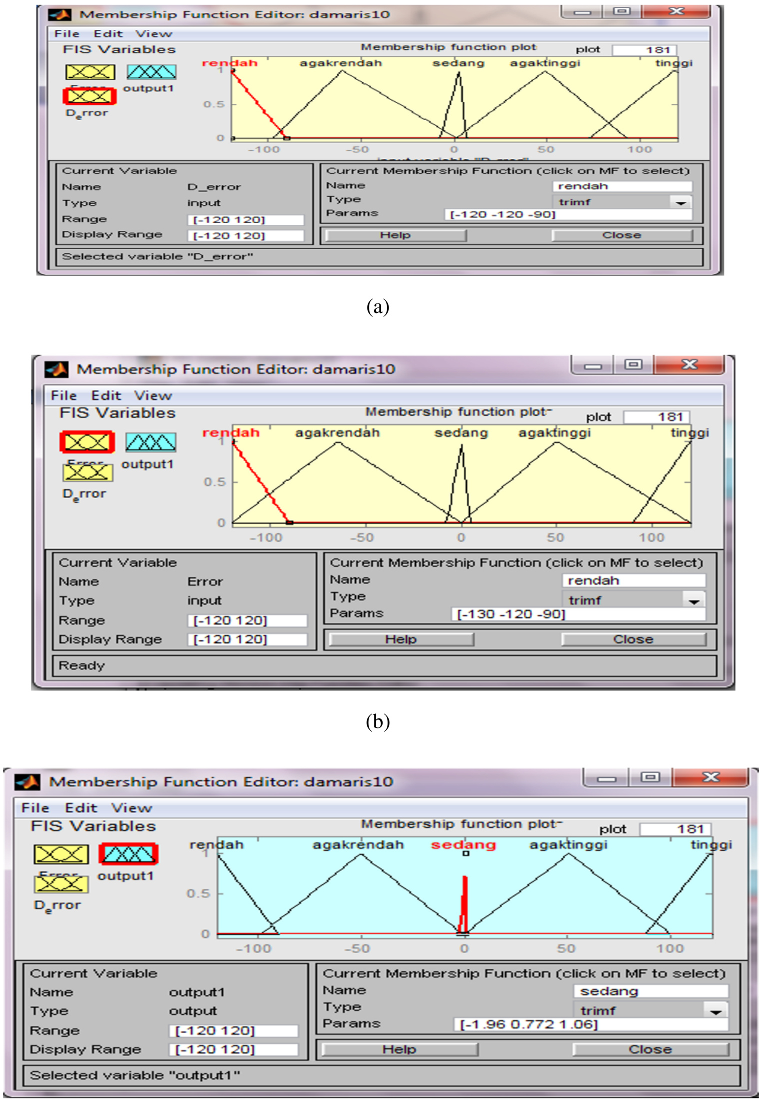
The second stage of the FLC process is rule evaluation, using the rules created to determine the control action that must be carried out according to the input value generated (fuzzy input). At this stage, each rule is evaluated with input from the previous process (fuzzyfication). Fuzzy rules are often if-then statements that specify the activities that must be performed in response to various fuzzy inputs. This system is implemented by selecting and clicking “edit rule” from the “view” menu in the membership function editor, resulting in a display similar to Figure 9. Table 1 shows the if-then rules used in designing fuzzy logic control.

The descriptions are as follows:

- To create a rule, after clicking one of the names in the “if” ($Derror$) column and in the “and” ($Error$) column, the “then” ($Output$) column is selected. After clicking on the “add rule” menu, the rule can appear, as shown in Figure 9. It is repeated until 25 rules can be obtained.

- If there is an error in the rule that is created, it can be changed by selecting “the rule to be changed” and then replaced with the correct rule by clicking “change rule.”

- To delete a rule, the rule can be selected by clicking ”deleted rule.”



Current Variable
Name D_error
Type input
Range [-120 120]
Display Range [-120 120]

Current Membership Function (click on MF to select)
Name rendah
Type trimf
Params [-120 -120 -90]

Selected variable "D_error"

(a)

Current Variable
Name Error
Type input
Range [-120 120]
Display Range [-120 120]

Current Membership Function (click on MF to select)
Name rendah
Type trimf
Params [-130 -120 -90]

Ready

(b)

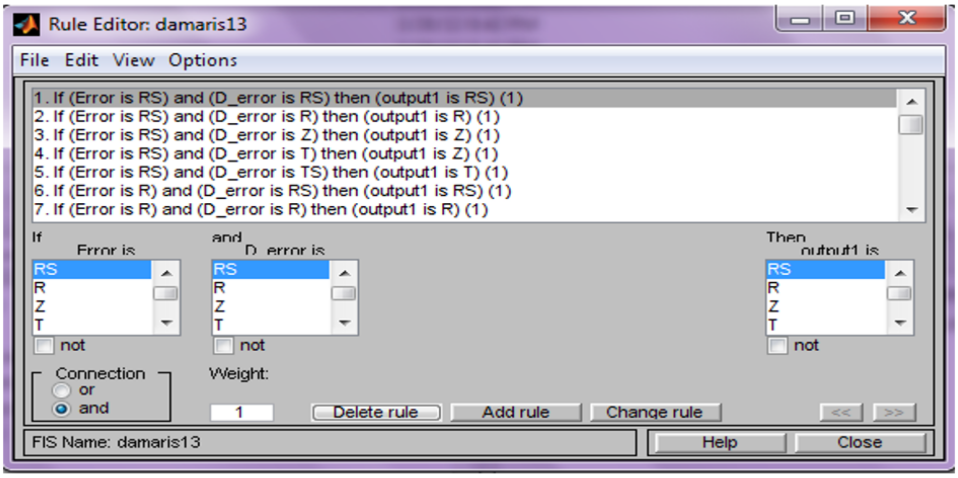
Current Variable
Name output1
Type output
Range [-120 120]
Display Range [-120 120]

Current Membership Function (click on MF to select)
Name sedang
Type trimf
Params [-1.96 0.772 1.06]

Selected variable "output1"

(c)

Figure 8. Membership functions for (a) $Derror$; (b) $Error$; (c) $Output$



1. If (Error is RS) and (D_error is RS) then (output1 is RS) (1)
2. If (Error is RS) and (D_error is R) then (output1 is R) (1)
3. If (Error is RS) and (D_error is Z) then (output1 is Z) (1)
4. If (Error is RS) and (D_error is T) then (output1 is Z) (1)
5. If (Error is RS) and (D_error is TS) then (output1 is T) (1)
6. If (Error is R) and (D_error is RS) then (output1 is RS) (1)
7. If (Error is R) and (D_error is R) then (output1 is R) (1)

Connection ○ or ● and

Weight: 1

FIS Name: damaris13

Figure 9. Display rule editor

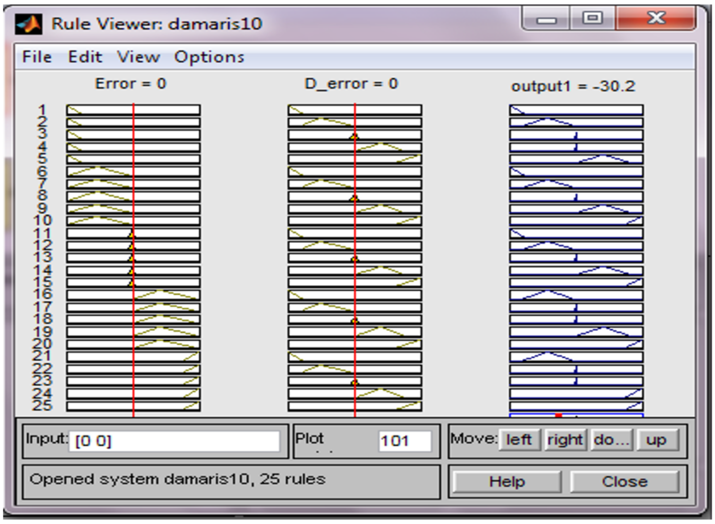
Table 1. Key parameters of our model

		ERROR				
		RS	**R**	**Z**	**T**	**TS**
DERROR	**RS**	RS	R	Z	Z	T
	R	RS	R	Z	T	TS
	Z	RS	R	Z	T	TS
	T	R	Z	Z	T	TS
	TS	R	Z	Z	TS	TS

Note: [R1]: if ($Derros$ is RS) and ($Error$ is RS) then ($Output$ is RS); [R2]: if ($Derros$ is RS) and ($Error$ is R) then ($Output$ is R); [R3]: if ($Derros$ is RS) and ($Error$ is Z) then ($Output$ is Z); [R4]: if ($Derros$ is RS) and ($Error$ is T) then ($Output$ is Z); [R5]: if ($Derros$ is RS) and ($Error$ is TS) then ($Output$ is T); [R6]: if ($Derros$ is R) and ($Error$ is RS) then ($Output$ is RS); [R7]: if ($Derros$ is R) and ($Error$ is R) then ($Output$ is R); [R8]: if ($Derros$ is R) and ($Error$ is Z) then ($Output$ is Z); [R9]: if ($Derros$ is R) and ($Error$ is T) then ($Output$ is T); [R10]: if ($Derros$ is R) and ($Error$ is TS) then ($Output$ is TS); [R11]: if ($Derros$ is Z) and ($Error$ is RS) then ($Output$ is RS); [R12]: if ($Derros$ is Z) and ($Error$ is R) then ($Output$ is R); [R13]: if ($Derros$ is Z) and ($Error$ is Z) then ($Output$ is Z); [R14]: if ($Derros$ is Z) and ($Error$ is T) then ($Output$ is T); [R15]: if ($Derros$ is Z) and ($Error$ is TS) then ($Output$ is TS); [R16]: if ($Derros$ is T) and ($Error$ is RS) then ($Output$ is R); [R17]: if ($Derros$ is T) and ($Error$ is R) then ($Output$ is Z); [R18]: if ($Derros$ is T) and ($Error$ is Z) then ($Output$ is Z); [R19]: if ($Derros$ is T) and ($Error$ is T) then ($Output$ is T); [R20]: if ($Derros$ is T) and ($Error$ is TS) then ($Output$ is TS); [R21]: if ($Derros$ is TS) and ($Error$ is RS) then ($Output$ is R); [R22]: if ($Derros$ is TS) and ($Error$ is R) then ($Output$ is Z); [R23]: if ($Derros$ is TS) and ($Error$ is Z) then ($Output$ is Z); [R24]: if ($Derros$ is TS) and ($Error$ is T) then ($Output$ is TS); [R25]: if ($Derros$ is TS) and ($Error$ is TS) then ($Output$ is TS).

2.5.3 Defuzyfication

The final stage in the fuzzy logic process is to convert the fuzzy output into a crisp output. Fuzzy logic data must be converted to crisp data since the plant only recognizes firm values as actual amounts for process regulation. The centroid approach was utilized for defuzzification. This centroid approach is known as the Center of Area (CoA) or Center of Gravity (CoG). In this method, the crisp output value was calculated using the CoG of the decision-making process outcome curve, as seen in Figure 9. After selecting "view rule" from the view menu in the rule editor, a display can appear, as shown in Figure 10.



Error = 0

D_error = 0

output1 = -30.2

Input: [0 0]

Plot 101

Opened system damaris10, 25 rules

Figure 10. Rule viewer display

The descriptions are as follows:

- Each rule is selected per row, where each variable is plotted in column form.

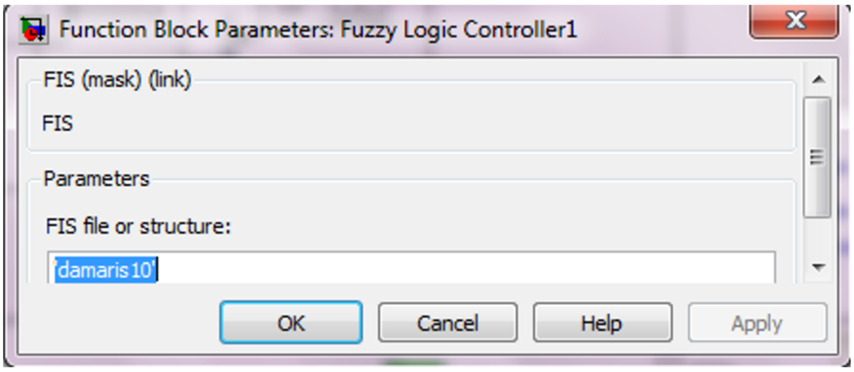
- The first three columns are the rule section using "if" (stating the condition). The following two columns are the rule section using "then," which is the action or decision-making.

- The rules in the first three columns plotted in yellow state the fulfilled rules, while the rules in the following two columns plotted in blue state the results or decision-making.

The FIS input stage on the FLC is as follows:

- After clicking on the fuzzy box, it can appear, as shown in Figure 11.

- Then the name of the FIS that has been created can be entered.
- After entering the FIS name, fuzzy logic can run by clicking “ok.”



FIS (mask) (link)

FIS

Parameters

FIS file or structure: 'damaris10'

Figure 11. FIS block in FLC

3 Results

3.1 DC Motor Testing with No-Load Field Control

Three comparison tests of DC motors were conducted in this study: without fuzzy logic control, FLC with field control, and armature control under no-load conditions. Figure 12 consecutively compares the transient response of DC motor speed without control and fuzzy logic control (field control and armature control) without load.

Table 2. Comparison of the response parameters of the FLC system without load

No.	Parameter	Without Control	FLC	
			Field Control	Armature Control
1	Armature voltage	250	280 volt	279 volt
2	Armature current	0 ampere	2 ampere	1 ampere
3	Fields current	1.5 ampere	1.6 ampere	-
4	Maximum overshoot	204%	191%	1.773%
5	Settling time	4.208 sec	2.930 sec	0.144 sec
6	Delay time	0.08 sec	0.15 sec	0.027 sec
7	Rise time	0.25 sec	0.112 sec	0.482 sec

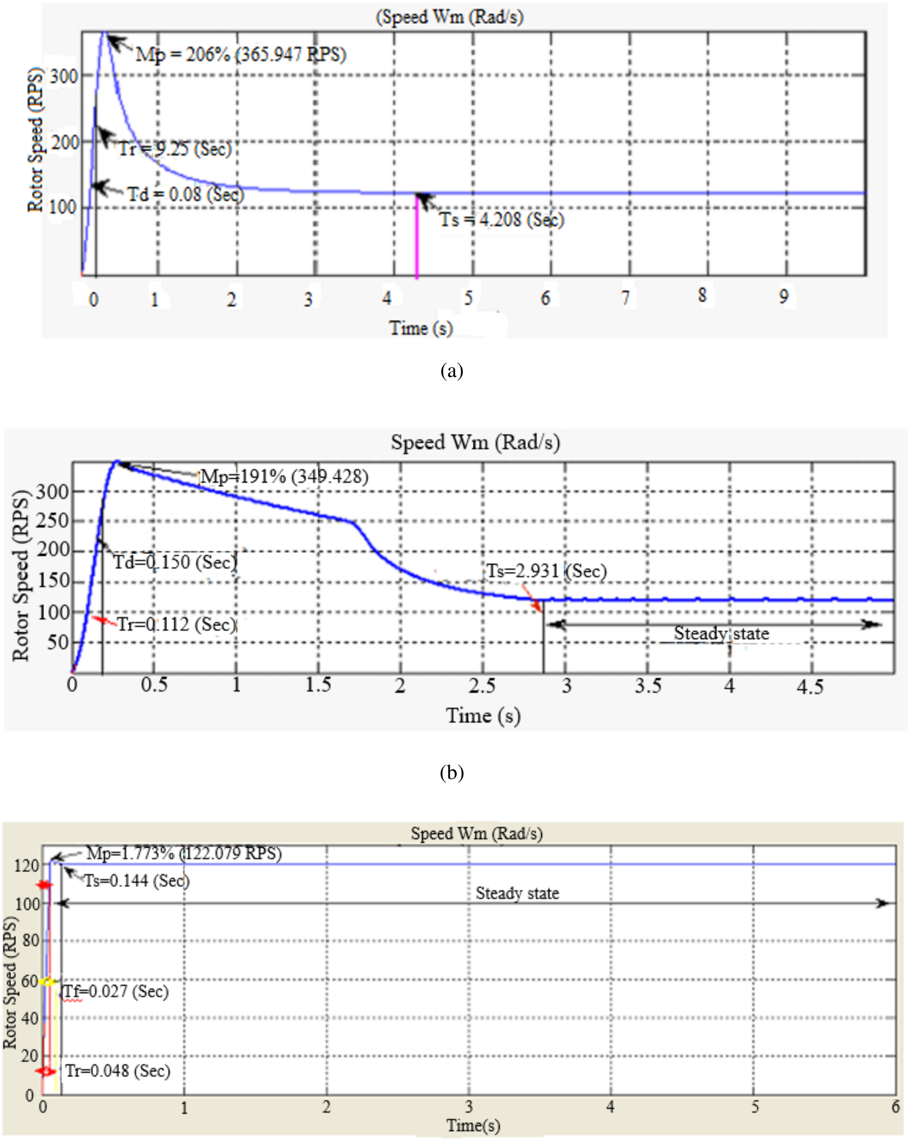
Based on Figure 12, it can be seen that the speed response results of the DC motor without control have 4.208 seconds to reach a steady state (120 RPS) with a maximum overshoot of 365.947 RPS or 206%. Meanwhile, the speed response results of the DC motor with a FLC for field control have 2.931 seconds to reach a steady state of 120 RPS with a maximum overshoot of 349.428 RPS or 190%. Compared to the FLC for armature control, the DC motor’s speed response takes 0.099 seconds to reach a steady state, with a maximum overshoot of 122.079 RPS (1.773%). Table 2 shows a comparison of the response characteristics of the FLC system from field control and armature control to motor speed.

3.2 Testing with Load Variations

In this study, two motor loading models were used, namely constant loading and step loading.

3.2.1 Constant loading (Disturbance)

Figure 13 compares the FLC response between field and armature control at a DC motor speed with a load of 45 Nm. It can be seen that the reaction of the FLC to the DC motor speed with field control at a constant load of 45 Nm to attain a steady state condition takes 1.15 seconds, whereas armature control takes only 0.099 seconds. Table 3 shows the response of the FLC system at DC motor speed with varying loads of 10, 20, 30, 40 and 45 Nm. It can be seen that despite the increase in loading on the DC motor, the motor RPM remains constant and in a steady state from a load of 10 to 45 Nm.



(a)

(b)

(c)

Figure 12. Transient response of DC Motor Speed: (a) Without fuzzy logic control; (b) Fuzzy logic control with field control; (c) Fuzzy logic control with armature control

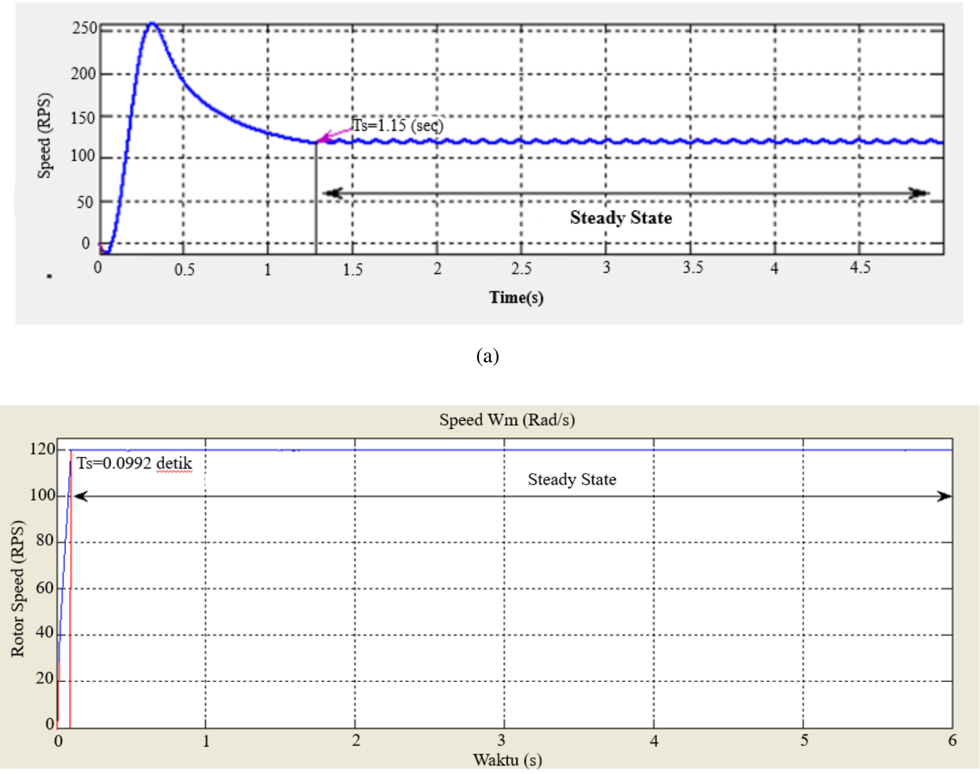
Table 3. Comparison of FLC responses between field and armature control on DC motor speed with load variations

Load (Nm)	Steady State (RPS)	Voltage (Volts)		Settling Time (Sec)		Armature Current (Ampere)		Fields Current (Ampere)
		Fc	**Ac**	**Fc**	**Ac**	**Fc**	**Ac**	**Field Control**
10	120	279	278.9	1.540	0.073	5	5	1.6
20	120	278.9	278.5	1.500	0.069	10	10	1.58
30	120	278.9	278.4	1.240	0.098	15	16	1.55
40	120	278.9	278.05	1.180	0.091	21	21	1.5
45	120	278.9	277.93	1.150	0.099	24	23	1.47

Note: Fc means field control and Ac means armature control.

3.2.2 Step loading (Disturbance)

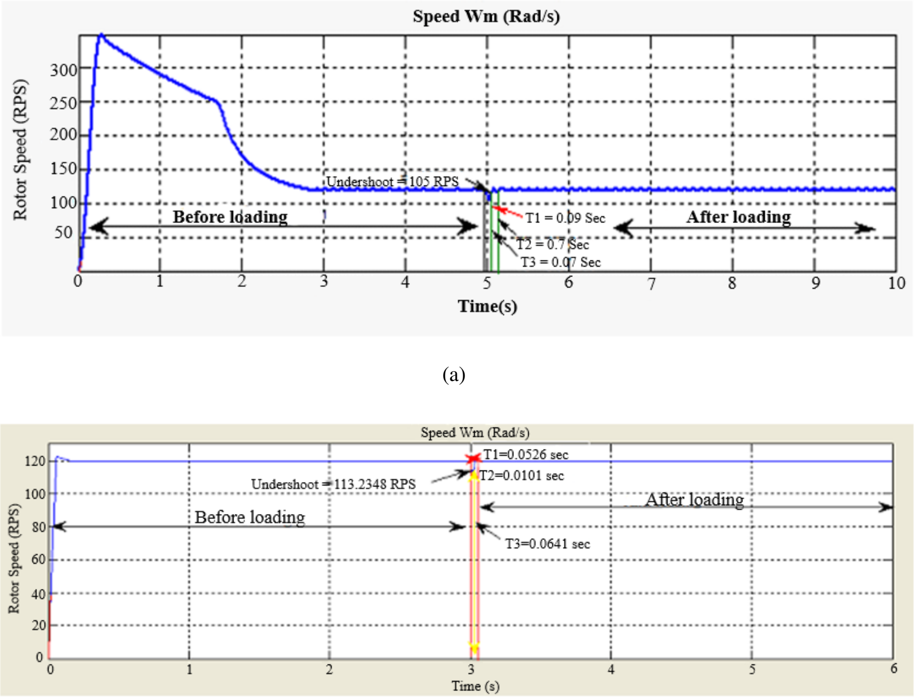
In this test, the provision of disturbance variations in step load variations is the same as the loading variations: 10, 20, 30, 40 and 45 Nm. Figure 14 shows the speed response of the step loading variation for a load with a sample of 45 Nm.



(a)

(b)

Figure 13. Fuzzy logic control speed response with a constant load of 45 Nm: (a) Field control; (b) Armature control



(a)

(b)

Figure 14. Transient response of FLC with a 45 Nm step load: (a) Field control; (b) Armature control

The results show that the DC motor speed control response with a step load of 45 Nm has a loading time of 5 seconds for field control, while armature control takes 3 seconds. Furthermore, the time required for the response from the condition of starting to be loaded to reaching a steady state again (recovery time) for the FLC with field control is 5.09 seconds, with a maximum overshoot of 258.92 RPS. As a comparison of armature control, the time required for the response from the condition of starting to be loaded to reaching a steady state again (recovery time) for the FLC takes 3.0526 seconds, with a maximum overshoot of 122.0798 RPS. Table 4 compares changes in the response of the DC motor speed FLC system with a step load of 10 Nm, 20 Nm, 30 Nm, 40 Nm and 45 Nm for both controls. Similar to the constant load, for step load, it can be seen that even though there is an increase in load on the DC motor, the motor RPM remains constant and steady from a load of 10 Nm to 45 Nm for both controls. The apparent difference is that the T1, T2, and T3 response times for the armature control are shorter than for the field control. In addition, the undershoot is also lower.

Table 4. FLC speed response to step load variation

Load (Nm)	**Steady State (RPS)**	**Response Time (Sec)**						**Undershoot (RPS)**		**Voltage (Volt)**		**Current (Ampere)**	
		T_1		T_2		T_3							
		Fc	**Ac**	**Fc**	**Ac**	**Fc**	**Ac**	**Fc**	**Ac**	**Fc**	**Ac**	**Fc**	**Ac**
10	120	0.11	0.008	0.05	0.002	0.09	0.006	116	119.58	278.9	279	5	6
20	120	0.15	0.023	0.05	0.002	0.11	0.021	114	118.50	278.9	279	10	10
30	120	1.22	0.035	0.51	0.006	0.15	0.029	110	116.79	278.9	279	15	15
40	120	0.33	0.041	0.42	0.008	0.12	0.033	106	114.53	278.9	279	21	21
45	120	0.09	0.053	0.72	0.010	0.07	0.046	105	113.23	279	279	24	23

Note: Fc means field control and Ac means armature control.

4 Discussion

Most researchers have employed the armature voltage control approach to regulate the speed of DC motors, with the rated motor speed serving as the reference speed. They have applied FLC [8, 13, 17], Nonlinear AutoRegressive Moving Average (NARMA) controllers [20–22], PI or PID controllers [6, 11], and a mix of both [2, 23]. In armature voltage control, the rated field voltage determines the rated speed, and the rated motor speed is typically proportionate to the armature voltage. Thus, adjusting the armature voltage can change the motor speed below its rated speed. Since the maximum torque output from the motor is anticipated, the rated voltage provided to the field is kept at its rated value. By altering the armature voltage in the constant torque area, Sadiq et al. [2] claimed that the armature voltage control approach can attain speeds lower than the specified speed. On the other hand, by altering the field voltage in the constant power zone, the field current control approach allows for speeds exceeding the rated speed; both can be accomplished using a combined control method.

Next, the speed of the DC motor can be controlled by adjusting the armature voltage while keeping the field voltage constant. As the voltage delivered to the armature grows, so does the armature current. As the armature current increases, the motor creates more torque, increasing its speed. According to Mthboob et al. [24], because armature resistance gradually decreases, motor speed increases approximately proportionally to armature voltage. However, the rated armature voltage represents the highest voltage that can be supplied to the armature.

The simulation of field control with various loadings was tested in this study. The response of the system test under constant load conditions, starting from 10, 20, 30, 40 and 45Nm, with field control, provides a setpoint of 120 RPS. At the initial start on the DC motor, the load is directly given without requiring loading time. The greater the constant load given, the decrease in voltage on the motor, increasing the field current and armature current. The time for the DC motor speed to reach a steady state changes according to the load given. In this study, a comparison of the DC motor speed response with field current and armature current control was also carried out. The findings in this study show that under no-load conditions, there is a difference in system response time between armature current and field current control. In armature current control, it has a faster response time than required for field control to reach a steady state. Armature current control takes 0.144 seconds to reach a steady state, and the resulting overshoot is 1.773%.

Meanwhile, field control takes 2.93 seconds to reach a steady state, and the resulting overshoot is more significant at 191%. In addition, the response of both controls at the initial start of the motor speed from 0% to 90% is similar between armature and field control. At the start, the motor speed reaches 90%, the armature current control requires a time rise of 0.048 seconds, and the field current control requires a time rise of 0.112 seconds. Likewise, when the motor speed reaches 50%, the armature current control requires a time delay of 0.027 seconds, while the field current control requires a time delay of 0.015 seconds.

Furthermore, in the condition of giving step load variation, a setpoint of 120 RPS is given. When given a disturbance with a load of 45 Nm, the motor speed drops below the setpoint. There is a difference in control response between field current and armature current control during loading. When the load is given, the DC motor speed drops, and the control functions to stabilize the motor speed back to a steady state. It can be seen that the field control of the motor speed drops to 105 RPS, slower than the armature current control, where the motor speed drops to 113.23 RPS. Based on the simulation results, armature control shows a faster rise time than field control. This shows that armature control is more responsive to setpoint changes, while field control provides better accuracy regarding motor speed drops when given a load. Therefore, the choice between field and armature control using fuzzy logic depends on the application's specific requirements. Field control is more suitable for applications that require high torque at low speeds and good stability, while armature control is more suitable for applications that require fast response and a wide speed range. The right fuzzy controller design can produce optimal performance in both cases. In addition, FLC can be applied to both control methods, field and armature control. The correct method depends heavily on the load characteristics and system performance requirements. By understanding the advantages and disadvantages of each method and the factors that influence them, the most optimal method can be selected for a particular application.

5 Conclusions

It can be concluded as follows:

a) Based on the research results, the comparison between field and armature control on separately excited DC motors using fuzzy logic shows that armature control provides a faster response but with a lower and more stable overshoot compared to armature control, which produces a more extended response to reach steady state conditions.

b) This study has successfully identified the advantages and disadvantages of both control methods, namely field and armature control. Armature control is generally better than field control under changing and constant load variations in speed response.

c) The choice between field and armature control on separately excited DC motors highly depends on load characteristics, performance requirements, and system constraints. For applications that require fast response and high acceleration, armature control can be the right choice. However, field control may be more appropriate for applications that prioritize stability and reliability. Further studies need to be conducted to explore combining both methods or applying adaptive control techniques to achieve optimal performance.

d) This study has opened up opportunities for further development in the field of DC motor control. One exciting direction is integrating fuzzy logic with other artificial intelligence techniques, such as neural networks or genetic algorithms, to improve the performance and flexibility of control systems. In addition, exploring the use of more sophisticated sensors and more accurate motor models can provide more precise results.

Author Contributions

Conceptualization, S.K. and S.S.; methodology, S.K.; software, N.; validation, S.K., S.S. and W.G.; formal analysis, S.K.; investigation, S.K.; resources, N.; data curation, W.G.; writing—original draft preparation, S.S.; writing—review and editing, S.S.; visualization, N.; supervision, S.K.; project administration, S.K.; funding acquisition, S.K.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

Ac	armature control
FC	field control
If	the field current
J	gravitational acceleration, m.s $\cdot^{-2}$
k	constant
K	thermal conductivity, W. $\mathrm{m}^{-1} \cdot\ \mathrm{K}^{-1}$
$M2$	maximum overshoot
PID	proportional integral derivative
PWM	pulse width modulation
ts	settling time