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Performance Comparison of a Buck Converter using PID Control and Fuzzy Logic Control Under Varying Load Characteristic

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Abstract- A buck converter, the type of controller used significantly affects the stability of the output voltage when the system is operated under varying load characteristics. MATLAB/Simulink was selected to support the research process, which will focus on comparing the performance of PID control with fuzzy logic control under three load characteristics: resistive (R), resistive-inductive (R), and resistive-capacitive (RC). The input voltage used in the system is 12 volts, while the reference voltage is 5 volts. The rise time, settling time, overshoot, and steady-state error parameters are used to evaluate the performance of a buck converter. Simulation results show that the output voltage of both methods falls within the range of 4.997-5.003 V, with a steady-state error of 0-0.06%. Fuzzy control has a faster rise time (0.007-0.015 s) and lower overshoot (1.5-5.8%) compared to PID, while PID has a shorter settling time (0.001-0.002 s) compared to fuzzy control (0.009-0.011 s). These results indicate that fuzzy logic control is superior at accelerating the initial response and reducing overshoot, whereas PID control is superior at accelerating the time to reach steady-state conditions. Thus, a comparison of the performance of the two methods shows that the selection of a controller must take into account the transient response characteristics and the accuracy of the output voltage for each load variation.

Keywords- Buck converter, PID, fuzzy logic control, load variations.

I. INTRODUCTION

Advances in power electronics technology have increased the need for efficient and reliable DC-DC power conversion systems, in which output voltage stability is maintained during operation under various conditions. The buck converter is one of several types of DC-DC converters used in this study. Thus, the buck converter serves to step down a high DC voltage to a lower DC voltage, adjusting to the load conditions. Applications of buck converters in everyday life include power supply systems, portable electronic devices, electric vehicles, and renewable energy systems, due to their simple circuit structure and high efficiency [1].

Output voltage stability is one of the key indicators for evaluating the performance of a buck converter. The switching process, as well as the use of inductors and capacitors, causes the system characteristics to become nonlinear. In addition, variations in load characteristics can also affect transient response and output voltage stability. In this study, a closed-loop control system is required to maintain the output voltage close to the specified reference value even when operating conditions change.

One of the control methods most commonly applied in previous studies on buck converter control systems is PID (Proportional-Integral-Derivative) control, which has a structure that is easy to understand, easy to implement, and capable of producing good responses in various applications [2]. However, the effectiveness of PID control is influenced by the accuracy of the control parameter settings. The performance of this method may deteriorate if there are significant changes in system parameters or load variations [3]. As a result, the system may experience higher overshoot, take longer to reach a steady state, and exhibit a less than optimal control response.

As an alternative, the fuzzy logic method is widely applied to power electronics systems because it is able to handle nonlinearity and system uncertainty

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without requiring complex mathematical models [4]. Fuzzy logic control works based on rule base and membership function that resembles the human decision-making process, so it has better adaptability to changes in operating conditions [5]. DC-DC converter applications that compare PID and fuzzy logic control methods have been extensively discussed in several previous studies [5], [6]. The results show that fuzzy logic control tends to provide better stability and adaptability than PID control under certain conditions. However, most of these studies still focus on testing using resistive loads and have not discussed the effect of variations in load characteristics containing inductance and capacitance elements on buck converter performance comprehensively. In addition, analysis of changes in transient response parameters due to load variations is still limited.

Based on the research gap, this study employs two control methods PID and fuzzy logic to compare the performance of a closed-loop buck converter under varying load characteristics, including resistive (R), resistive-inductive (RL), and resistive-capacitive (RC) loads, using MATLAB/Simulink. The simulation results will evaluate the impact of each load variation used; the analyzed parameters include rise time, overshoot, settling time, and steady-state error. Additionally, the study aims to determine and analyze which control method is the most effective and efficient in maintaining the stability of the output voltage produced by the buck converter system.

II. LITERATURE REVIEW

1. PID (Proportional-Integral-Derivative) Controller

In many DC-DC converters, a feedback control method is widely used to maintain the output voltage at a reference value; this is the concept behind PID control [7]. PID control in a buck converter system operates based on the difference between the reference voltage and the measured output voltage. This process generates a control signal that adjusts the PWM duty cycle to regulate the operation of the switch in the converter [2]. A block diagram of the PID control feedback system is shown in Figure 1.

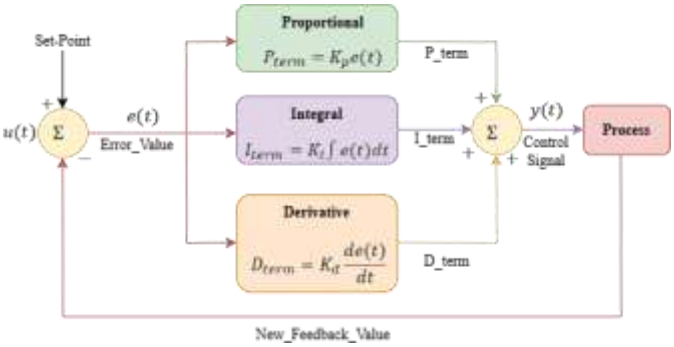


Figure 1: Block Diagram of a PID Controller Feedback System

The error signal in the system is derived from the difference between the reference voltage and the output voltage [7], which is expressed in Equation (1) as follows.

$$e(t) = V_{ref}(t) - V_o(t) \quad (1)$$

Equation (2) shows the general form of the PID control output [7] :

$$u(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \frac{de(t)}{dt} \quad (2)$$

where Kp, Ki, and Kd represent the proportional, integral, and derivative gain parameters, respectively [7]. Proportional action provides a response to instantaneous error, the integral action serves to minimize the error as the system reaches a steady state, while the derivative action responds to changes in the error value, and derivative action responds to changes in error, thereby influencing the system's transient characteristics [8].

The PID parameters must be tuned according to the buck converter circuit's characteristics, as resistance, inductance, and capacitance values can affect the closed-loop system response [7]. Developed a method to determine Kp, Ki, and Kd parameters based on the buck converter's R, L, and C values and tested the controller's performance under various

load conditions [7]. Load variations can also influence output voltage behavior and buck converter stability; therefore, load conditions must be considered when evaluating controller performance [9].

In this study, the PID control parameters Kp, Ki, and Kd were determined through a manual tuning process using MATLAB/Simulink. The determination of PID parameters is one of the key aspects in the design of a buck converter control system to achieve the desired response characteristics [2], [7]. The tuning process is performed by adjusting the values of each PID parameter and observing the resulting output voltage response of the buck converter. Each adjustment is evaluated based on transient and steady-state response characteristics, specifically rise time, settling time, overshoot, and steady-state error. [10]. The parameter values were then selected based on the simulation results to obtain an appropriate control response and keep the output voltage close to the 5 V reference under various load conditions. The parameter values are then selected based on simulation results to obtain an appropriate control response and keep the output voltage close to the 5 V reference under various load conditions. The results of the manual PID tuning process in MATLAB, for the Kp, Ki, and Kd values shown in Table 2.

In this research, the PID method was applied to a closed-loop control system to regulate the output voltage of a buck converter so that it remains stable when load characteristics change. The controller's performance was evaluated by analyzing transient and steady-state response parameters, including rise time, settling time, overshoot, and steady-state error. These parameters were used to assess the system's ability to reach and maintain the voltage at the specified reference value [8].

2. Fuzzy Logic Controller

In general, fuzzy logic control is a control method based on linguistic logic that mimics human decision-making through qualitative reasoning, eliminating the need for complex mathematical models [11]. The system operates by converting numerical values such as error and the rate of change of error into linguistic terms, which are then processed via "if-then" rules to generate adaptive decisions. This approach is effective for nonlinear systems, such as DC-DC converters and energy management applications, as it can handle uncertainty, enhance stability, and produce smooth, accurate responses to changing operating conditions [12].

Fuzzy Logic Control (FLC) is a control method that employs fuzzy sets and linguistic rules to determine control actions based on system conditions [5]. In the context of a buck converter, FLC can be utilized to regulate output voltage by adjusting the duty cycle based on voltage error and the rate of change of that error [1].

In voltage regulation systems, FLC input variables typically consist of error and the change in error, while the controller output determines the change in the converter's control signal [1]. These input values first undergo a fuzzification process to convert numerical values into linguistic variables based on predefined membership functions [1].

Subsequently, the linguistic values of both inputs are processed using a rule base comprising "if-then" rules to determine the control action appropriate for the system's conditions [1]. The result of the inference process is then converted back into a numerical value through defuzzification, enabling it to serve as a control signal to adjust the PWM duty cycle of the buck converter [1].

FLC can be implemented in buck converters to handle changing operating conditions, as the method utilizes rules based on input-output relationships and does not rely entirely on a linear mathematical model of the system [5], [1] applied FLC to a buck converter and demonstrated that fuzzy-based control can effectively manage transient characteristics such as overshoot, undershoot, settling time, and steady-state error. Changes in load resistance are also known to affect the behavior and stability of buck converters; consequently, load variation is a critical factor in system testing [13]. The basic structure of a fuzzy inference system (FIS) is shown in Figure 2.

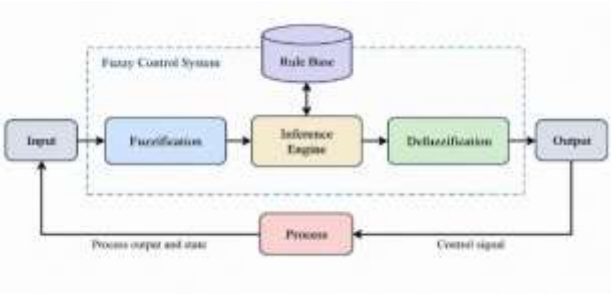


Figure 2: Basic structure of fuzzy inference system (FIS)

There are three main stages of fuzzy logic control: fuzzification, fuzzy inference, and defuzzification. Membership functions represent fuzzy variables. The values of these membership functions range from 0 to 1 [13].

1. Fuzzification

Input data, in the form of numerical values that are converted into consistent linguistic values based on membership functions, is the process of fuzzification. In fuzzification, membership functions in the form of trapezoids or triangles can be applied.

2. Fuzzy Inference System

Fuzzy output determination is performed based on input conditions by combining membership functions with control rules; this is a step in the fuzzy inference system.

3. Defuzzification

The process of converting fuzzy output values into crisp output values using a specified defuzzification method; this step yields the final value, which serves as the control system's output. This is the definition of defuzzification.

Determination of the Mamdani Fuzzy Logic Method

The fuzzy logic system used will be discussed in this section. Using the Mamdani fuzzy method, this system will implement a Multiple-Input-Single-Output (MISO) system with two input variables Input 1 and Input 2 represented as error (e) and change in error (pe), whose values are derived from the output voltage generated by the buck converter. There is also one output variable, the duty ratio (u), which serves as the PWM control signal applied to the MOSFET. In this case, the fuzzy logic controller: During the fuzzification process, membership functions convert the input values into linguistic

values for each variable. The description of the membership functions is based on the operational range of each variable. This serves as a tool for evaluating fuzzy rules to produce the desired control output. Triangular membership functions are used to represent each fuzzy variable. The FLC block diagram is shown in Figure 3.

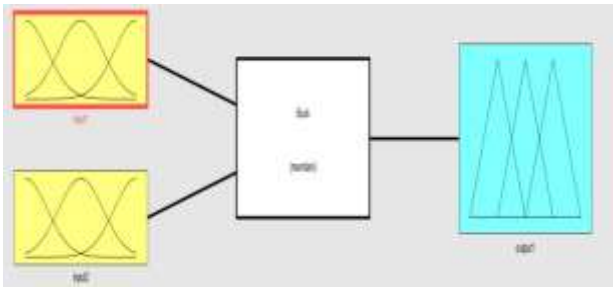


Figure 3: Structure diagram of FLC

The error change represents the rate of change of the voltage error over time and is used as an input variable in the Fuzzy Logic Controller (FLC). This can be expressed mathematically in Equation 3 below [14]. Change of error (ce):

$$ce(t) = \frac{de(t)}{dt} \quad (3)$$

Input 1 and Input 2 have the same membership functions. The five membership functions used in Input 1 and Input 2 are: NB, NS, ZE, PS, and PB. Input 1 with these five membership functions is shown in Figure 4, and Input 2 is shown in Figure 5. In this case, Input-1 and Input-2 are fed into the fuzzy control system. As shown in Figure 6, five different membership functions are also used in the output block: NB, NS, ZE, PS, and PB. The triangular membership function is a membership function defined using five linguistic sets, including the Large Negative (NB), Small Negative (NS), Zero (ZE), Small Positive (PS), and Large Positive (PB) sets. The triangular membership function can be expressed by a mathematical formula as shown in Equation (4) below.

$$\mu[x,a,b,c] = \begin{cases} 0; & x \le a \text{ or } x \ge c \\ \dfrac{x-a}{b-a}; & a \le x \le b \\ \dfrac{c-x}{c-b}; & b \le x \le c \end{cases} \quad (4)$$

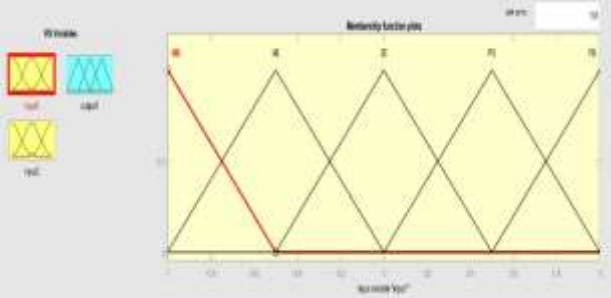


Figure 4: Membership Functions Input-1

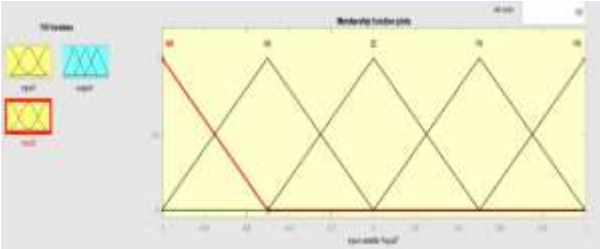


Figure 5: Membership Functions Input-2

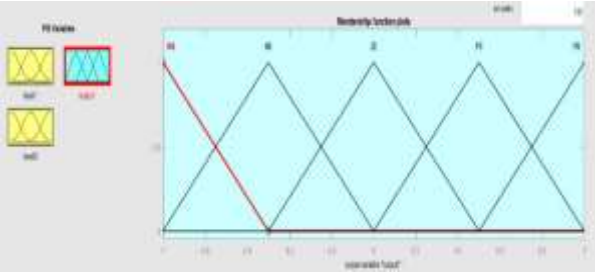


Figure 6: Membership Functions Output

The fuzzy logic control output is determined using a rule base that combines two input variables, namely inputs 1 and 2. The fuzzy rules are formulated in an IF–THEN format. There are five linguistic sets used in the system: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). Each combination of input conditions produces a fuzzy output value, which is then processed through inference and defuzzification mechanisms to obtain a control signal [5], [15]. The fuzzy rule base can be seen in Table 1.

Table -1: Fuzzy Rule Base Table

(e) / (Δe)	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

III. METHODOLOGY

The simulation parameters used in this study, including the electrical components, input voltage, reference voltage, and PID controller gains, are presented in Table 2.

Table 2: Ratings of Elements Employed in Simulation

Parameters	Values
Input Voltage (V_{in})	12 V
Reference Voltage (V_{ref})	5 V
Inductor Series Resistance (r)	0.001 Ω
Filter Inductor (L)	250 mH
Capacitor Equivalent Series Resistance (R_C)	0.001 Ω
Filter Capacitor (C)	100 µF
Switching Frequency (f_S)	2.5 kHz
Proportional Gain (P)	0.395306
Integral Gain (I)	45.396915
Derivative Gain (D)	0.000833
Resistive Load (R_L)	10, 20 Ω
Inductive Load (L_L)	1 mH
Capacitive Load (C_L)	200 µF

The testing of load characteristic variations for the buck converter, which will be performed in a MATLAB simulation using PID control and fuzzy logic, is shown in Table 3.

1. MATLAB/SIMULINK design of Buck Converter using PID Controller

In the MATLAB simulation, various load characteristics are used in the design of a buck converter with PID control, including resistive (R), resistive-inductive (RL), and resistive-capacitive (RC) loads. An RL load is a combination of a resistor and an inductor, while an RC load is a combination of a

resistor and a capacitor. In a buck converter system, the adjusted duty cycle refers to the difference between the reference voltage and the output voltage using PID control.

Resistive (R) Load

The resistive load (R) of the simulated PID controlled buck converter is shown in Figure 7.

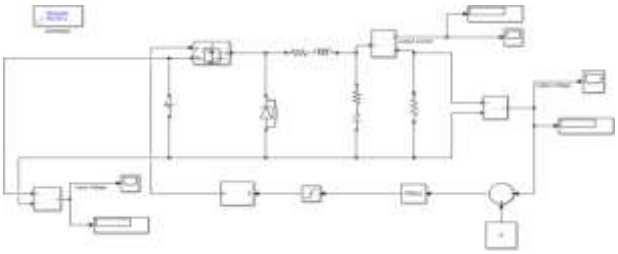


Figure 7: Simulation Model of a Buck Converter with PID Control for a Resistive Load (R)

Resistive-Inductive (RL) Load

The resistive-inductive load (RL) of the simulated PID controlled buck converter is shown in Figure 8.

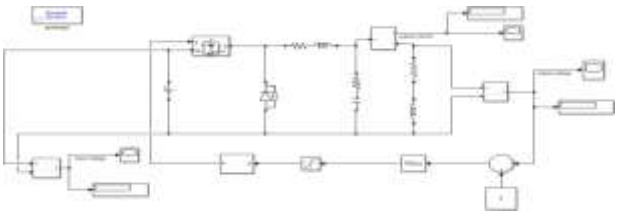


Figure 8: Simulation Model of a Buck Converter with PID Control for a Resistive-Inductive Load (RL)

Resistive-Capacitive (RC) Load

The resistive-capacitive load (RC) of the simulated PID controlled buck converter is shown in Figure 9.

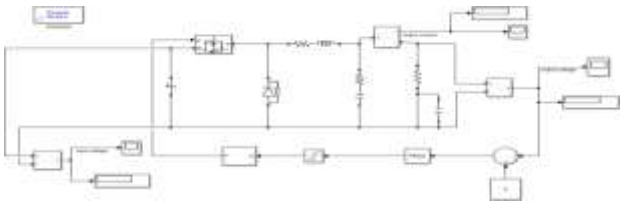


Figure 9: Simulation Model of a Buck Converter with PID Control for a Resistive-Capacitive Load (RC)

2. MATLAB/SIMULINK design of Buck Converter using Fuzzy Logic Controller

In the MATLAB simulation, different load characteristics were used in the design of a buck converter with fuzzy logic control, including resistive (R), resistive-inductive (RL), and resistive-capacitive (RC) loads. An RL load combines a resistor and an inductor, while an RC load combines a resistor and a capacitor. The Fuzzy Logic controller adjusts the switch's duty cycle based on fuzzy logic rules to evaluate the system's response under each load characteristic.

Resistive (R) Load

The resistive load (R) of the simulated fuzzy logic controlled buck converter is shown in Figure 10.

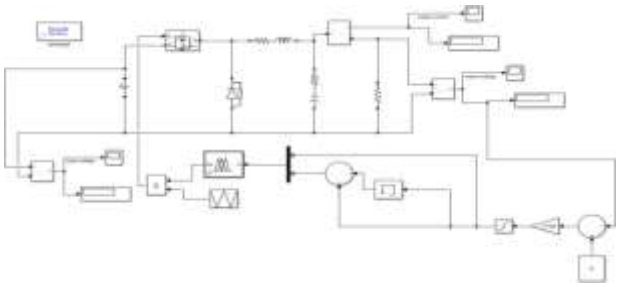


Figure 10: Simulation Model of a Buck Converter with Fuzzy Logic Control for a Resistive Load (R)

Resistive-Inductive (RL) Load

The resistive-inductive load (RL) of the simulated fuzzy logic controlled buck converter is shown in Figure 10.

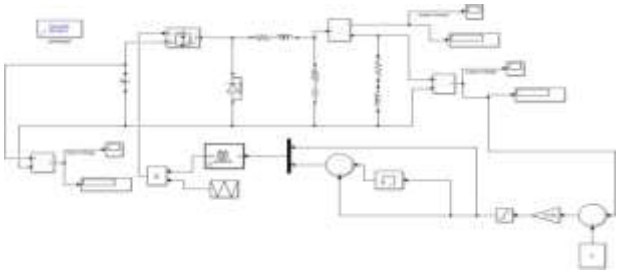


Figure 11: Simulation Model of a Buck Converter with Fuzzy Logic Control for a Resistive-Inductive Load (RL)

Resistive-Capacitive (RC) Load

The resistive-capacitive load (RC) of the simulated fuzzy logic controlled buck converter is shown in Figure 12.

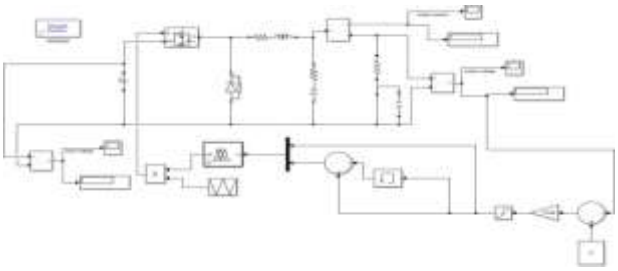
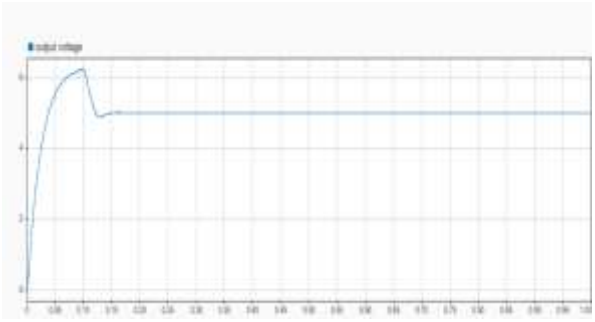


Figure 12: Simulation Model of a Buck Converter with Fuzzy Logic Control for a Resistive-Capacitive Load (RC)

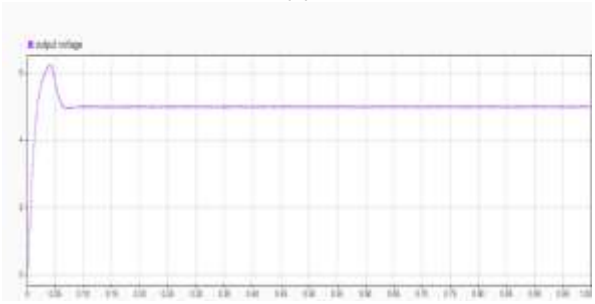
IV. RESULTS AND DISCUSSION

1. PID Controller

In PID control, the output voltage response of the buck converter is presented in Figures 13-15. Figure 13 shows the output voltage waveforms under resistive (R) loads of (a) 10 Ω and (b) 20 Ω. Figure 14 presents the output voltage waveforms under resistive-inductive (RL) loads of (a) 10 Ω and 1 mH and (b) 20 Ω and 1 mH. Figure 15 shows the output voltage waveforms under resistive-capacitive (RC) loads of (a) 10 Ω and 100 μF and (b) 20 Ω and 100 μF.

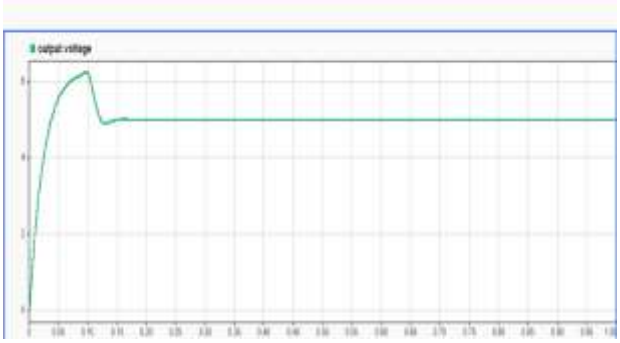


(a)



(b)

Figure 13: Output Voltage Waveform of a Buck Converter with Resistive (R) Load Variation Under PID Control (a) : 10 Ω (b) 20 Ω



(a)

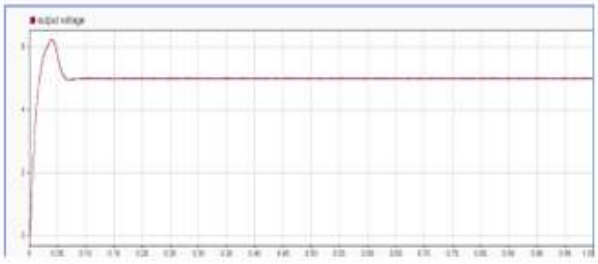


(b)

Figure 14: Output Voltage Waveforms of a Buck Converter with Varying Resistive-Inductive (RL) Loads Under PID Control: (a) 10 Ω & 1 mH (b) 20 Ω & 1 mH

(a)



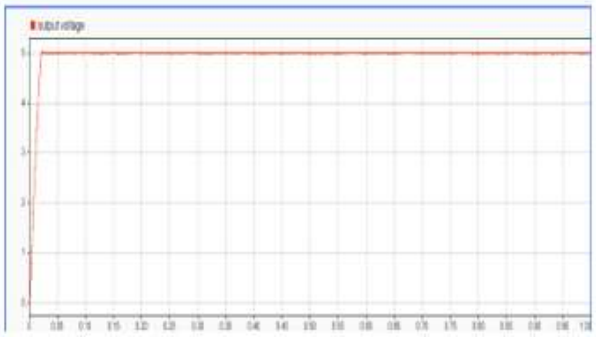


(b)

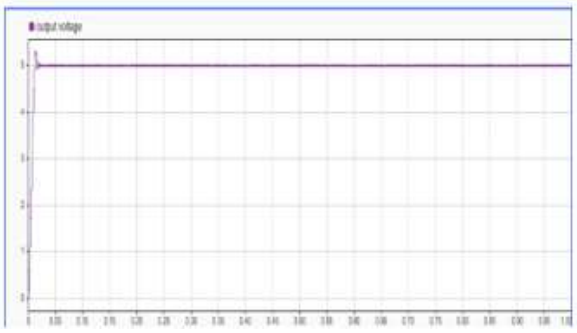
Figure 15: Output Voltage Waveforms of a Buck Converter with Varying Resistive-Capacitive (RC) loads under PID Control : (a) 10 Ω & 200 μF (b) 20 Ω & 200 μF

2. Fuzzy Logic Controller

In fuzzy logic control, the output voltage response of the buck converter is presented in Figures 16-18. Figure 16 shows the output voltage waveforms under resistive (R) loads of (a) 10 Ω and (b) 20 Ω. Figure 17 presents the output voltage waveforms under resistive-inductive (RL) loads of (a) 10 Ω and 1 mH and (b) 20 Ω and 1 mH. Figure 18 shows the output voltage waveforms under resistive-capacitive (RC) loads of (a) 10 Ω and 100 μF and (b) 20 Ω and 100 μF.



(a)

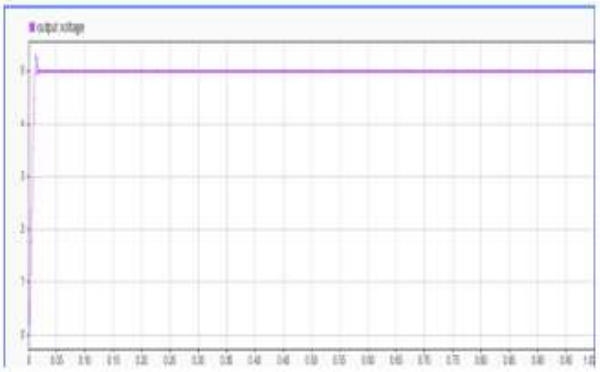


(b)

Figure 16: Output Voltage Waveform of a Buck Converter with Resistive (R) Load Variation Under Fuzzy Logic Control (a) : 10 Ω (b) 20 Ω

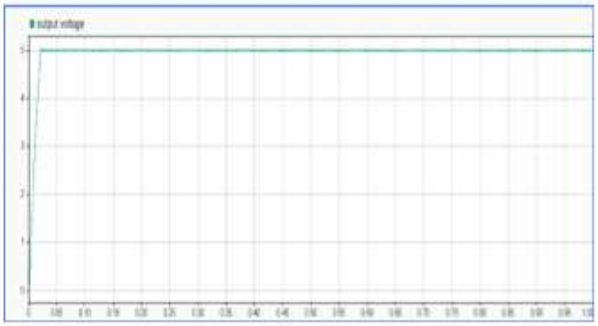


(a)

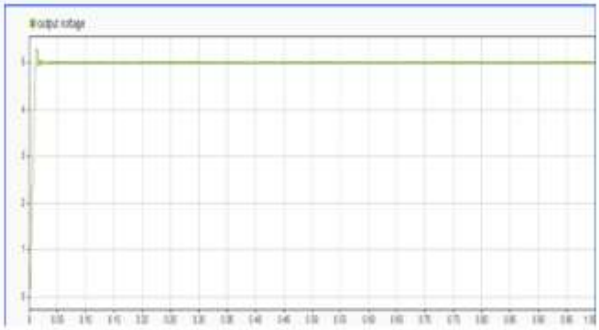


(b)

Figure 17: Output Voltage Waveforms of a Buck Converter with Varying Resistive-Inductive (RL) Loads Under Fuzzy Logic Control : (a) 10 Ω & 1 mH (b) 20 Ω & 1 mH



(a)



(b)

Figure 18: Output Voltage Waveforms of a Buck Converter with Varying Resistive-Capacitive (RC) loads under Fuzzy Logic Control: (a) 10 Ω & 200 μF (b) 20 Ω & 200 μF

The performance comparison of the buck converter using PID and fuzzy logic controllers under various load characteristics is presented in Table 4.

Table 4: Comparison of Buck Converter Performance Using PID and Fuzzy Logic Controllers under Various Load Characteristics

Resistive (R) 10 Ω							
Controller	Vin (V)	Vref (V)	Vout (V)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	12	5	4.998	0.027	0.002	24.9	0.04
Fuzzy	12	5	4.997	0.015	0.011	1.5	0.06
Resistive (R) 20 Ω							
Controller	Vin (V)	Vref (V)	Vout (V)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	12	5	5.001	0.012	0.0012	24.6	0.02
Fuzzy	12	5	5.001	0.007	0.009	5.8	0.02
Resistive-Inductive (RL) 10 Ω & 1 mH							
Controller	Vin (V)	Vref (V)	Vout (V)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	12	5	4.997	0.027	0.002	24.9	0.06
Fuzzy	12	5	4.997	0.015	0.011	1.5	0.06
Resistive-Inductive (RL) 20 Ω & 1 mH							
Controller	Vin (V)	Vref (V)	Vout (V)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	12	5	5.003	0.012	0.001	24.6	0.06
Fuzzy	12	5	5	0.007	0.009	5.8	0
Resistive-Capacitive (RC) 10 Ω & 200 µF							
Controller	Vin (V)	Vref (V)	Vout (V)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	12	5	4.998	0.027	0.002	24.9	0.04
Fuzzy	12	5	4.997	0.015	0.011	1.5	0.06
Resistive-Capacitive (RC) 20 Ω & 200 µF							
Controller	Vin (V)	Vref (V)	Vout (V)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	12	5	5.001	0.012	0.001	24.6	0.02
Fuzzy	12	5	5.001	0.007	0.009	5.8	0.02

V. CONCLUSION

This study was conducted using MATLAB simulations with various load characteristics, namely resistive (R), resistive-inductive (RL), and resistive-capacitive (RC). These three load characteristics were tested to compare the performance of two control methods PID and fuzzy logic control in a closed-loop buck converter system. The research results including output voltage, rise time, stabilization time, overshoot, and steady-state error will be analyzed to evaluate the system's performance.

Based on the simulation results, Fuzzy logic control and PID control produced output voltages in the range of 4.997-5.003 V, which were closer to the 5 V reference voltage across all variations of resistive (R), resistive-inductive (RL), and resistive-capacitive (RC) loads, with steady-state errors ranging from 0 to 0.06%. In terms of transient response characteristics, fuzzy logic control exhibits a faster rise time than PID control across all load variations. Additionally, fuzzy logic control produces lower overshoot ranging from 1.5-5.8% compared to PID control, which reaches 2.6-24.9%. From these research findings, it can be concluded that fuzzy logic control has a longer settling time than PID control.

Overall, fuzzy logic control demonstrated superior performance in accelerating the initial response and reducing overshoot, while PID control exhibited shorter settling times across all tested load variations. Both methods performed well in maintaining the output voltage close to the 5 V reference value, despite differences in their transient response characteristics. Therefore, further optimization of the membership functions and rule base in the fuzzy control system can be performed to improve settling time and enhance response stability. Future research could involve experimental testing to validate the simulation results under actual system conditions.

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REFERENCES

1. C. Kitala, D. N. Oyie, and D. O. Winston, 'Modeling and Performance of a Buck Converter Based on "Fuzzy Logic Soft Computing Technique" for Low Voltage Operations', Int. J. Eng. Adv. Technol., vol. 11, no. 6, pp. 115–122, Aug. 2022, doi: 10.35940/ijeat.F3746.0811622.
2. D. Prarthana, 'Digital Control of a Closed Loop Buck Converter', 2021. [Online]. Available: http://www.ijeast.com
3. S. M. Ghamari, H. G. Narm, and H. Mollaee, 'Fractional-order fuzzy PID controller design on buck converter with antlion optimization algorithm', IET Control Theory Appl., vol. 16, no. 3, pp. 340–352, Feb. 2022, doi: 10.1049/cth2.12230.
4. K. Kumari, 'Fuzzy sets and fuzzy logic: A review of concepts, trends, and applications', Int. J. Phys. Math., vol. 7, no. 2, pp. 155–161, Jan. 2025, doi: 10.33545/26648636.2025.v7.i2b.140.
5. S. Gousia and S. S. Nawaz, 'A study of Comparative analysis of fuzzy logic controller and neural network for dc – dc buck converter', vol. 01021, pp. 3–7, 2021.
6. A. Karaarslan and A. Shaibu, 'Performance Analysis and Comparison of Fuzzy Logic and PI Controlled Non-Inverting Buck-Boost Converter', Int. Conf. Eng. Nat. Sci., pp. 552–559, Jul. 2022.
7. A. S. Samosir, T. Sutikno, and L. Mardiyah, 'Simple formula for designing the PID controller of a DC-DC buck converter', Int. J. Power Electron. Drive Syst., vol. 14, no. 1, pp. 327–336, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp327-336.
8. A. B. Biju, 'Design of Controllers for DC-DC Buck Converters', J. Earth Environ. Sci. Res., pp. 1–9, Apr. 2025, doi: 10.47363/JEESR/2025(7)246.
9. E. L. Lahfid, A. El, F. Dkhichi, and A. Ouali, 'Impact of the variation of capacitance , inductance , and resistive load on the behavior of buck converter', vol. 04002, 2023.
10. L. K. Fong, M. S. Islam, and M. A. Ahmad, 'Optimized PID Controller of DC-DC Buck Converter based on Archimedes Optimization Algorithm', Int. J. Robot. Control Syst., vol. 3, no. 4, pp. 658–672, 2023, doi: 10.31763/ijrcs.v3i4.1113.
11. B. Leitao, W. Costa, F. Brito, and L. Tomaselli, 'Maximum Power Tracking of Photovoltaic Modules Based on Fuzzy Logic Employing Four-Phase Intervaled Boost Converter', J. Power Energy Eng., vol. 11, no. 04, pp. 17–38, 2023, doi: 10.4236/jpee.2023.114002.
12. R. I. Areola, A. O. Adetunmbi, and T. O. Okimi, 'Intelligent Energy Management System: Harnessing Fuzzy Logic for Charge Control', J. Eng. Res. Reports, vol. 26, no. 4, pp. 120–132, Mar. 2024, doi: 10.9734/jerr/2024/v26i41119.
13. N. D. Bhat, D. B. Kanse, S. D. Patil, and S. D. Pawar, 'DC/DC Buck Converter Using Fuzzy Logic

Controller', Institute of Electrical and Electronics Engineers (IEEE), Jul. 2020, pp. 182–187. doi: 10.1109/icces48766.2020.9138084.
14. A. Shibli, M. Ilyas, P. Anwar, and S. Siddiqui, 'Comparative Performance Evaluation of a Proposed Controller Tuning Strategy Against Conventional, Fuzzy Logic, and Optimization-Based Methods Using Key Control Indices', no. November, pp. 1–11, 2025.
15. A. Daraz, A. Basit, and G. Zhang, 'Performance analysis of PID controller and fuzzy logic controller for DC-DC boostconverter', PLoS One, vol. 18, no. 10 October, Oct. 2023, doi: 10.1371/journal.pone.0281122.