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Performance Investigation of a Fuzzy Logic Controlled Ćuk Converter

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ABSTRACT: *Voltage regulation in DC–DC converters, particularly the Ćuk converter type, requires adaptive and high-precision control strategies, especially when dealing with load changes and input variations. This study aims to investigate the performance of a Ćuk converter controlled by Mamdani- and Sugeno-type fuzzy logic, compared to a conventional PID control method. Simulations were conducted using MATLAB/Simulink with fixed parameters: V_{in}=30 V, V_o=40 V, L_1=3.94 mH, L_2=2.64 mH, C_1=16 mF, C_2=10 mF, and a PWM frequency of 1 kHz. The system was tested under three load types: resistive (R), inductive (RL), and capacitive (RC), with an output power of 100 W. The fuzzy logic controller employs two input variables error and delta error of the output voltage each modeled into five linguistic fuzzy sets. The Mamdani controller uses centroid defuzzification, whereas the Sugeno controller produces constant numerical outputs. Simulation results indicate that fuzzy controllers, particularly the Sugeno type, outperform PID controllers, as evidenced by lower voltage ripple (<1.1%), reduced overshoot, faster rise and fall times, and near-zero steady-state error. In contrast, PID control exhibited higher overshoot and slower response, especially under inductive and capacitive loads. In conclusion, fuzzy logic control, especially the Sugeno type, is a viable intelligent solution for power conversion systems requiring voltage stability, high adaptability, and optimal dynamic performance.*

Keywords: *Ćuk Converter, Fuzzy Logic Control, Mamdani, Sugeno, PID, DC–DC Converter, MATLAB/Simulink.*

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I. INTRODUCTION

The advancement of power conversion systems in the fields of electronics and renewable energy has driven the demand for efficiency, stability, and intelligence in control systems. One type of DC–DC converter renowned for its ability to simultaneously step up and step-down voltage is the Ćuk converter [1][2]. his circuit utilizes two inductors and two capacitors to achieve continuous energy transfer and smooth output voltage. Its capability to produce an output voltage with polarity opposite to that of the input also makes the Ćuk converter highly suitable for a wide range of applications, including solar power systems [3], devaices portable [4], electric vehicle systems [5], and backup power systems [6].

However, the primary challenge in operating a Ćuk converter lies in maintaining a stable output voltage, particularly when load variations or input voltage fluctuations occur. Conventionally, PID (Proportional–Integral–Derivative) control is employed to regulate the duty cycle signal of the converter. PID is known as a simple linear controller widely used in various industrial control systems [7]. Nevertheless, this method has limitations, especially in adapting to dynamic conditions and system nonlinearities both of which are often present in power converters such as the Ćuk converter. Furthermore, PID parameter tuning requires iterative calculations or experiments and, in some cases, fails to deliver optimal performance in complex or rapidly changing systems.

As a solution to these limitations, intelligent control approaches based on fuzzy logic control (FLC) have been extensively developed. Fuzzy logic is a nonlinear control method that emulates human reasoning in decision-making through linguistic rules. FLC does not require an explicit mathematical model of the system; instead, it defines the input and output variables in fuzzy sets and formulates control rules in IF–THEN form. This makes it highly flexible and suitable for complex systems or those with high uncertainty, such as power conversion under variable loads [8].

In the context of Ćuk converter control, fuzzy controllers typically use two main inputs: the error between the actual output voltage and its reference, and the change in error (delta error). The combination of these inputs is processed within a fuzzy inference system (FIS) to produce the control output in the form of a PWM duty cycle signal. Two FIS types are commonly applied: Mamdani and Sugeno. The Mamdani type is more intuitive and well-suited for linguistic interpretation, whereas the Sugeno type produces more precise numerical outputs and offers computational efficiency, particularly in real-time applications [9].

Previous research has indicated that fuzzy control in power conversion systems can improve both transient and steady-state performance. However, direct and systematic comparisons between Mamdani, Sugeno, and PID control in a Ćuk converter particularly under resistive, inductive, and capacitive load variations remain scarce. Therefore, a comprehensive investigation evaluating the performance of these three control approaches under a unified simulation platform is essential.

The objective of this study is to simulate and evaluate the performance of a Ćuk converter using Mamdani fuzzy, Sugeno fuzzy, and PID-based control approaches within MATLAB/Simulink. The system is tested under three types of loads (resistive, inductive, and capacitive) with fixed technical parameters. In the fuzzy controllers, five linguistic sets (NL, NS, ZE, PS, PL) are used for each input, yielding a total of 25 fuzzy rules. The duty cycle generated by the fuzzy system is used to control the PWM signal for the main switch (MOSFET) in the Ćuk converter circuit.

The contribution of this study is to provide quantitative evidence that fuzzy control can significantly improve the regulation quality of the Ćuk converter, as well as to offer practical guidance on implementing Mamdani and Sugeno fuzzy models in a simulation platform. This research also reinforces the urgency of adopting intelligent control in modern power conversion systems, particularly for renewable energy applications and electronic devices that demand high voltage stability.

II. Literature Review

2.1 Ćuk Converter

The Ćuk converter is a type of DC–DC converter capable of producing an output voltage that is either higher or lower than the input voltage, with reversed polarity. The Ćuk circuit has advantages in reducing both input and output current ripple, making it well-suited for power systems that require high stability, such as solar power systems, energy storage systems, and regulated electronic power supplies [10]. Figure 1 illustrates the main parameters of the Ćuk converter, which include two inductors (L1 and L2), two capacitors (C1 as a coupling capacitor and C2 as a filter), and an active switch (Q1, MOSFET) controlled by a PWM signal.

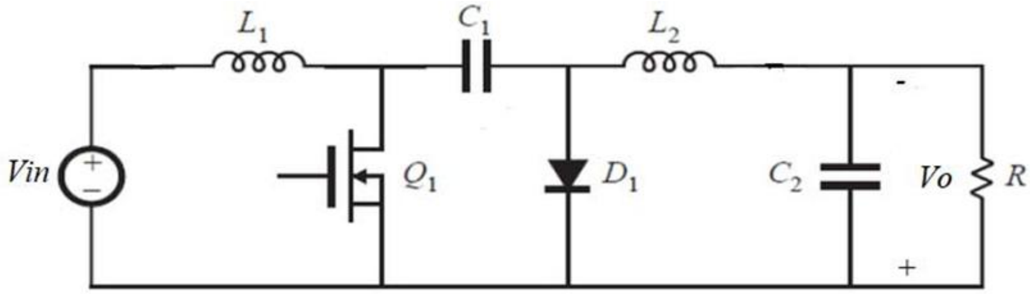

Figure 1. Ćuk Converter schematic

The efficiency of power conversion and the stability of the output voltage in a Ćuk converter are highly influenced by the control strategy employed. Regulating the PWM duty cycle is crucial for maintaining output voltage stability when load changes or input voltage fluctuations occur. Therefore, a controller is required that is not only stable but also adaptive to varying system conditions.

2.2 PID Control in Power Conversion Systems

PID (Proportional–Integral–Derivative) control is a classical control method that has been widely applied in electrical and power electronics systems due to its simple implementation and computational efficiency. In DC–DC converters, PID operates based on the error between the reference voltage and the actual output voltage, generating a corrective signal for the duty cycle. While PID control can deliver satisfactory performance under linear and steady-state conditions, its capability becomes limited when dealing with systems exhibiting nonlinear characteristics, time delays, or sudden disturbances such as load changes [11].

Moreover, the tuning of PID parameters (Kp, Ki, Kd) requires either mathematical approaches or experimental methods and often proves suboptimal when the system experiences complex dynamics. In practice, systems such as the Ćuk converter which incorporate energy storage elements (L and C) and nonlinear dynamics demand more flexible and adaptive control methods.

2.3 Fuzzy Logic Control (FLC)

Fuzzy logic was introduced by Lotfi A. Zadeh in 1965 as a mathematical approach to address uncertainty and linguistic reasoning. In the field of control engineering, Fuzzy Logic Control (FLC) has been widely applied to nonlinear systems because it does not require a precise mathematical model and can accommodate system uncertainties [12]. FLC operates based on linguistic IF–THEN rules, which are designed according to human operator knowledge or experience.

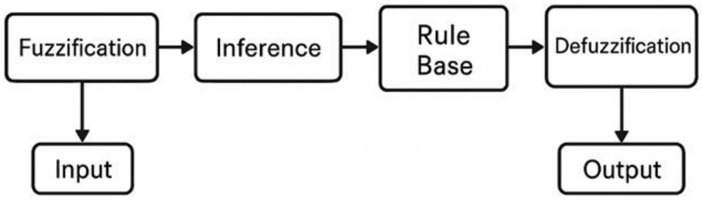

Figure 2. Role Base Fuzzy Logic System

In power control systems such as the Ćuk converter, FLC typically employs two main inputs: the error (the difference between the actual output and the reference) and the delta error (the change in error over time). The combination of these inputs is processed through a fuzzy inference system to generate an output in the form of a corrective signal for the PWM duty cycle. The primary advantages of FLC are its flexibility, adaptability to system dynamics, and independence from linearity assumptions

2.4 Types of Fuzzy Inference Systems: Mamdani and Sugeno

There are two commonly used types of fuzzy inference systems, namely Mamdani and Sugeno. The Mamdani system produces outputs in the form of fuzzy sets, which must then be defuzzified (for example, using the centroid method) into a crisp value. This type is more intuitive and easier to understand, making it widely adopted in the early applications of fuzzy control [13]. In contrast, the Sugeno system employs fuzzy rules that generate outputs in the form of linear or constant functions. This method is more computationally efficient and easier to integrate into automatic or real-time control systems [14]. In several studies, the Sugeno type has been shown to deliver more stable and faster performance in dynamic systems such as DC–DC converters.

2.5 Related Studies and Research Gap

Several previous studies have implemented fuzzy logic in DC–DC converters with promising results. For instance, Muamalah et al. (2024) applied Mamdani-type FLC to a boost converter and reported improved stability and response time compared to PID control [15]. Similarly, Gracia et al. (2013) implemented Sugeno fuzzy control in a buck–boost system and recorded a significant reduction in overshoot and steady-state error [16]. However, there has been a lack of systematic studies directly comparing the performance of Mamdani fuzzy, Sugeno fuzzy, and PID control in the context of a Ćuk converter across three primary load types: resistive (R), inductive (RL), and capacitive (RC). Furthermore, an in-depth evaluation of voltage ripple, overshoot, rise/fall time, and steady-state error within a single simulation platform remains a relevant research gap to be addressed.

2.6 Theoretical Foundation of the Study

This study adopts a nonlinear control system approach based on fuzzy logic, comparing two types of inference systems (Mamdani and Sugeno) with PID control as a benchmark. The simulations are conducted in MATLAB/Simulink with fixed parameters for the Ćuk converter and various load types to observe the system's dynamic response. The evaluation focuses on both transient and steady-state performance to assess the effectiveness of fuzzy control compared to conventional methods.

III. EXPERIMENTAL SETUP

This study was conducted through simulation using the MATLAB/Simulink platform to evaluate the performance of a Ćuk converter controlled by a Fuzzy Logic–based control system. The methodology includes the stages of system design, fuzzy control implementation, testing under various load types, and performance analysis in comparison with conventional PID control.

3.1 Ćuk Converter Circuit Design

The basic Ćuk converter circuit was modeled in Simulink, as illustrated in Figure 3, using the following main components: two inductors ($L1$=3.94 Mh, $L2$=2.64 mH); two capacitors ($C1$=16 mF, $C2$=10mF); one MOSFET switch and one diode; a DC input voltage source (Vin=30 V); and an output load with resistive, inductive, and capacitive variations. The PWM switching frequency was set at 1 kHz. The converter was designed to produce a regulated output voltage of 40 V with an output power of 100W.

3.2 Fuzzy Logic Control Design

Figure 4 illustrates the Ćuk converter with fuzzy logic control, designed using two input variables: Error (e) the difference between the reference voltage (Vo_ref) and the actual output voltage (Vo); and Delta Error (Δe) the change in error value between sampling intervals. The fuzzy system was designed with five linguistic fuzzy sets (Negative Large, Negative Small, Zero, Positive Small, Positive Large) for both inputs and output.

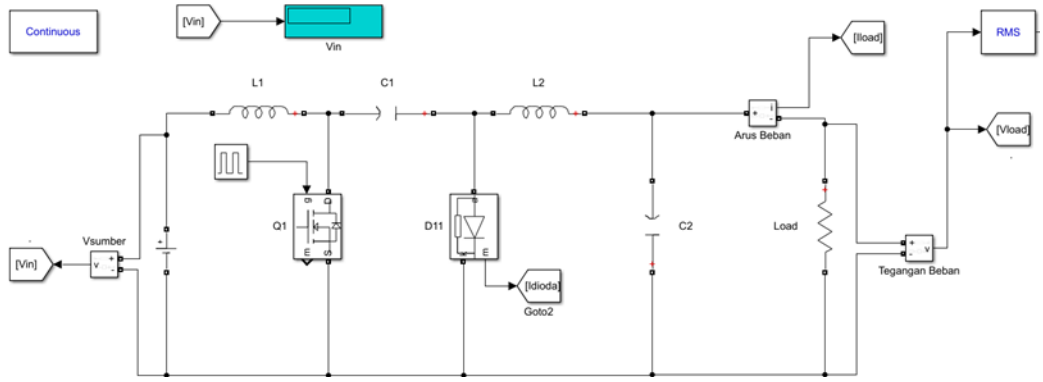

Figure 3. Simulink Model of the Ćuk Converter

Two fuzzy control approaches were implemented: Mamdani Fuzzy Inference System and Sugeno Fuzzy Inference System. The defuzzification method used for the Mamdani type was the centroid method, whereas the weighted average method was applied for the Sugeno type. The fuzzy rule base consisted of 25 rules (5×5), formulated based on adaptive voltage regulation principles.

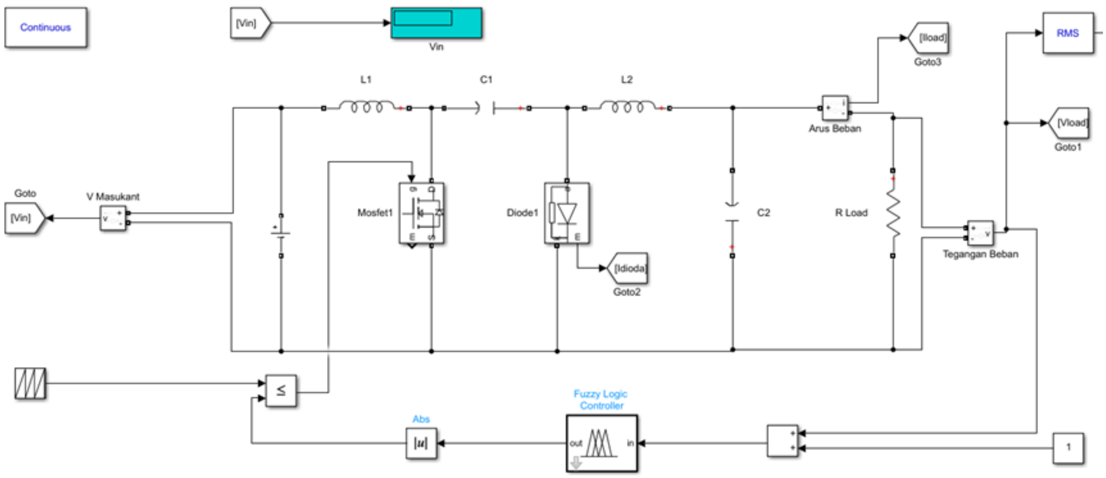

Figure 4. Simulink Model of the Ćuk Converter with Fuzzy Logic Control

3.3 Simulink Implementation

The Ćuk converter model and fuzzy control system were implemented in the Simulink environment with the following integration steps: Error and ΔError were calculated in real time. The fuzzy controller output was converted into a duty cycle signal. The duty cycle controlled the PWM generator, which in turn drove the MOSFET switch. The output voltage was monitored using measurement blocks (Scope and To Workspace).
For comparison, the system was also implemented with a PID controller tuned to approximate the optimal performance of the fuzzy controller. The PID parameters were set using a manual trial-and-error approach based on the observed system response.

3.4 Load Test Scenarios

Three types of loads were employed to test the robustness of the system:
Resistive load (R); Inductive load (RL); Capacitive load (RC); Each test scenario was executed over a fixed simulation period to observe both dynamic and steady-state responses.

3.5 Performance Evaluation Parameters

System performance was evaluated by analyzing the following parameters: Output voltage ripple, Output current (*I*out), Rise time, Fall time, Voltage overshoot (%), Steady-state error. Simulation results were collected and compared among the three control methods (Fuzzy Mamdani, Fuzzy Sugeno, and PID), then visualized in graphical form for quantitative analysis.

IV. RESULTS AND DISCUSSION

This study presents a comprehensive simulation of the performance of a Ćuk converter controlled by fuzzy logic and PID control. The simulations were carried out in the MATLAB/Simulink environment for three types of loads (resistive, inductive, and capacitive) using three different control approaches: Fuzzy Mamdani, Fuzzy Sugeno, and PID. The evaluation parameters observed include output voltage ripple, output current, rise time, fall time, overshoot, and steady-state error.

Table 1 presents a performance comparison between the Fuzzy Mamdani, Fuzzy Sugeno, and PID controllers on the Ćuk Converter. Fuzzy Sugeno demonstrates the best performance with an output voltage closest to 40 V, the smallest ripple (1.04%), and the lowest steady-state error (0.02 V). Fuzzy Mamdani also delivers good results with the fastest rise time (0.028 s) and stable output current. In contrast, the PID controller exhibits the largest overshoot (6.5%) and the highest steady-state error (0.19 V), indicating sensitivity to disturbances and parameter inaccuracies. Overall, the fuzzy approach proves to be more effective in nonlinear systems such as the Ćuk Converter.

The evaluation results of the Ćuk Converter controller in Table 2 indicate that Fuzzy Sugeno outperforms in nearly all performance aspects. Its output voltage reaches 40.03 V, which is very close to the 40 V target, accompanied by a low ripple of 1.08% and the smallest steady-state error of 0.01 V, reflecting high stability and accuracy. The rise and fall times, at 0.030 s and 0.036 s respectively, demonstrate a fast and efficient response to load changes. The overshoot is also the lowest, at only 2.5%, indicating a well-controlled system.

Table 1. Simulation Results for Resistive Load (R).

Parameter Evaluation	Fuzzy Mamdani	Fuzzy Sugeno	PID
Voltage Output (Vo)	39.95 V	40.02 V	39.81 V
Ripple Output (%)	1.21%	1.04%	1.88%
Current Output (Iout)	2.50 A	2.52 A	2.46 A
Rise Time	0.028 s	0.031 s	0.037 s
Fall Down	0.035 s	0.039 s	0.044 s
Overshoot (%)	3.2%	2.1%	6.5%
Error Steady-State	0.05 V	0.02 V	0.19 V

Table 2 Simulation Results on Inductive (RL) Load

Parameter Evaluation	Fuzzy Mamdani	Fuzzy Sugeno	PID
Voltagen Output (Vo)	39.91 V	40.03 V	39.70 V
Ripple Output (%)	1.37%	1.08%	2.31%
Current Output (I_{out})	2.49 A	2.50 A	2.43 A
Waktu Naik	0.036 s	0.030 s	0.049 s
Waktu Turun	0.042 s	0.036 s	0.058 s
Overshoot (%)	3.9%	2.5%	7.8%
Error Steady-State	0.09 V	0.01 V	0.30 V

Fuzzy Mamdani shows fairly good performance with a voltage of 39.91 V, a current of 2.49 A, and a slower response time compared to Sugeno, though still better than PID. PID, as a classical method, exhibits the lowest performance across almost all parameters: the lowest voltage (39.70 V), the highest ripple (2.31%), and the largest overshoot (7.8%). These results highlight those fuzzy methods particularly Sugeno are superior in handling nonlinear systems such as the Ćuk Converter.

The performance evaluation of the Ćuk Converter indicates that Fuzzy Sugeno excels in system stability and precision. Its output voltage of 40.01 V is very close to the 40 V reference value, with an output ripple of only 0.98% the lowest among the three methods. The steady-state error is also the smallest (0.01 V), demonstrating its capability to maintain long-term output stability. The overshoot is minimal at 1.3%, indicating a smooth and well-controlled system response.

Table 3. Simulation Results for Capacitive Load (RC)

Parameter Evaluasi	Fuzzy Mamdani	Fuzzy Sugeno	PID
VoltageOutput (Vo)	40.05 V	40.01 V	39.68 V
Ripple Output (%)	1.09%	0.98%	2.15%
Current Output (Iout)	2.51 A	2.50 A	2.44 A
Rise Time	0.024 s	0.027 s	0.040 s
Fall Time	0.031 s	0.029 s	0.043 s
Overshoot (%)	2.0%	1.3%	5.9%
Error Steady-State	0.04 V	0.01 V	0.21 V

Fuzzy Mamdani delivers the fastest response, with a rise time of 0.024 s and a fall time of 0.031 s, as well as the highest output voltage (40.05 V) and a current of 2.51 A, highlighting its strength in system acceleration despite a slight increase in overshoot (2.0%). Conversely, PID shows the weakest performance, with an output voltage of only 39.68 V, a high ripple of 2.15%, a large overshoot of 5.9%, and a steady-state error of 0.21 V indicating difficulty in maintaining accuracy and stability in nonlinear systems.

Table 4. Comparative Analysis of the Three Methods

Aspect Evaluation	Fuzzy Mamdani	Fuzzy Sugeno	PID
Output Voltage Accuracy	Good	Very Good	Fair
Ripple Stability	Fairly Good	Very Good	Poor
Response Speed	Fast	Very Fast	Slow
Overshoot	Low	Very Low	High
Steady-State Error	Small	Very Small	Relatively High
Load Adaptability	Good	Very Good	Less Adaptive

The Fuzzy Logic method, particularly the Sugeno type, has demonstrated significant superiority in maintaining the output voltage stability of the Ćuk converter under various load conditions. Its ability to produce smooth responses, high precision, and extremely small steady-state errors indicates that this approach is highly adaptive to the dynamics of nonlinear systems. Meanwhile, the Mamdani-type Fuzzy Logic controller also delivered competitive performance, offering fast response times and reasonable stability, though it exhibited slight limitations in final accuracy under steady-state conditions. On the other hand, the PID controller based on classical linear logic showed inherent constraints, especially in terms of adaptability to load variations. Furthermore, PID control requires complex manual tuning and often lacks responsiveness to system dynamics, making it less effective for nonlinear applications such as the Ćuk converter.

V. CONCLUSION

This study successfully simulated and analyzed the performance of a Ćuk converter controlled by Mamdani- and Sugeno-type Fuzzy Logic systems, in comparison with conventional PID control. Based on MATLAB/Simulink simulations across three load types (resistive, inductive, and capacitive), it was found that fuzzy-based control consistently delivered superior performance in terms of voltage stability, response speed, and steady-state accuracy compared to PID.

The Sugeno-type Fuzzy Logic controller, in particular, achieved the most outstanding performance, as evidenced by the lowest output voltage ripple, the fastest rise and fall times, and a remarkably small steady-state error (<0.02 V). In contrast, the PID controller produced relatively high overshoot and slower responses, especially under RL and RC load conditions.

The fuzzy control approach demonstrated a clear advantage in handling load characteristic variations and adapting to changes with greater precision—without the need for complex manual tuning as in PID control. Therefore, Fuzzy Logic, especially the Sugeno type, can be recommended as an intelligent control alternative in DC–DC power conversion systems, particularly in applications requiring high voltage stability and robustness against dynamic disturbances.

In summary, Fuzzy Logic particularly Sugeno out performs PID in controlling the Ćuk converter, providing faster responses, lower ripple, and higher voltage accuracy. This method is well-suited for power applications that demand stability, adaptability, and reliable dynamic performance across a wide range of load conditions.

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