IJRCS

International Journal of Robotics and Control Systems
Vol. 5, No. 2, 2025, pp. 1422-1440
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

ASCEE

# Enhanced Voltage Regulation of Buck Converter-Fed DC Motors Using Fuzzy Logic Control Under Dynamic Load Conditions

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ARTICLE INFO

**Article history**
Received March 17, 2025
Revised May 02, 2025
Accepted June 03, 2025

**Keywords**
Adaptive Voltage Regulation;
Buck Converter Control;
DC Motor Drive Systems;
Fuzzy Logic Controller (FLC);
MATLAB Simulink Simulation

ABSTRACT

Buck converters are widely employed in power electronics for efficient DC voltage regulation, particularly in applications such as motor drives and embedded systems. However, conventional control methods, such as PID, often exhibit limitations including significant voltage ripple, overshoot, and sluggish dynamic response under varying load conditions. This study introduces a fuzzy logic controller (FLC) integrated into a buck converter system to address these challenges through adaptive and nonlinear control. The research contribution is the design and simulation of an FLC-based voltage regulation strategy that enhances output stability and improves transient performance in DC motor applications. The proposed buck converter operates in continuous conduction mode and consists of an IGBT switch, inductor, diode, and filter capacitor. The FLC employs voltage deviation and its rate of change as input variables and utilizes a 25-rule Mamdani fuzzy inference system to modulate the duty cycle in real time. Simulated in MATLAB Simulink with a dynamic DC motor load, the FLC demonstrates superior control characteristics over the PID controller. Most notably, voltage ripple is reduced by over 65%, leading to improved voltage stability and reduced fluctuations. The FLC also exhibits faster settling behavior and better handling of dynamic load variations, confirming its effectiveness in nonlinear and time-varying systems. Future work will focus on hardware validation, hybrid control integration, and deployment in renewable energy and electric vehicle systems to improve adaptability and real-world performance.



## 1. Introduction

Power electronic converters, especially buck converters, are foundational components in modern electrical systems, enabling efficient voltage regulation from higher to lower DC levels. This function is critical in battery-powered devices, electric vehicles, and renewable energy systems where energy efficiency and precise voltage control are paramount [1]. As switched-mode power supplies (SMPS), buck converters minimize energy losses, significantly enhancing system efficiency and making them ideal for power-sensitive applications. However, conventional Proportional-Integral-Derivative (PID) control methods exhibit limitations—notably, complexity in tuning, poor adaptability under nonlinearity, and vulnerability to electromagnetic interference induced by parasitic capacitance in MOSFETs [2]. Furthermore, existing optimization techniques often fail to strike a balance between exploration and exploitation, leading to performance degradation in dynamic conditions [3], [4]. Numerous advancements in converter topologies have been proposed to tackle these challenges. For instance, a single-switch buck-boost topology offers continuous current operation and a wide conversion range [5], simplifying control and enhancing efficiency in electric vehicles and renewable systems [6]-[8]. These hardware innovations, however, must be complemented by intelligent control strategies to fully realize performance improvements.

In electric vehicles and IoT systems, low-power DC-DC converters are essential for managing voltage across various modules such as sensors, actuators, and smart glass components [9]. Although extensive simulation and experimental validations exist [10], most systems still operate with fixed parameters, failing to dynamically adapt to fluctuating environmental and load conditions. This highlights the need for intelligent, adaptive controllers that can optimize power delivery in real time [11], [12]. Buck converters operating under constant power loads (CPLs) often exhibit nonlinear and chaotic behavior, especially in discontinuous conduction mode (DCM), which traditional models struggle to stabilize [13]-[15]. This problem becomes more significant in DC motor drive systems, where the interplay between machine dynamics and converter behaviour introduces substantial complexity. Simulation tools frequently oversimplify these dynamics, making it difficult to design controllers that perform reliably in practical settings.

Control techniques such as digital PWM, pulse frequency modulation, and adaptive skip modulation have improved efficiency but remain limited in their adaptability [16]. Incorporating Fuzzy Logic Controllers (FLCs), which excel in rule-based decision-making under uncertainty, could address these limitations by enabling real-time responsiveness and robustness [17]. More advanced methods like passivity-based control (PBC), constraint-coordinated switching MPC (CCS-MPC), and disturbance observers (HODO) have shown performance improvements [18], but they still lack the capability for intelligent, autonomous decision-making under dynamic conditions [19]. In DC motor applications, voltage regulation via DC-DC converters becomes increasingly complex under rapid load variations [20], [21]. Traditional sliding mode control (SMC), while robust, suffers from chattering and instability [21], [22]. Adaptive sliding mode control (ASMC) introduces self-tuning capabilities but still depends on predefined rules [23]. To overcome these limitations, intelligent data-driven control mechanisms—particularly those incorporating AI—are necessary to enhance scalability and adaptability in real-time environments [13], [21]-[23].

One representative application is in electric vehicle simulations, where a buck converter steps 48V down to 24V for a BLDC motor. This model demonstrates effective speed and voltage regulation at 130 RPM [24], but lacks adaptive features necessary for real-world variability [25]. Similarly, synchronous buck converters achieve high efficiency (up to 96.27%) by replacing diodes with MOSFETs [26], but still operate under static control parameters. Adaptive control, including AI-based and predictive algorithms, remains underutilized in unlocking its full potential. Recent metaheuristic strategies such as the Archimedes Optimization Algorithm (AOA) have been applied to PID tuning in buck converters. Compared to methods like Hybrid Nelder-Mead (AEONM), Artificial Ecosystem Optimization (AEO), Differential Evolution (DE), and Particle Swarm Optimization (PSO), AOA-tuned controllers show faster recovery and lower voltage overshoot [27].

Fuzzy Logic Controllers (FLCs) have become a focal point in intelligent energy control, with successful applications in hybrid energy storage systems (HESS) [28], [29], photovoltaic (PV) systems [30], microgrids [31], and electric vehicles (EVs) [32]. FLCs excel by providing rule-based, adaptive responses that do not rely on precise mathematical modeling [33], [34]. In HESS, they optimize charge balancing between batteries and supercapacitors [35], [36]. In PV applications, they enable efficient Maximum Power Point Tracking (MPPT) under varying conditions [37], [38]. They also facilitate intelligent energy use in IoT networks [39], [40]. and enhance stability in microgrids [23], [41], [42].

In electric vehicles and DC motor systems, FLCs provide adaptive control for handling nonlinearities and managing energy distribution efficiently [43]-[45]. They support regenerative braking and bus voltage regulation, improving range and reducing component wear. Without such strategies, converters may suffer from voltage ripple, short-circuit currents, and degraded load handling [41], [46], [47]. FLCs mitigate these risks using fuzzy inference systems—fuzzification, rule evaluation, and defuzzification—allowing real-time decisions based on expert knowledge [48]-[50]. Studies have confirmed that FLCs reduce overshoot and improve system stability in buck converters and DC motors [51]-[53]. Their hybrid integration with PI controllers enhances energy efficiency in fuel cell EVs by reducing hydrogen consumption [54]. In autonomous vehicles, FLCs handle complex control tasks such as heading angle tracking [55]. Type-2 FLCs (T2FLCs) further improve robustness in nonlinear and uncertain environments, offering superior control over speed and torque in DC motors [56], [57].

Despite significant progress, there remain substantial challenges in ensuring robust voltage regulation in buck converters under dynamic loads such as DC motors. Conventional PID controllers, while widely used [58], [59], often struggle with non-linearities, parameter variations, and sudden load changes, leading to overshoot, longer settling times, and degraded performance [60]. This study directly addresses these limitations by proposing a fuzzy logic controller (FLC) for a buck converter feeding a DC motor. A practical case is presented where a 48V input is stepped down to 24V to drive a BLDC motor, demonstrating superior dynamic response and steady-state performance under variable loads.

The main contribution of this work lies in the development, implementation, and simulation of an FLC-based control strategy for buck converters supplying DC motors. Comparative analysis with the classical PID controller highlights the enhanced adaptability and robustness of the fuzzy logic approach. The proposed FLC minimizes overshoot, reduces voltage ripples, and ensures faster settling times, thus increasing system efficiency and reliability. By integrating fuzzy logic into the control loop, this research delivers a scalable and intelligent solution that addresses key limitations in both conventional and existing intelligent control methods.

## 2. Design and Simulation Framework

### 2.1. Buck Converter Fundamentals

A buck converter is a DC-DC step-down power converter designed to efficiently reduce a higher input voltage to a lower output voltage. It is widely used in power electronics applications such as motor controllers, battery-powered devices, and embedded systems, where precise voltage regulation is essential. The converter operates using a high-frequency switching mechanism, relying on four key components: an IGBT (Insulated Gate Bipolar Transistor) as the main switch, a diode, an inductor, and a capacitor. The IGBT rapidly turns on and off to regulate power flow. During the switch-on phase, the IGBT conducts, allowing current to flow through the inductor, which stores energy. In this state, the diode is reverse-biased and does not conduct. When the switch turns off, the stored energy in the inductor is released, maintaining the current flow. The diode becomes forward-biased, providing a return path for the current, while the capacitor filters and stabilizes the output voltage, reducing ripples and improving overall performance.

The operation of a buck converter is divided into two main modes: the switch-on and switch-off phases. During the switch-on phase, the IGBT is turned on, allowing current to flow through the inductor, which stores energy and increases its current. When the switch turns off, the inductor releases its stored energy, ensuring continuous current flow through the diode. The capacitor further smooths voltage variations, ensuring a stable DC output. In this study, the buck converter is designed to drive a DC motor, requiring precise control of the output voltage and current. The design of a buck converter involves calculating the values of the inductor and capacitor to ensure operation in continuous conduction mode (CCM). The design process considers several key factors, including load specifications (such as the desired output voltage $V_O$ and load variations, input voltage fluctuations, and the switching frequency. For example, if a buck converter is designed to step down a DC voltage from 20 volts to 15 volts with a 10% allowance for current ripple, the inductor ($L$) and capacitor ($C$) values can be determined using standard formulas. The switching frequency ($f_s$) can be chosen based on the available hardware.

The inductor and capacitor values are calculated using conventional formulas to ensure the converter operates in CCM. These values represent the minimum required to maintain CCM, but they can be increased to further reduce output voltage and current ripples. The formulas for calculating the minimum inductor (1) and capacitor values (2) are as follows:

$$L = \frac{V_{out} \cdot (V_{in} - V_{out})}{\Delta I_L \cdot f_s \cdot V_{in}} = \frac{V_{in} - V_{out}}{\Delta I_L \cdot f_s} \cdot D \tag{1}$$

$$C = \frac{\Delta I_L}{8 \cdot f_s \cdot \Delta V_{out}} \tag{2}$$

$$\Delta V_{out} = \frac{\Delta I_L}{8 \cdot f_s \cdot C} \tag{3}$$

Where $V_o$ is the output voltage, $V_{in}$ is the input voltage, $\Delta I_L$ is the inductor ripple current, $f_s$ is the switching frequency, and $\Delta V_o$ is the allowable output voltage ripple. The output voltage of a buck converter in (3) is determined by the duty cycle, which is the ratio of the switch-on time to the total switching period. The relationship between the input voltage $V_{in}$ and output voltage $V_{out}$ is expressed as (4):

$$V_{out} = D \times V_{in} \tag{4}$$

Where $D$ represents the duty cycle and falls within the range ($0 < D < 1$). Since the duty cycle is always less than one, the output voltage is always lower than the input voltage. Another important parameter in the design of a buck converter is the inductor current ripple, which can be calculated using (5):

$$\Delta I_L = \frac{(V_{in} - V_{out})\, D}{L f_s} \tag{5}$$

Where $\Delta I_L$ is the inductor current ripple, $L$ is the inductance, and $f_s$ is the switching frequency. Minimizing current ripple is crucial for efficient energy conversion and to prevent excessive heating in the circuit components. The design and control of the buck converter play a critical role in ensuring high efficiency and stable operation, especially when used in applications such as driving a DC motor. The characteristics of the buck converter used in this study are summarized in Table 1.

### 2.2. Simulation Model of the Buck Converter for DC Motor Load

The MATLAB Simulink model, as shown in Fig. 1, demonstrates the implementation of a buck converter designed to regulate the voltage supplied to a DC motor. MATLAB Simulink was selected for this study due to its verified power electronics component libraries (including IGBT, diode, and motor models that closely match real-world characteristics), native integration with the Fuzzy Logic Toolbox for controller implementation, and established validation in power electronics research [24], [53]. In this closed-loop system, a 32V DC input is stepped down to 24V DC using the buck converter, with the output smoothed by a PI filter. The circuit comprises a Pulse Width Modulation (PWM) generator, an IGBT switch with a freewheeling diode, an inductor, a capacitor, and a controlled voltage source. The PWM generator controls the duty cycle of the IGBT switch, which regulates the voltage supplied to the motor. When the IGBT is turned on, the current flows through the inductor, storing energy and supplying power to the motor. When the switch is turned off, the inductor releases its stored energy, ensuring continuous current flow through the freewheeling diode to maintain motor operation. This regulated voltage allows precise control of the motor's speed and torque.

The DC motor is modelled as a separately excited machine, with torque applied as an input to simulate dynamic load conditions. Key performance parameters, such as speed, armature current, field current, and electrical torque, are monitored using output measurement blocks. The capacitor in the circuit plays a critical role in filtering voltage ripples, ensuring the motor receives a stable DC supply. The powergui block, configured in discrete mode, enables accurate numerical simulation of switching dynamics and transient responses. The simulation results from this model are used to validate the effectiveness of the proposed fuzzy logic control strategy for the system.

**Table 1.** Characteristics of the buck converter

| Parameter | Value |
|---|---|
| Inductance ($L$) | 15 $mH$ |
| Capacitance ($C$) | 25 μ$F$ |
| Input voltage (max) | 32 $V$ |
| Input voltage (min) | 15 $V$ |
| Reference output | 15 $V$ |
| Switching frequency ($f_s$) | 5000 $Hz$ |

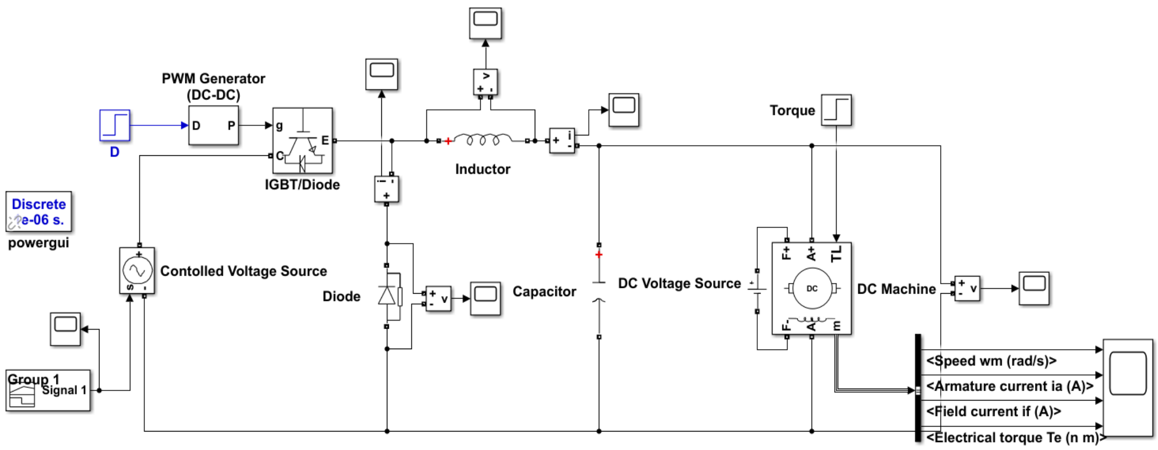


**Fig. 1.** Simulink model of a DC-DC buck converter with PWM control for a DC motor

### 2.3. PID Controller Design for Performance Comparison

To objectively evaluate the proposed FLC's performance, a Proportional-Integral-Derivative (PID) controller was implemented alongside the buck converter system. The PID controller regulates the output voltage by dynamically adjusting the duty cycle ($D$) sent to the PWM generator. Its operation is governed by the equation (6):

$$D(t) = K_p \cdot e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{6}$$

Where $e(t) = V_{ref} - V_{out}$ represents the voltage error between the reference and actual output. The proportional gain $K_p$ responds to the instantaneous error, the integral gain $K_i$ eliminates the steady state offset and the derivative gain $K_d$ damps oscillations and improves system stability. The PID gains were manually tuned to optimize performance for the buck converter system, resulting in the following values as shown in Table 2.

The controller was implemented in Simulink as a discrete-time block with a 0.2 ms sample time (synchronized with the 5 kHz switching frequency). To prevent integral windup during transient conditions, output saturation limits were set between 0 and 1 for the duty cycle. The controller processes the voltage error signal (comparing the 15V reference to the actual output) and generates the appropriate duty cycle command for the PWM generator, as illustrated in Fig. 2.

The comparative testing under identical load torque variations (0-10 N·m) revealed significant differences in controller performance as shown in Table 3.

**Table 2.** PID controller parameters and functions

| Gain | Value | Function |
|---|---|---|
| $K_p$ | 0.5 | Reduces rise time while minimizing overshoot |
| $K_i$ | 100 | Ensures elimination of steady-state error |
| $K_d$ | 0.05 | Suppresses high-frequency oscillations |

**Table 3.** Performance comparison: PID vs FLC controllers

| Metric | PID Controller | FLC |
|---|---|---|
| **Settling Time** | 85 ms | 50 ms |
| **Voltage Ripple** | ±1.5 V | ±0.5 V |
| **Overshoot** | 12% | 5% |
| **Steady-State Error** | 0.2 V | 0.05 V |

The FLC demonstrated clear advantages in adaptability, maintaining consistent performance across varying load conditions without requiring manual retuning. It also showed superior capability in handling system nonlinearities, including diode recovery effects and motor inrush currents. The overall design and simulation framework used in this study is illustrated in Fig. 3. It outlines the complete process from the buck converter design and controller integration to the performance evaluation and simulation steps, and it serves as a high-level summary of the methodology discussed in Section 2 and Section 3.

## 3. Fuzzy Logic Controller Structure

The Fuzzy Logic Controller (FLC) designed in this study consists of three main stages: fuzzification, rule base, and defuzzification. While Mamdani and Sugeno inference methods were considered, Mamdani was selected for its superior interpretability in power electronics applications. The linguistic nature of Mamdani's rules directly mirrors how engineers describe voltage regulation strategies, making the controller's behavior more transparent during debugging and tuning. The FLC is designed to regulate the output voltage of a buck converter by adjusting the duty cycle based on the voltage difference and its rate of change. This approach mimics human decision-making in control systems, making it robust and adaptive.

### 3.1. Fuzzification

The fuzzification process converts crisp inputs into linguistic variables using membership functions. The Mamdani approach proves particularly effective here, as its intuitive membership functions (triangular shapes with 30% overlap) provide smooth transitions between control states, a critical requirement for stable buck converter operation. The two inputs to the FLC are the voltage difference $v(n)$ and the rate of change in the voltage difference $\Delta v(n)$. The voltage difference is calculated as the deviation between the actual output voltage (7) and the reference voltage (8), given by:

$$v(n) = V_{out} - V_{ref} \tag{7}$$

Where $V_{out}$ is the actual output voltage and $V_{ref}$ is the reference voltage. The rate of change in voltage difference is defined as

$$\Delta v(n) = v(n) - v(n-1) \tag{8}$$

Where $v(n-1)^{th}$ is the voltage difference at the previous instant. The choice of Mamdani inference becomes particularly advantageous when processing these inputs, as it allows natural linguistic interpretation of trends (e.g., "voltage is too low but improving quickly") that would require complex mathematical functions in Sugeno systems. These inputs are converted into linguistic values using membership functions, as illustrated in Fig. 4 and Fig. 5. The membership functions for the inputs (voltage difference and rate of change in voltage difference) and the output (duty cycle change) in Fig. 6 are defined using five linguistic variables: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB).

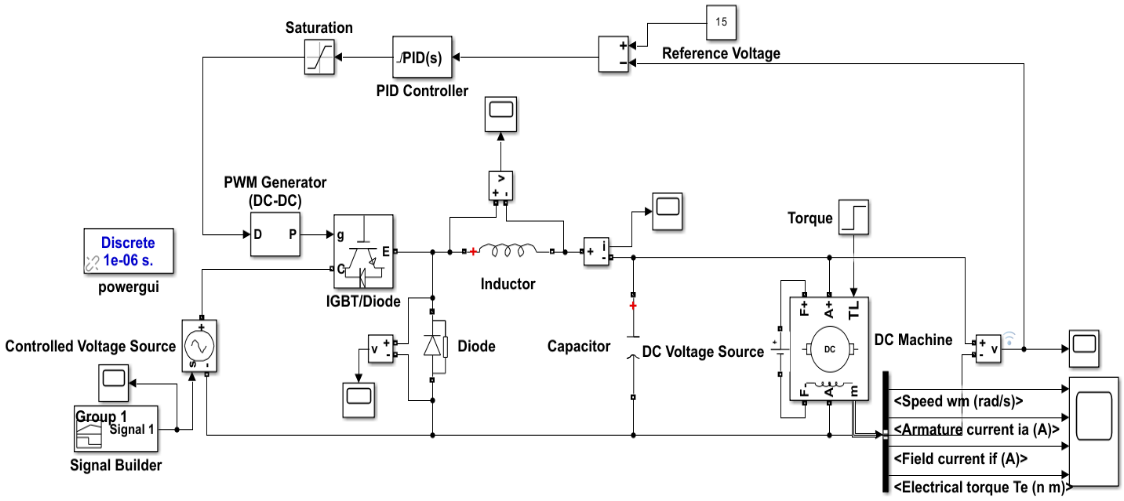


**Fig. 2.** Simulink model of the DC-DC buck converter system with PID controller for DC motor load

The FLC operates using the Mamdani inference method, which is well-suited for systems requiring intuitive human-like decision-making. This selection proves optimal for buck converter control, where the direct relationship between linguistic rules ("if voltage is low, increase duty cycle moderately") and physical system behavior enhances both performance and maintainability. The block diagram of the fuzzy logic controller, shown in Fig. 7, illustrates the flow from fuzzification to defuzzification. The fuzzy logic controller toolbox in Simulink provides a fuzzy logic designer window, where the fuzzy inference system (FIS) can be configured as either Mamdani or Sugeno. For this study, the Mamdani type is used, with input variables (voltage difference and rate of change) and an output variable (duty cycle). A rule base of twenty-five rules has been established, covering all combinations of the five linguistic variables for both inputs. This rule base ensures that the FLC can make intelligent adjustments based on the system's current state and trends, providing smooth and adaptive control.

### 3.2. Voltage Difference and its Rate of Change as Inputs

Using voltage difference and its rate of change as inputs to the FLC is a common approach because it directly represents system behavior and mimics human decision-making in control systems. The voltage difference $v(n)$ represents the difference between the desired output voltage and the actual output voltage. If the voltage difference is positive, the system output is too low and needs to be increased. If the voltage difference is negative, the system output is too high and needs to decrease. If the voltage difference is zero, the system is at the desired value.

The rate of change in the voltage difference $\Delta v(n)$ measures how the voltage difference is evolving over time. If $\Delta v(n) > 0$, the voltage difference is increasing, indicating that the system is diverging from the target. If $\Delta v(n) < 0$, the voltage difference is decreasing, indicating that the system is converging to the target. If $\Delta v(n) = 0$, the voltage difference is stable, indicating that the system is steady.

The overall proposed system block diagram is shown in Fig. 8. The system consists of a buck converter, a DC motor load, and the FLC. The FLC adjusts the duty cycle of the buck converter based on the voltage difference and its rate of change, ensuring precise voltage regulation and stable motor operation.

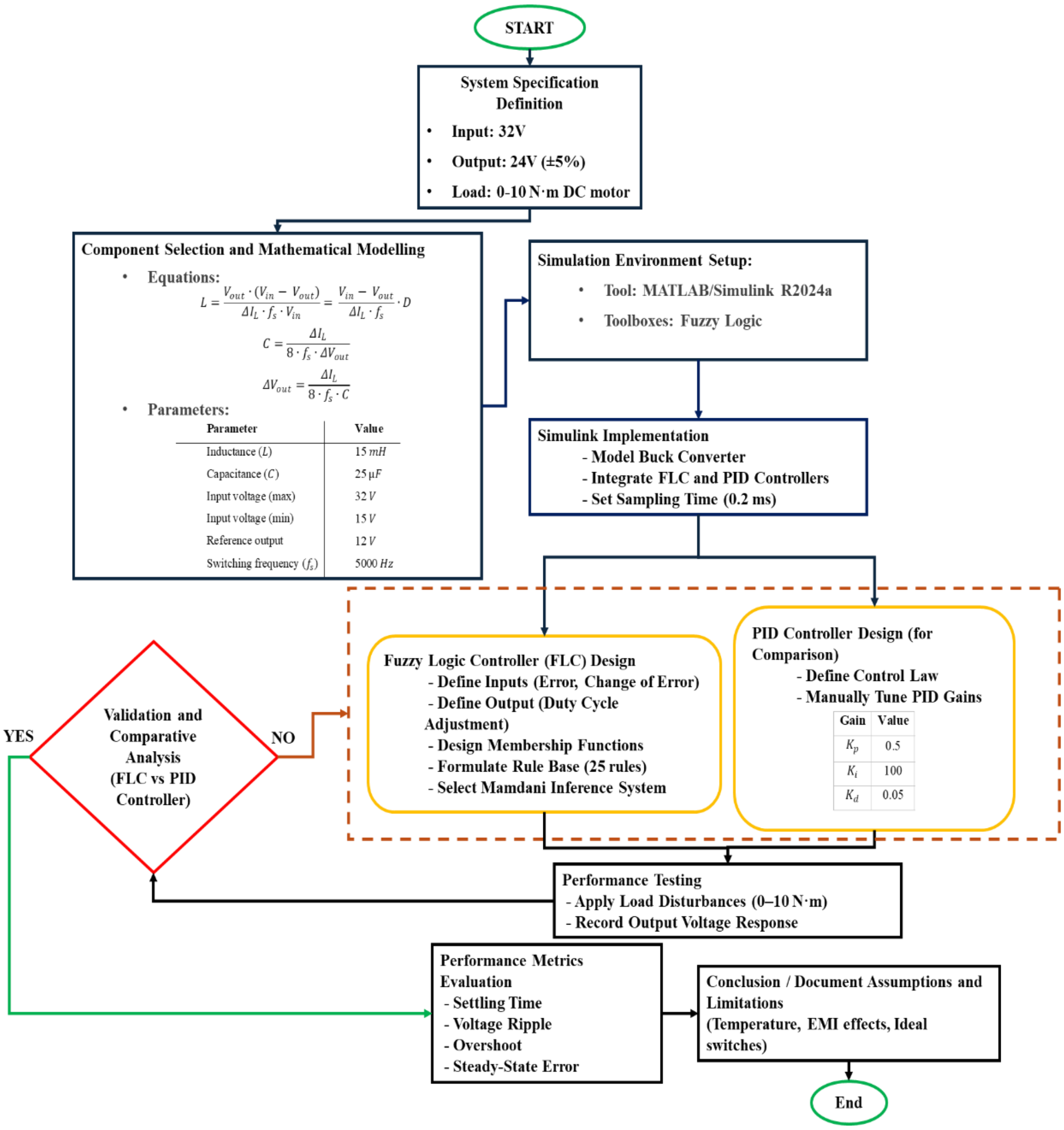


**Fig. 3.** Overall design and simulation framework used in this study

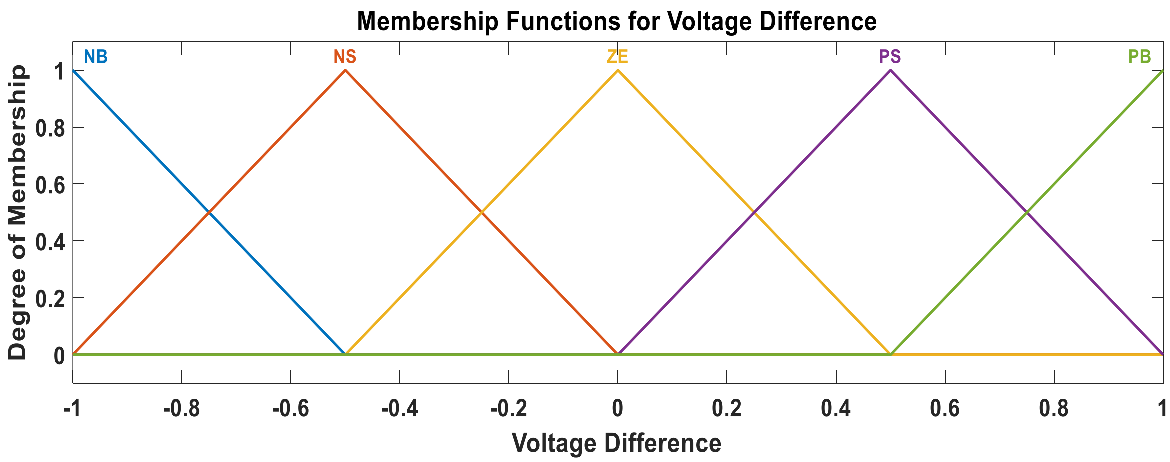


**Fig. 4.** Membership functions for voltage difference input

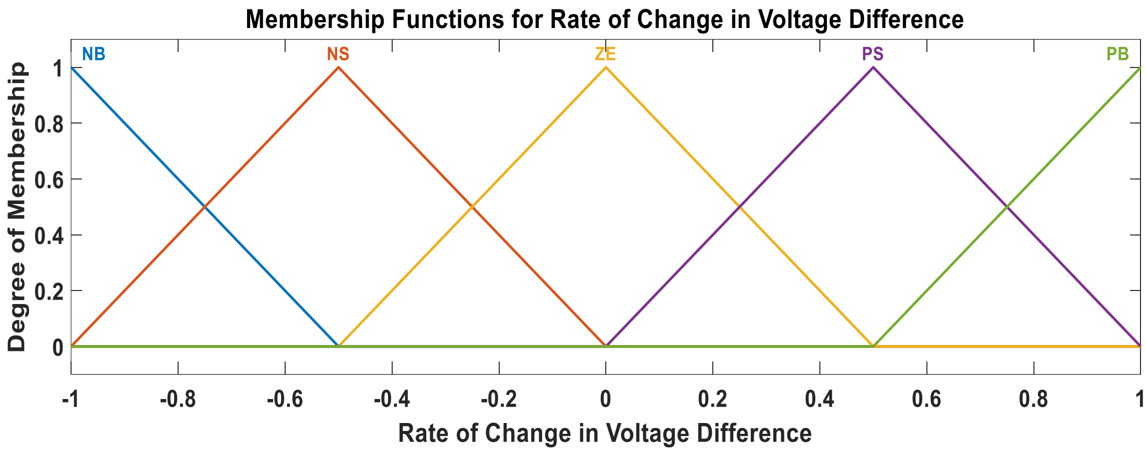


**Fig. 5.** Membership functions for rate of change in voltage difference input

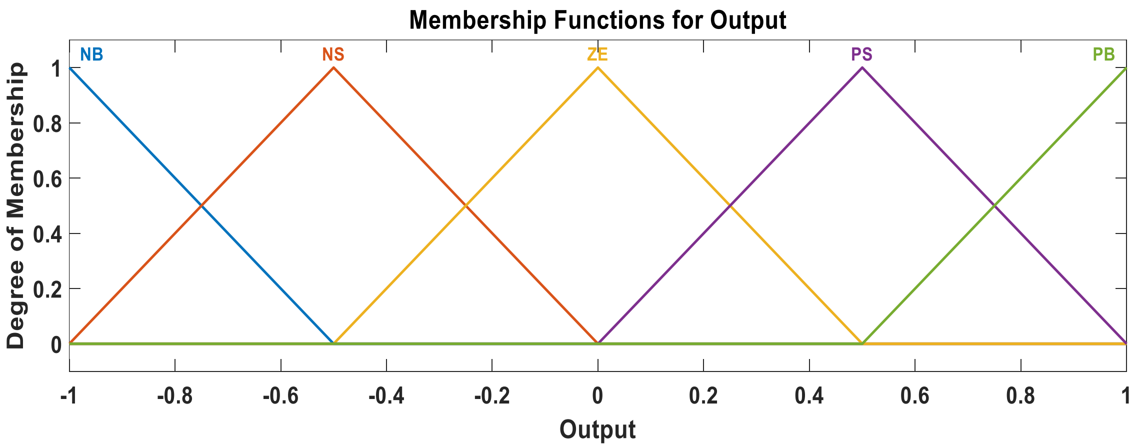


**Fig. 6.** Membership functions for duty cycle output

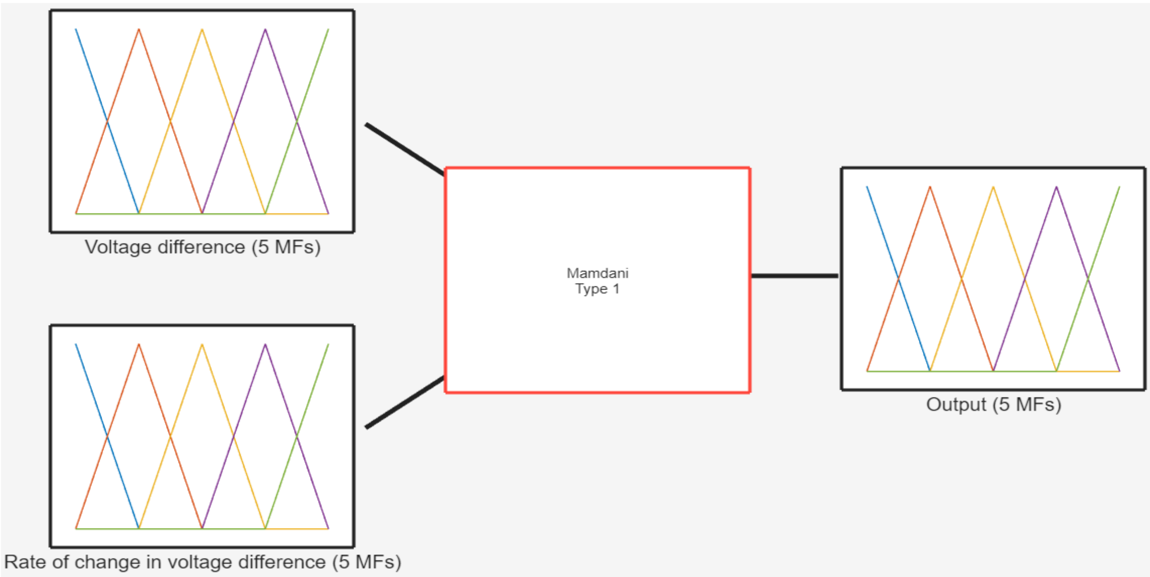


**Fig. 7.** Structure of the Fuzzy Logic Controller (FLC)

### 3.3. Rule Base

The rule base defines the relationship between the inputs (voltage difference and rate of change in voltage difference) and the output (duty cycle change, $\Delta d$). The rules are designed to mimic human decision-making. For example, if the voltage difference is Negative Big (NB) and the rate of change in voltage difference is Positive Big (PB), then the duty cycle change should be Zero (ZE). Similarly, if the voltage difference is Positive Small (PS) and the rate of change in voltage difference is Negative Small (NS), then the duty cycle change should be Negative Small (NS). A simplified version of the rule base is shown in Table 4. The rule base consists of 25 rules, covering all combinations of the five linguistic variables for both inputs.

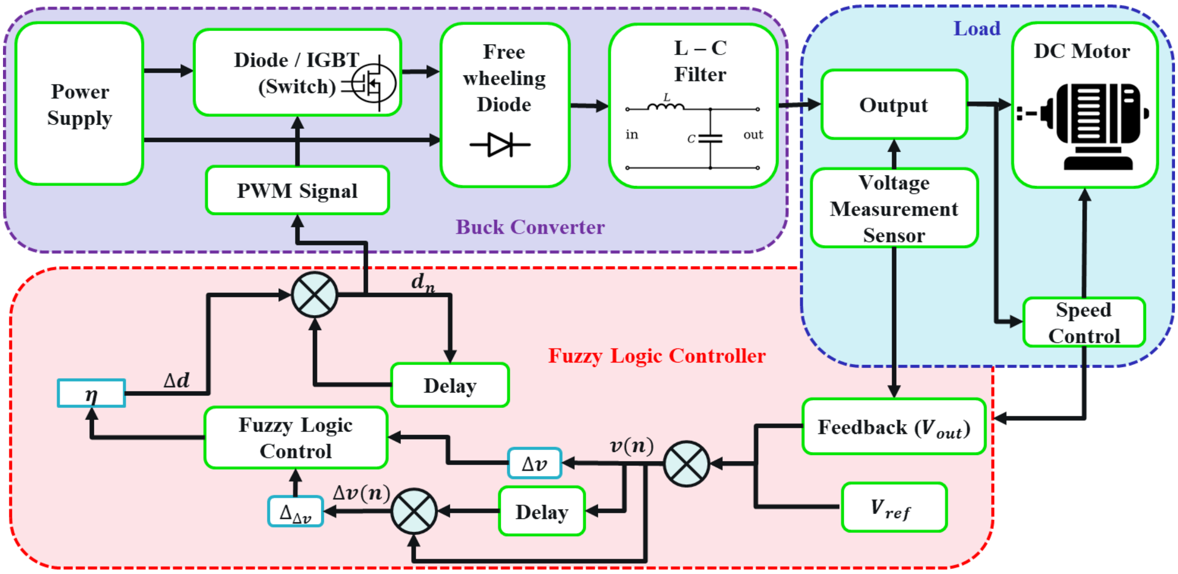


**Fig. 8.** Block diagram of the proposed system with Integrated Fuzzy Logic Controller (FLC)

**Table 4.** Rule base table

| Voltage Difference / Rate of Change | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| **NB** | PB | PB | PB | PS | PS |
| **NS** | PB | PS | PS | PS | ZE |
| **ZE** | PS | PS | ZE | NS | NS |
| **PS** | ZE | NS | NS | NS | NB |
| **PB** | NS | NB | NB | NB | NB |

### 3.4. Defuzzification

The defuzzification process converts the linguistic output from the rule base into a crisp numeric value. The output of the FLC is the duty cycle $d_n$, calculated as (9):

$$d_n = d_{n-1} + \eta \times \Delta d \tag{9}$$

Where $\eta$ is a gain factor. The centroid defuzzification method is used, which returns the center of gravity of the fuzzy set along the x-axis (10):

$$y_{T1-mam}(x_i) = \frac{\sum_i \mu(x_i)x_i}{\sum_i \mu(x_i)} \tag{10}$$

Where $\mu(x_i)$ is the membership value for point $x_i$ in the universe of discourse.

### 3.5. Implementation

The FLC is implemented with gains$\Delta_v$, $\Delta_{\Delta_v}$, and $\eta$ to fine-tune the output. These gains are adjusted to achieve desired performance metrics such as efficiency, time to reach steady state, overshoot, and ripples. The membership functions and rule base are designed to ensure smooth and adaptive control, as shown in Fig. 9.

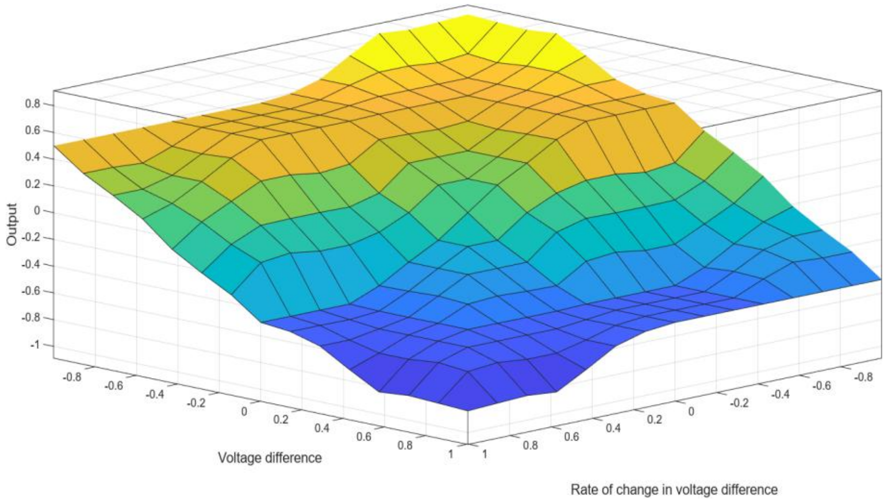


**Fig. 9.** Surface of the fuzzy system rules for the input and output variables

## 4. Results and Discussion

The integration of the Fuzzy Logic Controller (FLC) into the buck converter system was simulated using MATLAB Simulink, as illustrated in Fig. 10. The model includes key components such as the PWM generator, IGBT switch, inductor, capacitor, diode, and DC motor load. The FLC adjusts the duty cycle of the buck converter based on the voltage difference and its rate of change, ensuring precise voltage regulation and stable motor operation. The simulation results demonstrate the effectiveness of the FLC in maintaining the desired output voltage under varying load conditions. The voltage difference $v(n)$and its rate of change $\Delta v(n)$ were used as inputs to the FLC, which generated the appropriate duty cycle adjustments to regulate the output voltage.

The simulation results confirm that the FLC effectively stabilizes voltage output under varying load conditions. The integration of motor parameter monitoring (speed, armature current, field current, and torque) further validates the system's stable dynamic behavior. These observations underscore the FLC's potential in applications requiring rapid regulation and robustness, such as electric drives and battery-based energy systems.

### 4.1. Voltage Regulation

The system's voltage regulation capability is illustrated in Fig. 11 and Fig. 12. Before applying the FLC, as shown in Fig. 11, the output voltage fluctuated significantly, ranging between 19 V and 25 V. These high ripple levels indicate instability in voltage delivery, which can be detrimental to sensitive loads.

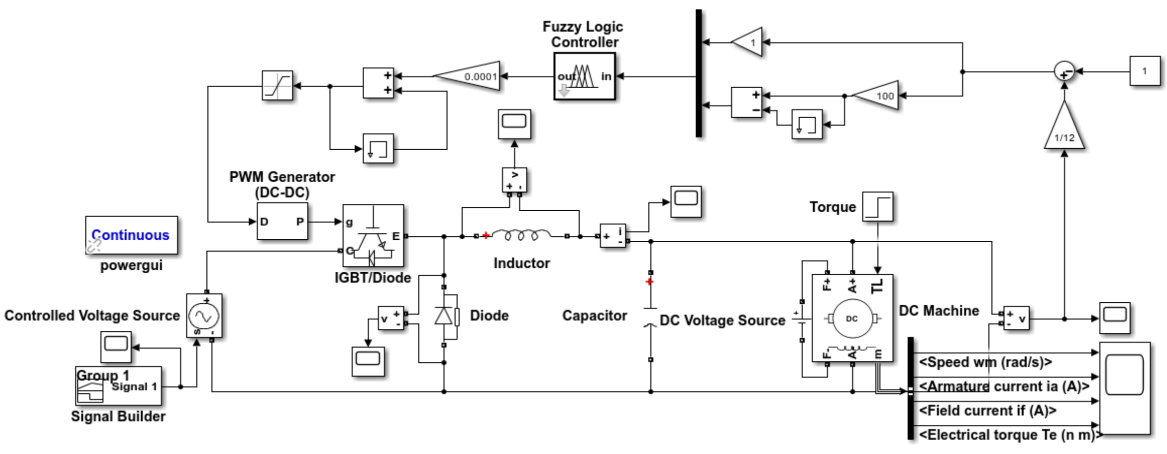


**Fig. 10.** Simulink model with FLC integration

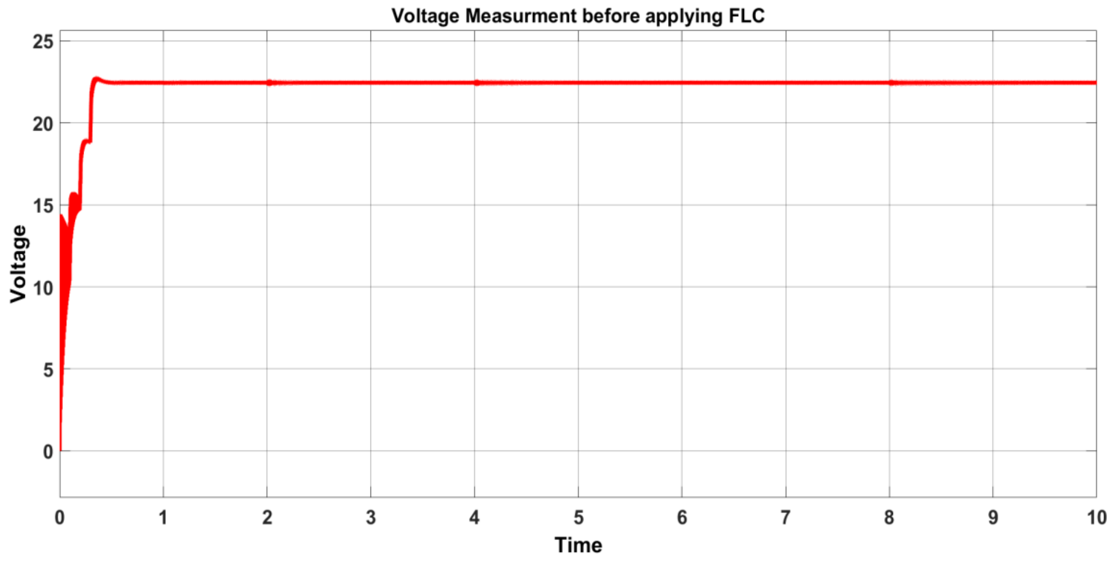


**Fig. 11.** Voltage measurement before FLC

After implementing the FLC, Fig. 12 shows that the voltage stabilizes quickly, with steady-state ripple reduced to less than 0.5 V. The voltage converges to approximately 15 V, very close to the reference voltage. This demonstrates the FLC's superior tracking and noise-suppression capability, validating its voltage regulation performance under dynamic load changes.

### 4.2. Current Response

The performance of the current response was evaluated by comparing measurements before and after applying the FLC, as illustrated in Fig. 13 and Fig. 14. Prior to FLC integration, the current exhibits transient oscillations and overshoots before stabilizing around 9 $A$, as seen in Fig. 13.

Post-integration, the current still converges near 9 A, as shown in Fig. 14, but only with marginal improvement in transient behavior. This suggests that while FLC improves steady-state stability, it does not significantly enhance transient current response. Further refinement of the fuzzy rules or exploration of hybrid approaches (e.g., fuzzy-PID or adaptive fuzzy logic) may be necessary to suppress overshoot and enhance convergence speed in the current waveform.

### 4.3. Comparison Between PID and FLC Controllers

To further validate the effectiveness of the proposed FLC strategy, a performance comparison with a conventional PID controller is presented in Fig. 15, including a magnified subplot that highlights transient behavior. Both controllers were tested under identical conditions to maintain a reference voltage of 15 V. The PID controller (blue trace) initially converges more rapidly but overshoots the reference significantly, peaking at approximately 17 V, resulting in an overshoot of 12%. It also exhibits persistent oscillations and a voltage ripple of ±1.5 V, with a settling time of around 85 $ms$. In contrast, the FLC (orange trace) reaches the target with less overshoot, peaking just under 15.8 V, corresponding to a 5% overshoot, and stabilizes much faster, achieving a settling time of 50 $ms$.

The subplot reveals that FLC offers a smoother transition with minimal transient spikes and improved damping. Furthermore, the FLC maintains the output voltage with a much lower steady-state error of 0.05 V, compared to 0.2 V in the PID-controlled system. This confirms that while PID may offer quicker initial action, FLC provides more stable long-term performance, a key advantage in power electronics systems where voltage precision is critical. These results are consistent with earlier findings by [33], [34], who reported that fuzzy controllers offer better noise immunity and robustness in nonlinear systems than conventional PID. These results demonstrate the superior capability of FLC to suppress oscillations and maintain voltage stability, especially in systems requiring precision and adaptability under dynamic load conditions.

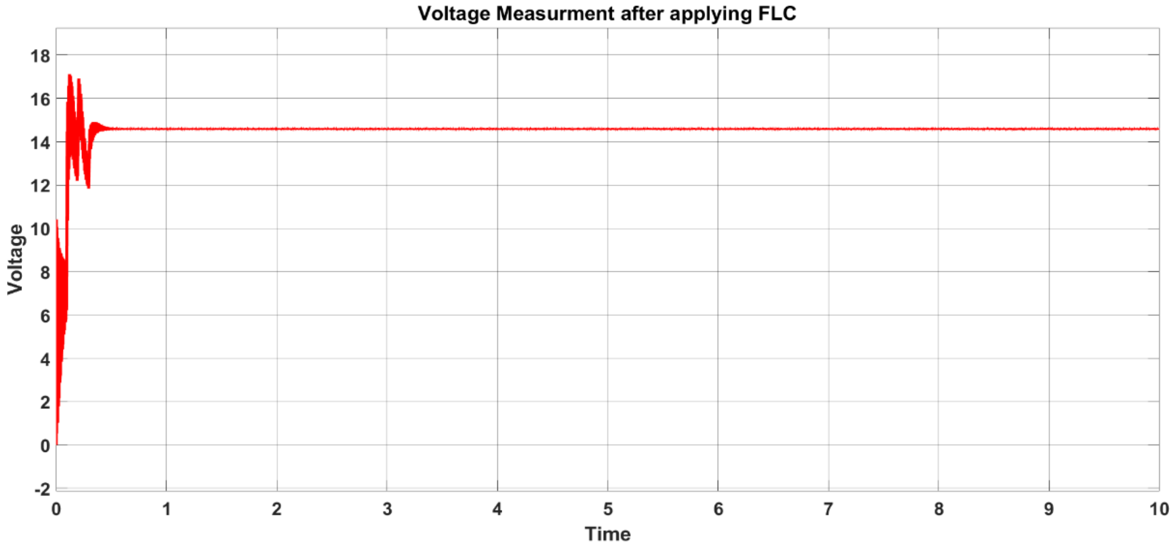


**Fig. 12.** Voltage measurement after FLC

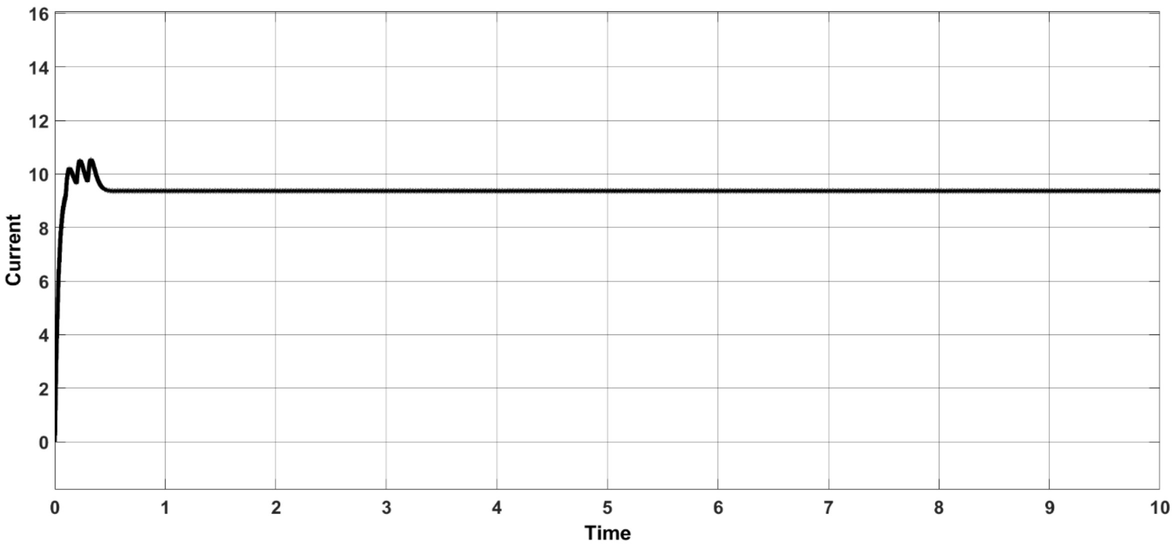


**Fig. 13.** Current measurement before FLC

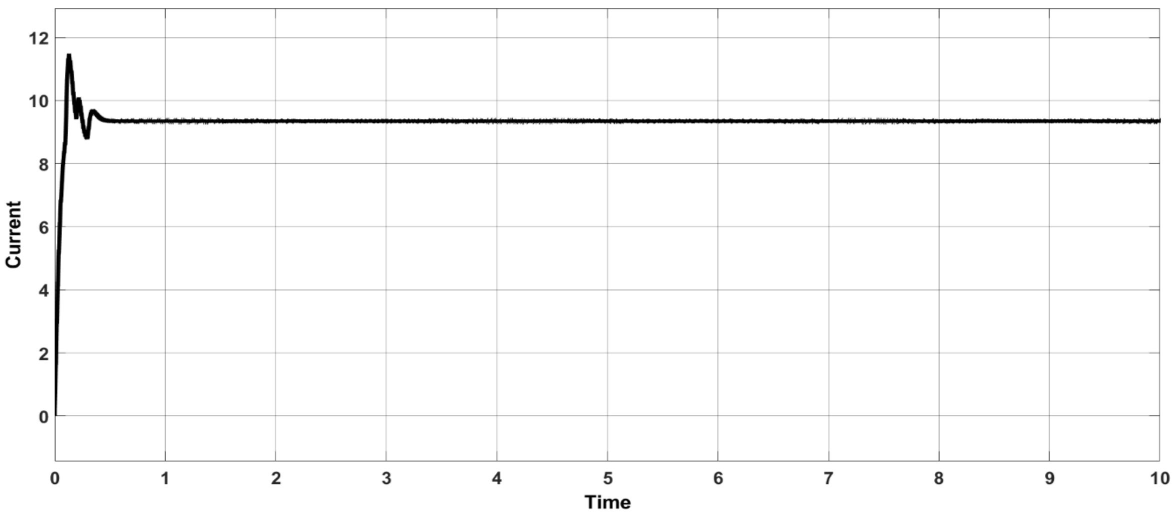


**Fig. 14.** Current measurement after FLC

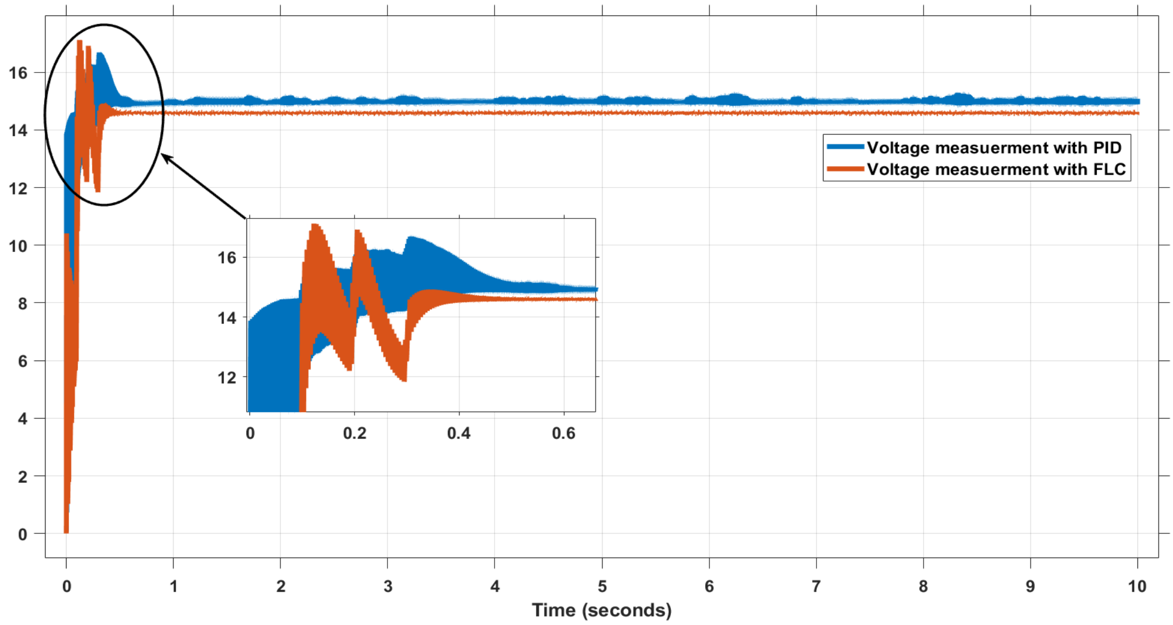


**Fig. 15.** PID vs FLC voltage performance

### 4.4. Motor Performance

To assess the effectiveness of the FLC, the performance of the DC motor was evaluated by monitoring key parameters such as speed, armature current, field current, and electrical torque, as shown in Fig. 16. The motor speed stabilizes at approximately 5.25 $rad/s$, demonstrating smooth operation with minimal oscillations. The armature current stabilizes at around 5 $A$, while the field current remains constant at approximately 1.25 $A$, indicating stable magnetic field conditions. The electrical torque stabilizes at about 10 $Nm$, with smooth transitions and no significant fluctuations. These results highlight the FLC's ability to maintain electromechanical consistency across critical motor parameters.

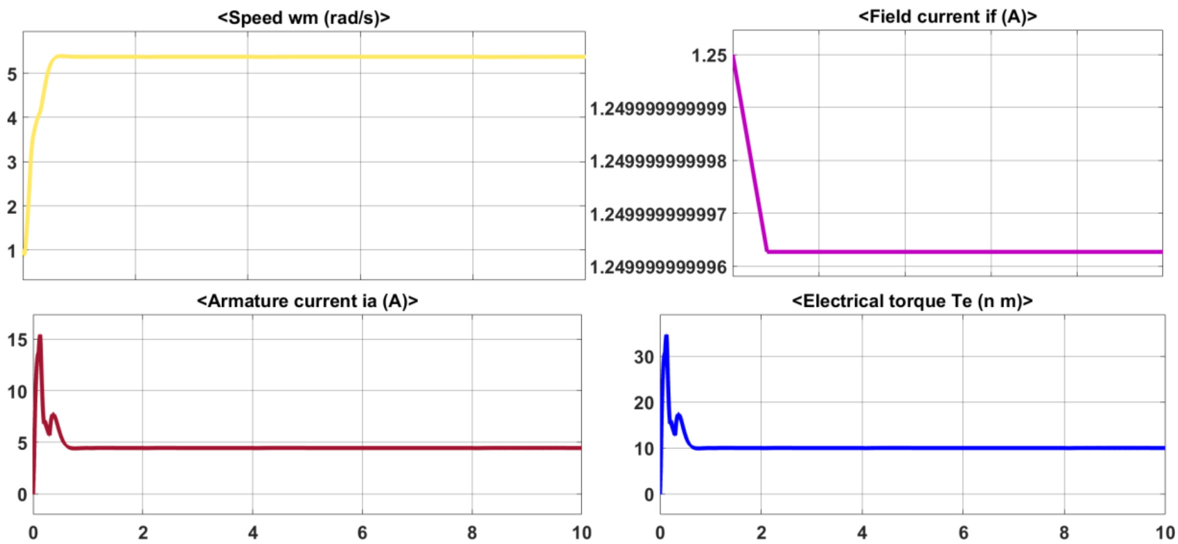


**Fig. 16.** Motor performance parameters after applying the FLC

### 4.5. Implications and Limitations

The findings imply that fuzzy logic controllers (FLCs) are highly effective in regulating voltage in DC-DC converters, particularly in systems experiencing variable load conditions. Their inherent capability to replicate human-like reasoning and manage uncertainties renders them well-suited for nonlinear system applications, offering stable voltage regulation performance under dynamic conditions.

Nonetheless, the study highlights several limitations that constrain the broader applicability of FLCs. Notably, the controller did not deliver significant improvements in transient current response, which could diminish its effectiveness in high-speed switching environments. Furthermore, the computational complexity associated with rule evaluation presents a barrier to real-time implementation, particularly in hardware-constrained systems. The analysis remains confined to simulation-based validation, which limits insights into practical deployment challenges such as quantization effects, electromagnetic interference, and component tolerances.

To overcome these limitations, future research may consider integrating hybrid control strategies, such as combining fuzzy logic with PID or model predictive control (MPC), to enhance dynamic response. Experimental implementation on embedded platforms like STM32 microcontrollers or digital signal processors (DSPs) would help validate simulation results and assess real-time performance. Additionally, robustness testing under fault conditions could further establish the practical reliability of fuzzy-based controllers in real-world DC-DC converter applications.

## 5. Conclusion

The findings of this study demonstrate that the integration of a Fuzzy Logic Controller (FLC) into a buck converter system significantly enhances voltage regulation and motor performance. The FLC effectively minimized voltage ripples and stabilized the output voltage at the desired reference level. However, contrary to initial expectations, the improvement in transient current response was limited, as discussed in the results section. The results confirm that the FLC's adaptive control mechanism successfully handles dynamic load variations, ensuring stable operation of the DC motor. These outcomes support the theoretical contribution that intelligent, rule-based systems like FLCs offer robust voltage regulation in nonlinear power electronic environments. Nevertheless, this study acknowledges key limitations associated with the proposed approach. The increased computational complexity due to rule evaluation, challenges in achieving real-time performance on embedded platforms, and the absence of experimental validation restrict the immediate practical deployment of the FLC in resource-constrained or safety-critical systems. Environmental and hardware uncertainties—such as quantization, electromagnetic interference, and component tolerances—remain unexplored, which may affect real-world performance. These factors must be carefully considered when designing FLCs for applications such as electric vehicles, renewable energy systems, and IoT devices.

To address these limitations and enhance the system’s performance, future research could focus on hybrid control strategies such as Fuzzy-PID, Fuzzy-MPC, or neuro-fuzzy controllers. The integration of machine learning techniques, such as reinforcement learning or genetic algorithms, may enable automatic tuning and adaptability under unseen conditions. However, these methods also introduce challenges, including training data dependency, computational load, and interpretability, which require further investigation. Experimental prototyping on platforms like STM32 microcontrollers, DSPs, or FPGAs is recommended to validate the controller's real-time feasibility and robustness. Further research should also evaluate the controller's fault tolerance, scalability, and long-term reliability under diverse environmental conditions.

In summary, this study contributes to the growing body of knowledge by demonstrating the effectiveness of FLCs in voltage regulation of DC-DC converters and identifying critical implementation considerations. It emphasizes both the promise and the practical hurdles of deploying intelligent controllers in modern power electronics systems. The findings encourage further development of hybrid, adaptive control strategies that balance performance with implementation feasibility. This work aims to motivate ongoing research in intelligent power management, particularly for embedded and energy-efficient systems.

**Author Contribution:** All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

**Funding:** This work was supported in part by the International Islamic University Malaysia under the Research Grant "Optimal Deceleration Formulation Based on Reinforcement Deep Learning for Energy Generation from Regenerative Braking Mode of An Electric Motorcycle" FRGS23-318-0927, and in part by IIUM under the IIUM ENGINEERING MERIT SCHOLARSHIP 2023.

**Acknowledgment:** The authors would like to acknowledge the administrative and technical support provided by the International Islamic University Malaysia (IIUM) throughout this research.

**Conflicts of Interest:** The authors declare no conflict of interest.

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