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Investigation and Analysis of Fuzzy Logic Controller Method on DC-DC Buck-Boost Converter

I Ketut Wiryajati[1*], I Nyoman Wahyu Satiawan[1], I Made Budi Suksmadana[1], Bagas Briantara Putra Wiwaha[1]

[1]Electrical Engineering Departement, Mataram University, Mataram, Indonesia.

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Corresponding Author:
I Ketut Wiryajati
kjatiwirya@uram.ac.id

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Abstract: This study evaluates the performance of PID, Mamdani FLC, and Sugeno FLC controllers on a DC-DC Buck-Boost Converter to determine their suitability for various control applications. The Buck-Boost Converter, operating in conventional configuration, was modeled using MATLAB/Simulink with parameters: input voltage (12 V), output voltage (24 V), resistor (6.5 Ω), capacitor (1.5 μF), and inductor (10 μH). The converter's switching frequency was set at 20 kHz to ensure stability under varying load and input conditions. PID control was implemented using the Ziegler-Nichols tuning method, while fuzzy controllers utilized Gaussian membership functions and 3×3 fuzzy rule bases. Mamdani employed the centroid defuzzification method, whereas Sugeno used weighted average defuzzification. The simulation tested performance metrics, including rise time, overshoot, output stability, and voltage ripple, under conditions of load and input voltage variations. Results show that PID achieved the fastest rise time (72.452 ms) but exhibited higher sensitivity to input changes. Sugeno provided the most stable output with minimal ripple, while Mamdani demonstrated greater adaptability but less stability compared to Sugeno. Statistical analysis confirmed significant differences in rise time but no differences in overshoot across methods. These findings highlight the strengths of each method, with Sugeno being optimal for stability and precision, PID for fast response, and Mamdani for complex fuzzy logic applications.

Keywords: Buck – boost; DC-DC converter; Fuzzy logic controller; Mamdani; Sugeno

Introduction

In the modern era, the increasing demand for renewable and efficient energy sources has driven the development of advanced technologies to meet these needs (Flatley, 2023; Bhattacharya & Kumar, 1997). One of the key innovations gaining significant attention is the DC-DC converter, particularly the buck-boost converter, which plays a vital role in various renewable energy applications (Makoundi et al., 2024; Raghavendra et al., 2020). As highlighted in recent studies by Dharavath & Pradabane (2024) and Yuan et al. (2023), this converter possesses a unique ability to convert DC voltage between higher and lower levels bidirectionally. This feature makes it highly suitable for renewable energy systems such as solar panels, and wind turbines, where input voltage often fluctuates significantly (Hashemzadeh et al., 2022; Razali et al., 2023).

Voltage fluctuations present a significant challenge for buck-boost converters, prompting researchers to focus on mitigating these fluctuations by employing conventional and modern control systems (Al-attwani et al., 2024a; Al-Attwani et al., 2024b; Ennajih et al., 2024). Beyond voltage regulation, another major challenge in

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utilizing buck-boost converters lies in improving their performance through control design and optimization. The primary objective is to maintain system stability and responsiveness under varying operating conditions (Lainfiesta & Zhang, 2020). In addition to conventional controllers, the Fuzzy Logic Controller (FLC) has proven to be a relevant and effective control method in education (Devita & Defit, 2024), banking (Sugiharto et al., 2023), as well as in electronic devices such as AVR, robotics, temperature control, and others (Kodaloğlu & Kodaloğlu, 2023; Mazibukol et al., 2022; Kamis et al., 2022). FLC offers a flexible and adaptive approach, standing out compared to conventional controllers, which often struggle to manage nonlinearities and uncertainties commonly encountered in healthcare technologies with complex data, as well as in renewable energy systems (Dewi et al., 2023; Restiani & Purwadi, 2024; Benzaouia et al., 2024; Eswaraiah & Balakrishna, 2024). FLC has been practically implemented by Mamdani and Sugeno, each with their respective rule bases (Wahyuni et al., 2022).

Mamdani FLC is renowned for its ease of interpretation. By employing linguistic variables, this approach is intuitive and straightforward, making it an ideal choice for applications requiring high flexibility without demanding extreme control accuracy (Fayaz et al., 2019). According to research by Al-Attwani et al. (2024b) Mamdani FLC applied to a buck-boost converter achieves an average response time of 0.5 seconds, satisfactory steady-state stability, and a voltage ripple of 2.5%.

In contrast, Sugeno FLC uses mathematical functions for its output, enabling more precise and efficient control. This makes it particularly suitable for applications prioritizing voltage ripple reduction and energy efficiency enhancement (Kumar et al., 2024). Research by Ibrahim et al. (2023) reported that the Sugeno FLC achieved an energy efficiency of 93%, with a voltage ripple of 1.8% and a response time that is 35.49% faster, outperforming Mamdani in these aspects.

Despite its numerous benefits, the implementation of FLC is not without challenges (Duong et al., 2022). One major obstacle is selecting the most appropriate FLC method for a specific application, as its effectiveness depends on system parameters, operating conditions, and control objectives. Additionally, designing an FLC requires a deep understanding of fuzzy logic principles, including the development of membership functions and inference rules (Simo et al., 2022). This complexity can pose significant barriers for engineers unfamiliar with the methodology.

This study aims to discuss and analyze the suitability of Mamdani and Sugeno FLCs for controlling buck-boost converters. Simulation models for both methods are designed using software tools that allow precise variable control, enabling direct performance comparison. Key performance parameters compared include system response time, stability, energy efficiency, and voltage ripple (Ahmed, 2020). The analysis results are presented in graphs and tables to facilitate interpretation.

This research not only focuses on comparing the performance of Mamdani and Sugeno FLCs in the context of buck-boost converters but also seeks to provide practical guidelines for engineers in selecting the most appropriate method based on specific requirements. Mamdani FLC offers ease of implementation and high flexibility, while Sugeno FLC excels in control accuracy and energy efficiency. By exploring the strengths and limitations of each method, this study supports the development of more efficient, reliable, and adaptive energy systems to address the challenges of modern technology.

Method

The research methodology consists of five main stages, which can be detailed as follows:

Step 1: Identification of Key Parameters for the Buck-Boost Converter (Makoundi et al., 2024)

Key parameters, such as input voltage, output voltage, inductance, capacitance, and resistance, are identified based on real-world conditions. In this study, the input voltage is set within the range of 12V–24V, while the desired output voltage is between 5V–48V. The calculations for minimum inductance and output capacitance are performed using the buck-boost converter equations (Gaozhong et al., 2024), as shown in Equations (1) and (2).

$$L_{min} = \frac{(V_{out} - V_{in}).D.T}{I_{ripple}} \tag{1}$$

$$C_{out} = \frac{I_{Load}.D}{\Delta V_{out}.I_{switching}} \tag{2}$$

With L_{min} as the minimum inductance, V_{out} as the output voltage, V_{in} as the input voltage, D as the duty cycle, T as the period, I_{ripple} as the ripple current, C_{out} as the capacitor value, I_{Load} as the load current, $I_{switching}$ as the switching current, and ΔV_{out} as the change in output voltage.

Step 2: Design of the Buck-Boost Converter Model

The buck-boost converter model is designed as illustrated in Figure 1, using MATLAB/Simulink software. The simulation is then conducted following the procedures in Simulink (Yang, 2024). In this study, real-time modeling is employed by setting the parameters according to the converter specifications.

The simulation model of the DC-DC buck-boost converter is designed to capture system behavior under various input conditions, including voltage fluctuations that reflect actual operational scenario fluctuations that reflect actual operational scenarios.

Step 3: Design of the Fuzzy Logic Controller (FLC)

Two FLC methods, Mamdani and Sugeno, are designed for performance evaluation. The membership functions are constructed in triangular and trapezoidal forms, with input/output domains encompassing voltage error and voltage change. Fuzzy rules are applied based on linguistic logic (Yin & Hadjiloucas, 2023), such as:

If the error is small and the voltage change is positive, then the output is moderate.

If the error is large and the voltage change is negative, then the output is low.

The membership function structure is kept consistent to facilitate evaluation; however, the parameter values and the number of rules are adjusted for each method (Mamdani and Sugeno).

In this study, trapezoidal and linear models are used. The trapezoidal membership function is a type of membership function employed in fuzzy logic to determine the degree of membership of a value in a fuzzy set (Maity et al., 2019). Its shape resembles a trapezoid, with two parallel sides and two sloping sides forming the incline. This function is defined by four key parameters: the starting point (a), the rising point (b), the falling point (c), and the ending point (d), which control the position and width of the trapezoidal shape (Lin, 2023). as shown in Eq. 3 is as follows.

$$\mu(x) = \begin{cases} 0; & x \leq a \text{ or } x \geq d \\ \dfrac{x-a}{b-a}; & a \leq x \leq c \\ 1; & b \leq x \leq b \\ \dfrac{d-x}{d-c}; & c \leq x \leq d \end{cases} \quad (3)$$

A linear membership function is a type of membership function in fuzzy logic that uses a straight line to determine the degree of membership of a value within a fuzzy set. It consists of two main forms: the rising linear function and the falling linear function, each used to represent changes in membership degree from low to high or vice versa. This function is simpler compared to trapezoidal or triangular shapes, yet it remains effective for systems requiring minimal computational effort in membership calculations. as shown in Equation 4 is as follows.

$$\mu(x) = \begin{cases} 0; & x \leq a \\ \dfrac{x-a}{b-a} & a \leq \ x \leq b \\ 1; & x \geq b \end{cases} \quad (4)$$

Where: (a) is the starting point where membership begins to increase, and (b) is the point where membership reaches its full value (1).

Step 4: Implementation of FLC on the Buck-Boost Converter Model

Both FLC methods are implemented in the simulation model to evaluate how each controller influences system performance (Téllez-Velázquez & Miranda-Luna, 2023). To facilitate comparison, the structure of the membership functions is kept consistent, while the number of rules and fuzzy parameters are adjusted for each method.

Step 5: Performance Analysis

Performance analysis is conducted by comparing key parameters, including response time, system stability, voltage ripple, and energy efficiency (Sharma, 2022; Andrianto et al., 2024). The simulation results are presented in the form of graphs and tables to facilitate interpretation and comparison.

Result and Discussion

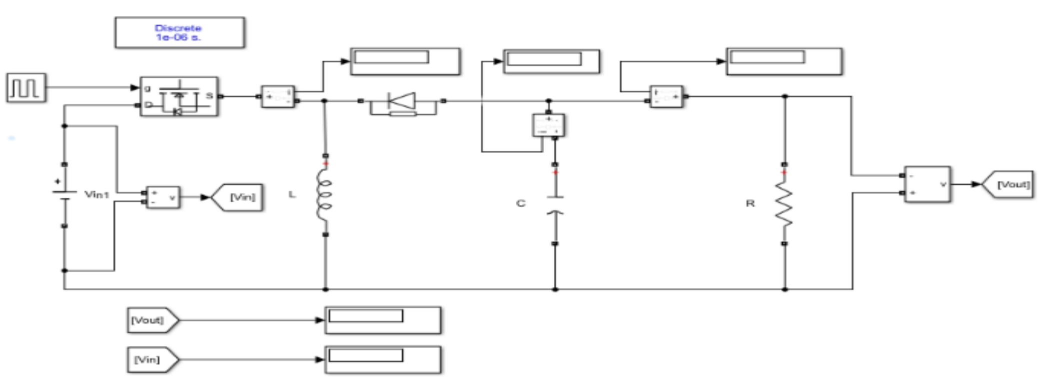

Figure 1. Basic DC-DC buck-boost converter

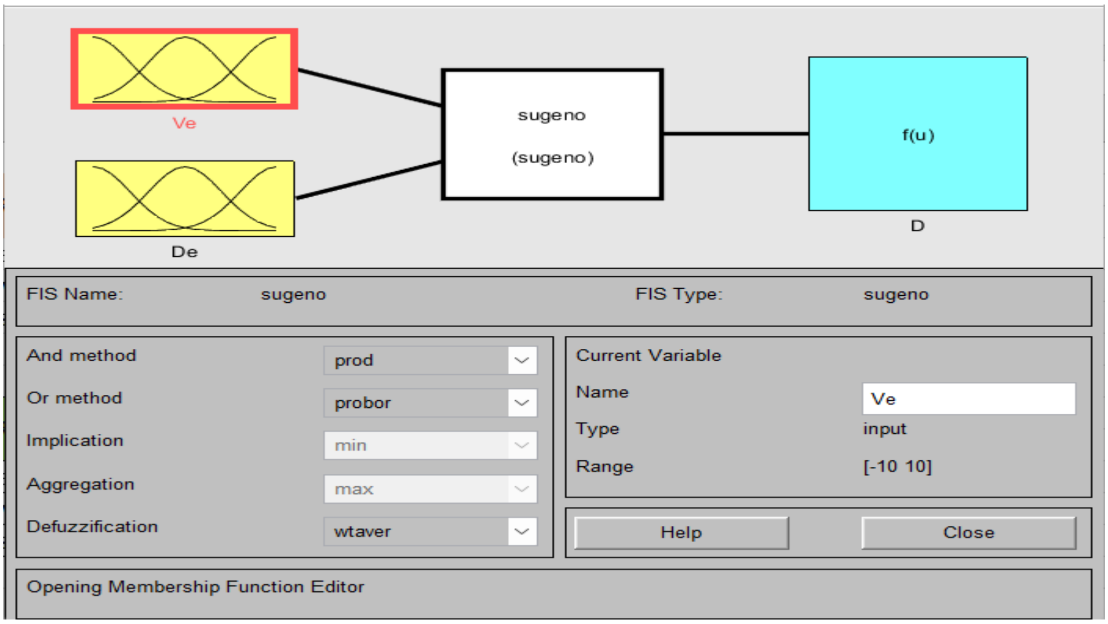

Figure 2. Sugeno fuzzy logic controller model scheme on DC-DC buck-boost converter

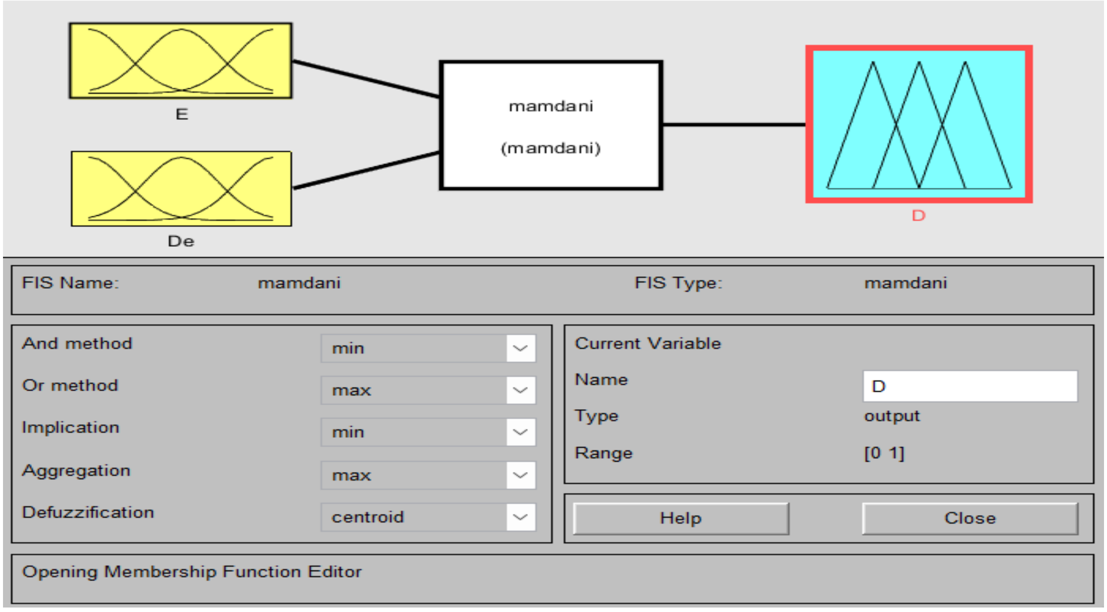

Figure 3. Mamdani fuzzy logic controller model scheme on DC-DC buck-boost converter

In this test, a DC-DC Buck-Boost Converter scheme is used as shown in Figure 1, with parameter data presented in Table 1. The DC-DC Buck-Boost converter has technical specifications of an input voltage of 12 Volts and an output voltage of 24 Volts, indicating that the converter functions as both a step-down (buck) and a step-up (boost) converter. The resistor used has a value of 6.5 Ohms, the capacitor is 75×10^{-4} Farads, and the inductor is 10×10^{-6} Henry. The converter's switching frequency is set at 20 kHz to ensure a fast and stable response. These parameters are chosen to represent real-world applications, aiming to maximize the converter's efficiency and stability under various load conditions and input voltage variations.

Table 1. Parameter DC-DC buck-boost converter

Parameter	Value	Unit
Input Voltage	12	Volt
Output Voltage	24	Volt
Resistor	6.5	Ohm
Capacitor	1.5e-6	Farad
Inductor	10e-6	Henry
Frequency	20	KHz

Figure 2 shows the control scheme of a Sugeno Fuzzy Logic System (FLS) with two input variables, Ve (Error) and De (Derivative of Error), and one output variable, D. Each input has a Gaussian-shaped membership function used to determine the degree of membership of each input value. In the Sugeno block at the center, processing is done by applying fuzzy rules using the product method for the "AND" operation and the probabilistic OR (probor) for the "OR" operation. The final stage, defuzzification, uses the weighted average (wtaver) method, resulting in the control output f(u) , which is then used to regulate the controlled system. This structure provides a more linear response and is suitable for high-precision control applications.

Figure 3 shows the control scheme of the Mamdani Fuzzy Logic System (FLS) with two input variables, E (Error) and De (Derivative of Error), and one output variable, D (Voskoglou, 2022). The input variables E and De each have Gaussian-shaped membership functions that classify the input values into several membership categories. The Mamdani block acts as an inference engine that applies fuzzy rules using the "min" logic method for the AND operation and "max" for the OR operation. After applying the fuzzy rules, the defuzzification stage is performed using the Centroid method, which calculates the average of the centroid area to obtain the final output value. This defuzzified result is displayed as control output D, with a range of [0, 1], which functions to regulate the system response based on the given input.

The primary distinction between the two methods lies in both their defuzzification techniques and the nature of their output types. Sugeno's defuzzification method, which relies on weighted average calculations, is designed to produce a quicker and more stable response, making it particularly well-suited for adaptive control systems that require real-time adjustments and steady performance under varying conditions (Zangeneh et al., 2020). On the other hand, Mamdani's approach, known for its intuitive logic and interpretability, is ideal for applications that involve complex fuzzy logic reasoning, where intricate rule-based interpretations are necessary to handle nuanced control tasks or accommodate a broader range of logical inferences within the system.

In Table 2 and 3, the rule bases with 3x3 dimensions for Mamdani and Sugeno are shown, respectively. In Its, the difference between the Mamdani and Sugeno rule bases can be analyzed based on the given 3x3 table. Both models have a rule arrangement with the same structure, a 3x3 matrix connecting the two main inputs: Error (E/Ve) and Derivative of Error (De); however, the output response differs according to the characteristics of each method.

Table 2 Mamdani rule-based scheme in fuzzy logic controller on DC-DC buck-boost converter

E/De	N	Z	P
P	P	P	Z
Z	P	Z	N
N	Z	N	N

Table 3. Sugeno rule-based scheme in fuzzy logic controller on DC-DC buck-boost converter

E/De	N	Z	P
N	N	N	P
Z	N	Z	N
P	P	Z	P

Table 4 shows the simulation results with the controllers used, where it can be seen that the three methods (PID, Mamdani, and Sugeno) exhibit different performance characteristics for the tested performance parameters, namely maximum value, average (mean) value, minimum value, rise time, and overshoot. This study compares the performance of three control methods—PID, Mamdani, and Sugeno—on a buck-boost converter system. The analysis is conducted using descriptive and inferential statistical approaches to evaluate five performance parameters: maximum value (Max), average value (Mean), minimum value (Min), rise time (Time Rise), and overshoot.

Table 4. Performance parameters on DC-DC buck-boost converter

Performance	PID	Mamdani	Sugeno
Max	24.20	24.16	24.16
Mean	23.77	23.72	23.72
Min	21.54	6.96	6.96
Time Rise (ms)	72.452	107.013	107.000
Overshoot (%)	0.995	0.990	0.990

From Table 4, it is also evident that the PID method has a slightly higher maximum value (24.20) compared to Mamdani and Sugeno (24.16). The average output value for PID is also higher (23.77) than the two fuzzy methods (23.72). However, the minimum value for PID (21.54) is significantly larger compared to Mamdani and Sugeno, which is only 6.96. This difference indicates that PID has a more stable output range, while the fuzzy methods tend to be more adaptive to extreme changes in input conditions.

A faster rise time is observed with PID (72.452 ms) compared to Mamdani (107.013 ms) and Sugeno (107.000 ms), indicating that PID is more responsive, but it carries a higher potential risk of overshoot. However, in terms of overshoot, all three methods show very close results: PID (0.995%) and both fuzzy methods (0.990%), meaning there is no significant difference in managing peak values.

To test the significance of differences between the three methods, T-tests and ANOVA were used (Cai, 2023). For the rise time parameter, the T-test shows a p-value < 0.05, indicating a significant difference between PID and the two fuzzy methods, which means PID reaches steady-state faster than Mamdani and Sugeno. Meanwhile, for the overshoot parameter, the T-test results show a p-value > 0.05, suggesting no significant difference among them, indicating that all three have similar performance in controlling overshoot.

ANOVA test for minimum and maximum values indicates that PID has a narrower output range compared to the two fuzzy methods, which tend to show a greater response under extreme load conditions (Kumar, 2024). Figure 4 shows the system response graph of three types of controllers: PID, Fuzzy Mamdani, and Fuzzy Sugeno on a DC-DC Buck-Boost converter, measured based on output voltage over time. Each controller's response curve provides information about performance characteristics such as rise time, settling time, and stability (Abdulla, 2022).

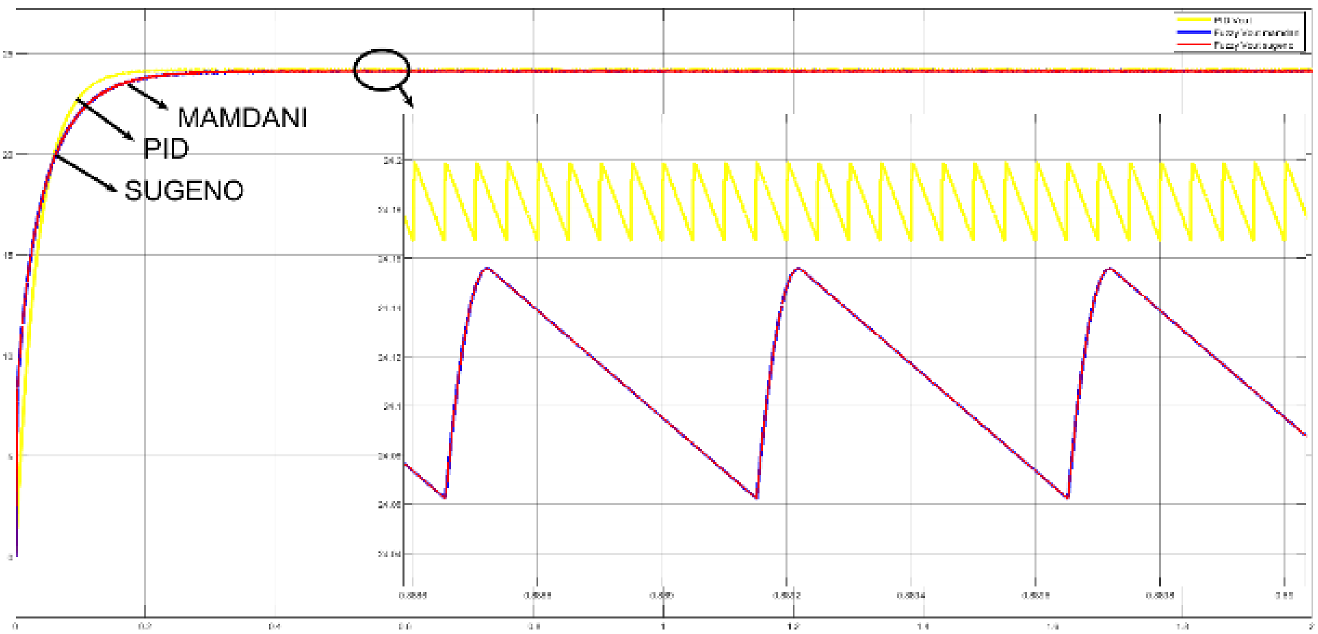

Figure 4. Comparison of fuzzy logic output signal on DC-DC buck-boost converter

PID experiences a slight overshoot, but overall, its response is faster without large fluctuations. Mamdani has a relatively higher initial overshoot and exhibits a larger ripple pattern in the output voltage after the system reaches steady-state. This suggests that Mamdani is less stable when responding to rapid input changes. Sugeno, on the other hand, delivers a more stable performance, with almost no overshoot and lower fluctuations compared to Mamdani, indicating that Sugeno is more effective in maintaining system stability after reaching steady-state.

When the system reaches steady-state, PID and Sugeno demonstrate better stability with outputs that approach the setpoint value (24 Volts) without significant fluctuations. In contrast, Mamdani shows more pronounced ripple in the output, which may indicate that the system is still experiencing internal oscillations even after reaching steady-state.

Conclusion

The simulation results and performance analysis of PID, Mamdani FLC, and Sugeno FLC on the DC-DC Buck-Boost Converter reveal the following key findings: PID achieves the highest maximum output value (24.20 Volts) and a higher average output (23.77 Volts) compared to Mamdani and Sugeno (24.16 Volts and 23.72 Volts). However, PID's minimum output value (21.54 Volts) is also higher than Mamdani and Sugeno (6.96 Volts), indicating that PID provides better stability in maintaining output range, while Mamdani and Sugeno are more responsive to extreme changes. In terms of rise time, PID demonstrates the fastest response (72.452 ms) compared to Mamdani (107.013 ms) and Sugeno (107.000 ms). However, all three methods exhibit similar overshoot performance: PID at 0.995% and Mamdani and Sugeno at 0.990%. Sugeno demonstrates the best stability with the lowest fluctuations after reaching steady-state, while Mamdani shows larger ripples, indicating less stability under rapid changes. Although PID is the fastest, it achieves a steady-state stability nearly equivalent to that of Sugeno. Statistical tests support these findings, showing a significant difference in rise time (p-value < 0.05) but no significant difference in overshoot (p-value > 0.05). In conclusion, PID is suitable for applications requiring fast response, Sugeno excels in long-term stability and precise control, while Mamdani is better suited for complex fuzzy logic reasoning. The combination of these methods could be a focus of future research to further enhance control system performance.

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Author Contributions
The writing of this article was supported by the team from Power Electronics and Drive, with a well-defined division of tasks. Among them, the main thinker and executor of the research was I.K.W. followed by I.N.W.S. who simulated the converter model, and I.M.B.S. who executed the Fuzzy Logic. After the data was obtained, it was compiled by the leader and analyzed collaboratively. Dissemination was handled by B.B.P.W. and translation was done collectively in both Indonesian and English.

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Conflicts of Interest
The authors declare that there are no financial conflicts of interest or personal relationships that could be considered to affect the quality of the research presented in this study.

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