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Comparative Study of the Open-loop Buck Converter and the Closed-loop PID Controlled and Fuzzy Logic Buck Converter.

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***Abstract*— this research paper presents a comparative analysis of open-loop control, closed-loop PID control, and closed-loop fuzzy logic control buck converter. The main objective is to reduce harmonic distortion in buck converter. The experimental results show that the open-loop buck converter output voltage THD is 328.48%. On the other hand, the closed-loop PID controller output voltage THD is 227.73%, and the fuzzy logic-controlled buck converter output voltage THD is 202.26% for 400V. The simulation results clearly demonstrate that the fuzzy logic controller outperforms the other two control methods. It exhibits the fastest response to changes in input voltage and load current while maintaining the output voltage consistently within a predetermined range. The PID controller also shows commendable performance, but the fuzzy logic controller excels in compensating for disturbances. Conversely, the open-loop converter displays the least favorable performance, characterized by slowness. Based on these findings, it is evident that the closed-loop fuzzy logic control offers the most advantageous solution for efficient and precise voltage regulation, making it a preferred choice for buck converter applications in practical scenarios.**

Keywords*— *Fuzzy Logic, open loop, close loop, PID controller.

I. INTRODUCTION

DC-DC converters play a crucial role in modern electronic systems, facilitating the conversion of one DC voltage level to another. Their efficiency and ability to deliver adjustable voltage outputs make them indispensable components in a wide range of electronic devices [1]-[4]. Voltage level converters, found in virtually all electronic equipment, are tasked with converting power between different voltage levels to meet various operational requirements. Among the various DC-DC converter types, buck converters stand out as popular choices for stepping down high DC voltages to more manageable levels [5]. Their versatility is evident in applications such as battery chargers, solar panels, and LED lighting, where they deliver reliable and efficient voltage reduction solutions. In designing a buck converter, the primary objective is to maintain output voltage stability even in the face of load or input voltage fluctuations [6]. To achieve this, an effective buck converter controller becomes necessary, as it regulates the switching signal of the semiconductor device to ensure the desired duty cycle [5].

The operational modes of buck converters can be classified into open-loop and closed-loop configurations. Open-loop converters are simpler to implement but lack the ability to correct errors, while closed-loop converters utilize feedback from the output to employ a comparator circuit for error compensation [7]. This paper focuses on a comparative analysis of buck converters operating in both open-loop and closed-loop modes, using PID-controlled and fuzzy logic-controlled circuits. To ensure fairness in the comparison, all models have been standardized with identical parameter values [8]. Prior research has explored various approaches to enhance buck converter performance. In one study [9], a basic open-loop buck/boost converter was proposed for mobile phone applications. Another investigation [10] introduced a variable on-time control strategy for a CRM buck PFC converter, seeking improved control over output voltage and current. Additionally, in [11], optimal PID control was employed for voltage mode control of a buck converter, effectively stepping down the voltage. Harmonics, which manifest as unwanted frequencies at multiples of the fundamental frequency, present a significant challenge in achieving precise and accurate output signals [7].

Total Harmonic Distortion (THD) serves as a metric to quantify the level of distortion introduced by harmonics in a signal. Minimizing THD is crucial to ensure the reliability and efficiency of the output. This thesis investigates and compares the harmonic distortion performance of three distinct types of buck converters: open-loop, closed-loop PID-controlled, and closed-loop fuzzy logic buck converters. Preliminary findings reveal that fuzzy logic buck converters exhibit lower harmonic distortion compared to their open-loop and closed-loop PID-controlled counterparts, holding promise for enhanced converter performance and accuracy. A fuzzy logic buck converter has less harmonic distortion compared to an open-loop and closed-loop buck converter.

II. METHODOLOGY

The analysis will be divided into three sections to discuss open-loop control, closed-loop PID control, and closed-loop Fuzzy logic control buck converter.

A. Open Loop Buck Converter

In this research, we focus on the analysis of a buck converter, which falls under the category of DC-to-DC converters and is specifically designed to decrease the voltage of an input DC voltage. We will investigate an open-loop system, where the generation of gate pulses is inherently designed and cannot be deliberately controlled. The schematic diagram of the open-loop buck converter is represented as "Fig. 1" for reference throughout this study.

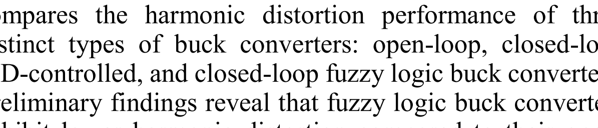


Fig. 1. Shows a schematic diagram of the open-loop buck converter.

A power MOSFET is used as a switch to regulate the input voltage in this circuit. The freewheeling diode (FD) prevents damage to the MOSFET. The essential components of the buck converter circuit include a power MOSFET acting as a switch to regulate the input voltage and a freewheeling diode (FD) that plays a critical role in safeguarding the MOSFET from potential damage during its off state [12]. Our focus will be on understanding the behavior and characteristics of this open-loop buck converter. The primary objective of this methodology is to examine the operational modes of the buck converter, particularly the ON mode and the OFF mode. During the ON state, when the switch (S) is closed, we will observe the flow of the supply voltage through the inductor and the load. Additionally, we will investigate the role of the freewheeling diode (FD), which ensures the continuous flow of current through the inductor even when the switch is turned off, without rectifying the current. To accomplish this analysis, we will refer to "Fig. 2," which illustrates the schematic diagram of Mode-I (ON state) in the open-loop buck converter circuit. This diagram will serve as a visual aid throughout our investigation.

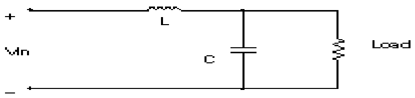


Fig. 2. Shows a schematic diagram of the buck converter when S is on.

The investigation of the buck converter continues with a focus on another mode which is Mode-II, which corresponds to the OFF state of the circuit when the switch (S) is open. During this state, the supply voltage does not actively contribute power to the circuit. Instead, the inductor assumes the role of a current source, supplying current to both the load and the capacitor through the freewheeling diode (FD). As a result, the current within the circuit diminishes, facilitated by the discharge of the energy stored in the inductor [13]. To comprehensively understand the behavior and characteristics of Mode-II, we will refer to "Fig 3," which provides the schematic diagram of this particular state in the buck converter circuit. This visual representation will serve as an invaluable tool throughout our examination of the OFF state. Our methodology encompasses a detailed analysis of the OFF state, including the behavior of the inductor as a current source, the roles of the load and capacitor, and the operation of the freewheeling diode (FD) in facilitating the current flow.

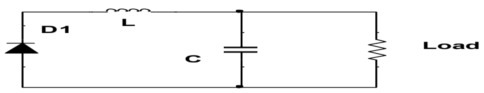


Fig. 3. Shows a schematic diagram of the buck converter when S is off.

The values of the inductor and capacitor can be found by using equations (1), (2), and (3) [13]

$$L = \frac{V_o(V_S - V_o)}{\Delta I V_S . f} \tag{1}$$

$$C = \frac{\Delta I}{8 \Delta V f} \tag{2}$$

$$V_o = D V_S \tag{3}$$

Where, V_{in} = Supply (input) voltage, V_o = Output voltage, D = Duty cycle, L= Inductance, C = Capacitance, ΔI= Ripple current, ΔV= Ripple capacitance-voltage, f = Switching frequency.

B. Closed-Loop Pid-Controlled Buck Converter

In this research, we delve into the crucial role of the feedback loop, specifically within the context of the PID (Proportional-Integral-Derivative) controller, commonly employed in closed-loop buck converters. The PID controller utilizes the feedback loop to continuously fine-tune the duty cycle, aiming to minimize any discrepancies between the measured output voltage and the desired set point value [5]. It is important to note that the underlying working principle of a buck converter remains consistent for both open-loop and closed-loop configurations.

In a closed-loop buck converter, negative feedback plays a pivotal role in automatic duty cycle adjustment, based on the load demand. This ensures that the output voltage consistently aligns with the desired level [15]. To achieve this, the buck converter employs a controller that regulates the gate pulse, which is responsible for controlling the flow of current through the MOSFET.

Central to the operation of the PID controller are its three essential components: the Proportional (P) gain controller, the Integral (I) gain controller, and the Derivative (D) gain controller [7]. These elements work in harmony to analyze the difference between the output voltage of the buck converter and a reference voltage.

The methodology of this research will delve into the intricacies of the feedback loop in closed-loop buck converters, with a particular focus on the PID controller's functionality and its significance in maintaining stable and accurate output voltage.

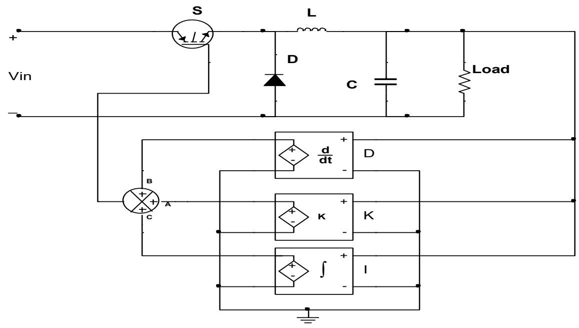


Fig. 4. Closed loop buck converter using PID controller.

The PID controller equations are [15]

$$u(t) = K_p e(t) + K_p K_i \int e(t)dt + K_p K_d \frac{de(t)}{dt} \tag{4}$$

Where, U= Control Variable; e= Control Error; K_p = Proportional Gain; K_i = Integral Gain; K_D = Differential Gain

C. Closed-Loop Fuzzy Logic-Based Buck Converter

Here, we focus on the application of a closed-loop fuzzy logic controller in a buck converter, which ensures a consistent output voltage despite fluctuations in the input voltage or changes in load conditions. The closed-loop fuzzy logic controller employs a fuzzy logic-based approach to regulate the buck converter's operation. It is essential to note that the fundamental working principle of the buck converter remains unchanged, whether operating in open-loop or closed-loop Fuzzy Logic Controller configurations. The closed-loop fuzzy logic controller's general structure is visually depicted in "Fig. 5," illustrating its components and how they interact to maintain output voltage stability. In this research methodology, we will explore the intricacies of the closed-loop fuzzy logic controller in the buck converter, analyzing its components and decision-making process. By gaining insights into the operation of the fuzzy logic controller, we aim to contribute to the advancement of closed-loop buck converter technology, enhancing its performance and applicability in diverse electronic systems. Through our investigation of the closed-loop fuzzy logic controller's functionality, we seek to provide valuable findings that can be applied to optimize and refine the design and implementation of this type of buck converter, ensuring its reliability and effectiveness in practical-applications.

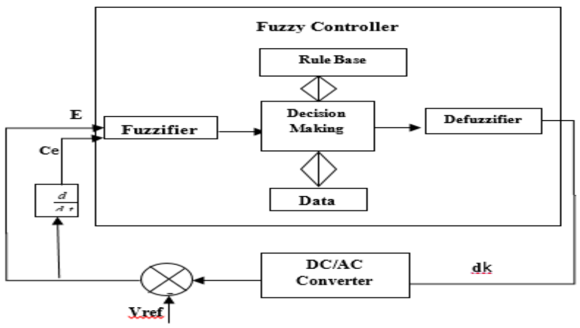


Fig.5. Closed loop buck converter using Fuzzy logic controller.

(1) Fuzzilifier: Fuzzification is a fundamental step within the fuzzy logic system, involving the transformation of numerical data into linguistic terms, such as "high," "medium," or "low.

(2) Rule base: At the core of the fuzzy logic system lies the rule base, a collection of IF-THEN rules that establish the mapping between linguistic terms and corresponding control actions. These rules provide the necessary logic for the fuzzy logic system [6]. By leveraging this rule set, the fuzzy logic controller can effectively navigate the complexities of real-world scenarios and generate appropriate control responses. The membership features of this project are used as:

- NB (Negatively Big)
- NM (Negatively Medium)
- NS (Negatively Small)
- Z (Zero)
- PS (Positively Small)
- PM (Positively Medium)
- PB (Positively Big)

TABLE-I: FUZZY TABLE

e / ce	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PB	PM	PS	Z	NS
NS	PB	PB	PM	PS	Z	NS	NM
Z	PB	PM	PS	Z	NS	NM	NM
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	ZE	NS	NM	NB	NB	NB
PB	Z	NS	NM	NB	NB	NB	NB

(3) Decision-making: The pivotal process of decision-making in the fuzzy logic system involves employing the control rules and linguistic variables. By leveraging these control rules, the fuzzy logic controller can interpret the linguistic variables and determine the optimal control response based on the input data.

(4) Defuzzifier: The defuzzification interface plays a vital role in the fuzzy logic system by converting the fuzzy output obtained from the inference mechanism into a precise numerical value. This numerical value is then utilized to effectively control the plant, facilitating a seamless integration between the fuzzy logic controller and the real-world system. The defuzzifier ensures that the fuzzy control action is translated into a meaningful and actionable output.

III. RESULT ANALYSIS

The simulation for this study was conducted within the MATLAB-Simulink environment. The analysis will commence by presenting the outcomes obtained from the open-loop approach. Subsequently, the results from both the closed-loop PID-controlled and Fuzzy logic controller approaches will be provided for a comprehensive comparison and evaluation. By conducting the simulation in the MATLAB-Simulink platform, we ensure a robust and reliable assessment of the different control methods used in the buck converter system.

A. Open-Loop System

The values of inductor L, capacitor C, and duty cycle D were determined using equations (1), (2) and (3). Subsequently, these calculated values are compiled and presented in Table-Ⅱ for reference and further analysis.

TABLE-II: BUCK CONVERTER PARAMETERS

Parameters	Values
Inductance	52mH
Capacitance	180µF
Duty	50%
Resistance	4Ω

During the observation phase, the system's output was examined under the influence of three distinct input voltages. Throughout this testing, the inductance, capacitance, and duty cycle were maintained at the predetermined and consistent values listed in Table Ⅱ. By keeping these crucial parameters constant, we ensured a controlled and accurate assessment of the buck converter's behavior and performance across varying input conditions. "Fig. 6" displays the input current and output voltage for an input voltage of 100 volts.

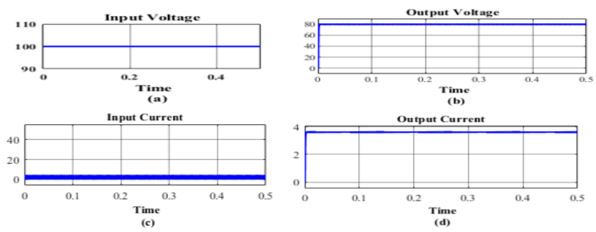


Fig.6. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=100V (a) Input voltage (b) Output voltage (c) Input current (d) Output current.

“Fig. 7” shows the gate pulse for the open loop switching signal.

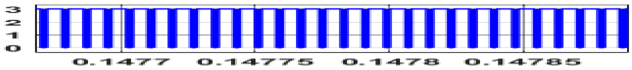


Fig.7. Open loop pulse signal for buck converter which is same for 100 – 400V.

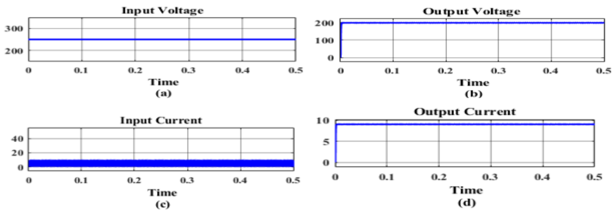


Fig.8. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=250V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

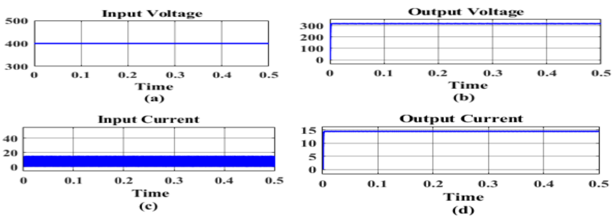


Fig.9. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=400V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

Table III presents the results of the simulation, showing the input voltage and current values, along with the corresponding output voltage and current values.

TABLE-III: BUCK CONVERTER OUTPUT IN OPEN LOOP METHOD

Input voltage	Output voltage	Input current	Output current
100V	79.47V	3.60A	3.62A
250V	198V	9.04A	9.05A
400V	318.1V	13A	14.56A

The harmonics analysis only considers frequencies between 50 Hz and 250 Hz, with 50 Hz being the fundamental frequency.

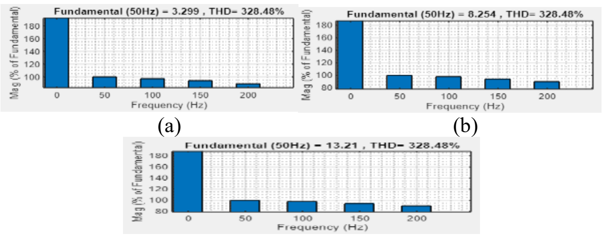


Fig.10. shows the output voltage harmonics distortion for the open loop buck converter, (a) output harmonics for 100v input; (b) output harmonics for 250v input; and (c)output harmonics for 400v input.

“Fig. 10” shows the output voltage in an open-loop buck converter. The total harmonic distortion (THD) of both output voltage increases as the input voltage increases but (THD) rate is the same.

B. Closed-Loop Using Pid-Controller

Throughout both the open-loop and closed-loop simulations of the PID-controlled buck converter, a consistent set of values for inductance, capacitance, and duty cycle were maintained, as presented in Table Ⅱ. Furthermore, a steady duty cycle of 50% was sustained throughout the entire simulation process.

The output response of the buck converter was closely monitored under three distinct input voltages while ensuring that the inductance, capacitance, and duty cycle remained fixed at the specified values outlined in Table Ⅱ. This approach allowed for a controlled and precise evaluation of the buck converter's performance under varying input conditions. By maintaining a constant set of parameters, we could effectively analyze the influence of different input voltages on the output behavior, gaining valuable insights into the system's operational characteristics.

The results obtained when the input voltage was set at 100 volts are depicted in "Fig. 11," displaying both the input current and output voltage profiles

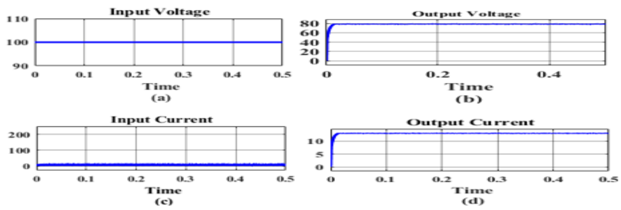


Fig.11. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=100V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

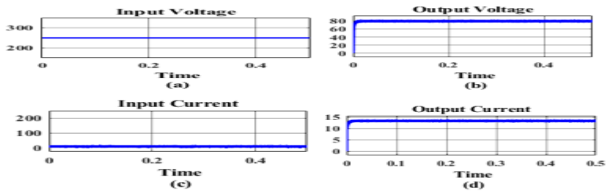


Fig.12. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=250V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

The input current and output voltage and current may be seen in "Fig. 13" after raising the input voltage to 400V again.

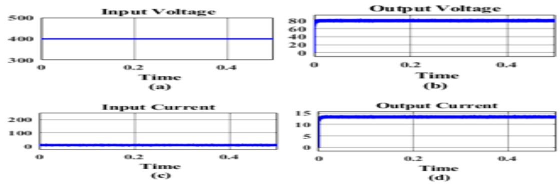


Fig.13. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=400V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

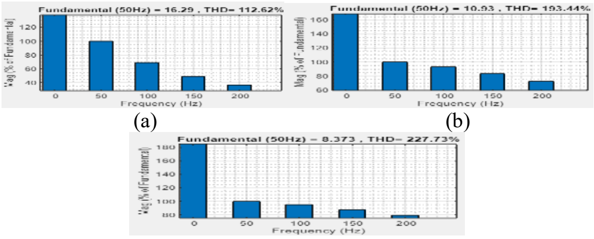
The input voltage and current values, as well as the output voltage and current values, discovered by simulation for the closed-loop system are shown in Table-IV.

TABLE-IV: BUCK CONVERTER OUTPUT IN CLOSED LOOP METHOD

Input voltage	Output voltage	Input current	Output current
100V	78.71V	9.98A	11.06A
250V	79.98V	10.04A	12.9A
400V	80V	10.54A	13.01A

Like the open loop technique, the harmonics analysis method focuses solely on frequencies ranging from 50 Hz to

250 Hz, where the fundamental frequency is at 50 Hz. In the context of a closed-loop PID-controlled buck converter, the output voltage harmonics distortion is depicted in "Fig. 14."



(c)

Fig.14. shows the output voltage harmonics distortion for a closed-loop PID-controlled buck converter, (a) output harmonics for 100v input; (b) output harmonics for 250v input; (c) output harmonics for 400v input.

However, it is important to highlight that even with this increase in input voltage, the THD of the output voltage remains substantially lower compared to the corresponding values observed in the open-loop configuration.

C. *Closed-Loop Using Fuzzy Logic Controller*

In both the open-loop and closed-loop simulations of the Fuzzy logic-based buck converter, the inductor and capacitor values, along with the duty cycle, were maintained at a constant level. During the simulations, the output was observed under three distinct input voltages, with the inductance, capacitance, and duty cycle consistently set to the values specified in Table II

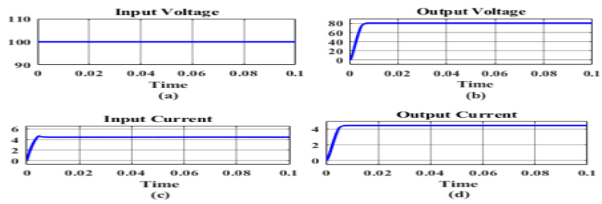


Fig.15. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=100V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

"Fig. 16" displays the input current and output voltage for an input voltage of 100 volts.

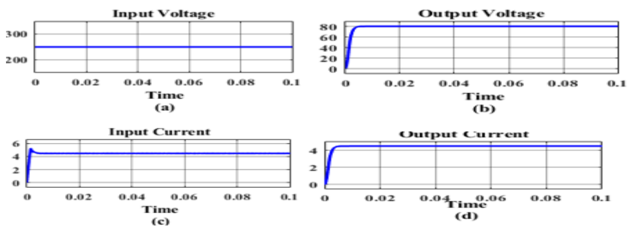


Fig.17. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=250V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

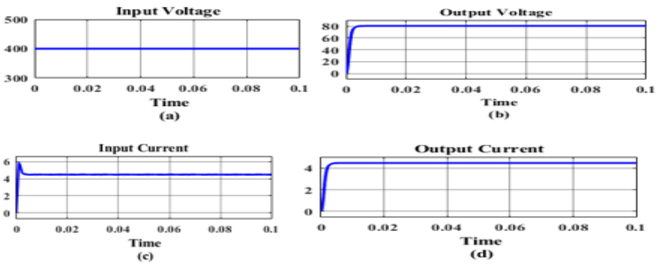


Fig.18. shows the voltage-current characteristics of a buck converter with a D=50%, Vin=400V (a) Input voltage (b) Output voltage (c) Input current (d) Output current

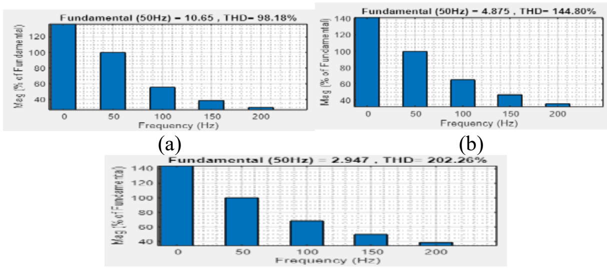
Table V presents the results obtained through simulation for the closed-loop system, encompassing the input voltage and current values, as well as the output voltage and current values.

TABLE-Ⅴ: BUCK CONVERTER OUTPUT IN FUZZY LOGIC METHOD

Input voltage	Output voltage	Input current	Output current
100V	79.99V	4.36A	4.47A
250V	80V	4.45A	4.58A
400V	80.01V	4.46A	4.59A

Much like the open-loop approach, the harmonics analysis in the closed-loop Fuzzy logic converter focuses on frequencies ranging from 50 Hz to 250 Hz, with 50 Hz representing the fundamental frequency.

The closed-loop Fuzzy logic converter maintains a precise and constant output voltage and current, effectively handling fluctuations in the input voltage and variations in load conditions. This stability is corroborated by Table-Ⅴ, which demonstrates that the output voltage remains unaffected by changes in the input voltage or load conditions.



(c)

Fig.19. shows the output voltage harmonics distortion for a closed-loop Fuzzy Controlled buck converter, (a) output harmonics for 100v input; (b) output harmonics for 250v input; (c) output harmonics for 400v input.

In "Fig. 19," the analysis pertains to the output harmonics of the voltage in the context of the closed-loop buck converter Notably, the THD for the output voltage in the closed-loop Fuzzy logic buck converter is significantly lower than that observed in both the open-loop and closed-loop PID-controlled buck converters.

Closed-loop Fuzzy logic controller has less output voltage harmonic distortion than the open-loop and closed-loop PID-controlled buck converter. The switching pulses in a converter are modified using closed-loop fuzzy logic control to reduce harmonic distortion. This is accomplished by training a fuzzy logic controller on the properties of the load and the converter.

The simulation result of total harmonic distortion discovered from open-loop and closed-loop buck converters are shown in Table-VI.

TABLE-VI: BUCK CONVERTER HARMONIC DISTORTION

Buck converter	Harmonic distortion
Open-loop	High
Closed-loop PID	Lower than open-loop
Closed-loop Fuzzy logic	Lowest

IV. CONCLUSION

This research paper delves into the simulation and harmonic distortion analysis of DC to DC buck converters, both in open-loop and closed-loop configurations. The simulation results have provided valuable insights into the performance of these converters. The open-loop buck converter exhibits a relatively high output voltage harmonic distortion and the THD rate is the same for 100 to 400V. However, its output voltage shows significant variations in response to changes in the input voltage. Efficiency-wise, the open-loop buck converter showcases slightly higher efficiency than the closed-loop PID-controlled and Fuzzy logic buck converters. However, the closed-loop converters excel in providing improved voltage regulation and enhanced performance in challenging and dynamic operational scenarios. In conclusion, the closed-loop Fuzzy logic buck converter stands out as a favorable choice due to its constant output voltage, reduced THD, and satisfactory efficiency, making it a promising candidate for various practical applications. The findings presented here open new avenues for developing more efficient and reliable DC-to-DC buck converters in the future.

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