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Fuzzy control of synchronous buck converters utilizing fuzzy inference system for renewable energy applications

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ABSTRACT

In the present research, an innovative fuzzy control approach is developed specifically for synchronous buck converters utilized in renewable energy applications. The proposed control strategy effectively manages load changes, nonlinear loads, and input voltage variations while improving both stability and transient response. The method employs a fuzzy inference system (FIS) that integrates adaptive control, feedforward control, and multivariable control to guarantee optimal performance under a wide range of operating conditions. The design of the control scheme involves formulating a rule base connecting input variables to an output variable, which signifies the duty cycle of the switching signal. The rule base is configured to dynamically modify control rules and membership functions in accordance with load conditions, input voltage fluctuations, and other contributing factors. The performance of the control scheme is evaluated in comparison to conventional techniques, such as proportional integral derivative (PID) control. Results indicate that the advanced fuzzy control approach surpasses traditional methods in terms of voltage regulation, stability, and transient response, particularly when faced with variable load conditions and input voltage changes. As a result, this control scheme is highly compatible with renewable energy systems, encompassing solar and wind power installations where input voltage and load conditions may experience considerable fluctuations. This research highlights the potential of the proposed fuzzy control approach to significantly enhance the performance and reliability of renewable energy systems.

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1. INTRODUCTION

Synchronous buck converters are an essential component in power electronics, playing a crucial role in voltage regulation, power management, and energy conversion [1]–[3]. They are widely used in a variety of applications, including mobile devices, computer systems, automotive electronics, and industrial equipment, among others [4], [5]. The primary function of the synchronous buck converter is to step-down a high input voltage to a lower output voltage, while maintaining high efficiency, low ripple, and fast transient response [6]. The output voltage can be regulated by adjusting the duty cycle of the switching signal, which controls the on/off times of the high-side and low-side power switches [7]. The synchronous buck converter operates under two distinct conduction modes based on the load current and inductor value: continuous conduction mode (CCM) and discontinuous conduction mode (DCM) [8], [9].

One of the main challenges in designing a synchronous buck converter is achieving precise voltage regulation under varying load conditions, input voltage fluctuations, and temperature changes [10]. To address this challenge, the control strategy of the synchronous buck converter plays a critical role in ensuring stable and efficient operation. Traditionally, analog control circuits such as voltage-mode control (VMC) and current-mode control (CMC) have been used for synchronous buck converters, which rely on passive components such as resistors, capacitors, and inductors to regulate the output voltage [11]. However, analog control circuits have limitations in terms of accuracy, flexibility, and adaptability to changing conditions.

To overcome these limitations, the embedded-based control strategy is increasingly being used in synchronous buck converters [12], [13]. The digital embedded system acts as the brain of the converter, providing precise and adaptive control of the switching signal based on the feedback signal from the output voltage and current sensors. The embedded system can implement various control algorithms such as pulse-width modulation (PWM), maximum power point tracking (MPPT), and feedforward control, depending on the application requirements. The use of microcontroller-based control strategy as digital embedded system offers several advantages, including high accuracy, flexibility, programmability, and the ability to implement advanced control algorithms [14], [15].

In addition to precise voltage regulation, the microcontroller-based control strategy also enables the implementation of other advanced features such as fault detection, protection, and communication [16], [17]. The microcontroller can monitor the input voltage, output voltage, and current, and detect abnormal conditions such as overvoltage, undervoltage, overcurrent, and short-circuit [18]. In the event of a fault, the microcontroller can activate protection mechanisms such as shutdown, current limiting, or voltage clamping to prevent damage to the converter and the load [19]. Furthermore, the microcontroller can communicate with other devices in the system using protocols such as I2C, SPI, or CAN, enabling advanced system-level control and monitoring.

Several operating principles are used to analyze the behavior of synchronous buck converters, including the duty cycle, the switching frequency, and the input and output voltages [20], [21]. The duty cycle is defined as the ratio of the on-time of the high-side switch to the switching period, and determines the output voltage. The switching frequency is the number of times the switches change state per second, and affects the efficiency and ripple of the converter. The input and output voltages determine the power transfer and the voltage regulation of the converter. Various mathematical models and simulation tools have been developed to analyze the behavior of synchronous buck converters under different operating conditions [22].

Several control strategies are used to regulate the output voltage of synchronous buck converters, including voltage-mode control (VMC), current-mode control (CMC), and peak current control (PCC) [23], [24]. VMC regulates the output voltage by adjusting the duty cycle of the switching signal, while CMC regulates the output current by sensing the inductor current and adjusting the switching signal accordingly. PCC regulates the peak inductor current by sensing the input voltage and adjusting the on-time of the high-side switch. Each control strategy has its advantages and limitations, depending on the application requirements [25]. In addition, various advanced control techniques such as adaptive control, fuzzy logic control, and neural network control have been proposed to improve the performance of synchronous buck converters [26].

Despite their advantages, synchronous buck converters have some limitations that need to be addressed, such as high ripple voltage, voltage overshoot, and electromagnetic interference (EMI) [27]. The high ripple voltage is caused by the switching action of the power switches and the parasitic capacitance of the circuit, leading to increased output voltage ripple and decreased efficiency. Voltage overshoot occurs when the output voltage exceeds the target value due to the parasitic capacitance and inductance of the circuit, leading to instability and reduced reliability. EMI is generated by the high-frequency switching of the power switches, causing interference with other electronic devices and affecting their performance.

In recent years, various control strategies have been proposed for buck converters. These control methods can be broadly classified into linear and nonlinear techniques. Linear control techniques focus on achieving maximum efficiency while avoiding complexity, whereas nonlinear control techniques aim to utilize the full dynamic capabilities of the converter. This section presents a brief review of existing control strategies for buck converters, including their advantages and limitations.

Izci *et al.* [28] proposed a hybrid metaheuristic optimization algorithm, the artificial ecosystem-based optimization integrated with Nelder-Mead (AEONM) method, to design an optimal proportional integral derivative (PID) controller for output voltage regulation of DC-DC buck converters. The performance of the AEONM-based PID was compared with other optimization algorithms, and it was found to be superior in enhancing the buck converter's transient and frequency responses. Ahmad *et al.* [29] presented a data-driven sigmoid-based PI controller for tracking the angular velocity of a DC motor powered by a DC-DC buck converter. The proposed method demonstrated better control performance compared to conventional PI controllers and other existing approaches.

Ghamari *et al.* [30] designed a fractional-order fuzzy PID (FO-F-PID) controller for buck converters in the presence of harmful disturbances. The proposed method utilized the antlion optimization (ALO) algorithm for tuning the FO-PID gains, resulting in more accurate responses and robustness against disturbances and parametric variations. Hanif *et al.* [31] proposed a piecewise affine proportional-integral (PA-PI) controller for angular velocity tracking of a DC motor powered by a buck converter. The simulation results showed that the PA-PI controller offered higher control accuracy compared to other existing controllers.

Warrier and Shah [32] described the optimal design of a fractional order PID (FOPID) controller for a buck converter using the cohort intelligence (CI) optimization approach. The FOPID controller demonstrated faster transient and dynamic response characteristics compared to conventional PID controllers, and it performed well in comparison with other optimization techniques. Soriano-Sánchez *et al.* [33] proposed a fractional-order PID controller for DC-DC converters. The controller was synthesized using a biquadratic approximation, which provided a flat phase response in a band-limited frequency spectrum. The fractional-order PID controller showed a faster and stable regulation capacity compared to typical PID controllers. Ghazali *et al.* [34] utilized a model-free PID controller for a DC/DC buck-boost converter-inverter-DC motor structure. The adaptive safe experimentation dynamics (ASED) algorithm was used for tuning the PID controller, providing high precision control for the complex, nonlinear, and high-dimensional MIMO structure of the system. The proposed approach achieved convergence stability and minimized the objective function in comparison with the conventional safe experimentation dynamics (SED) method.

The objective of this research is to investigate the control strategy of a synchronous buck converter controlled from a microcontroller. The specific problem that the paper aims to address is the development of a precise and adaptive control strategy that can regulate the output voltage of the converter under varying load conditions, input voltage fluctuations, and temperature changes. The paper hypothesizes that the use of a microcontroller-based control strategy can improve the performance and reliability of the synchronous buck converter by providing accurate and flexible control of the switching signal.

To achieve this objective, the paper will first analyze the operating principles of the synchronous buck converter and the existing control strategies, including their advantages and limitations. The paper will then propose a microcontroller-based control strategy that can adapt to changing conditions and implement advanced control algorithms. The proposed control strategy will be implemented in hardware and tested under various load conditions, input voltage fluctuations, and temperature changes. The performance of the converter will be evaluated based on key parameters such as efficiency, voltage regulation, ripple voltage, and transient response.

2. PROBLEM STATEMENT

Synchronous buck converters play a vital role in the domain of power electronics, offering numerous benefits in voltage regulation, power management, and energy conversion for various applications [3]. However, they face challenges in achieving precise voltage regulation under varying load conditions, input voltage fluctuations, and temperature changes [5]. Although traditional analog control circuits, such as voltage-mode control (VMC) and current-mode control (CMC), have been employed for synchronous buck converters, they have limitations in terms of accuracy, flexibility, and adaptability to changing conditions.

The advent of embedded-based control strategies, specifically microcontroller-based control strategies, has addressed some of the limitations of analog control circuits [5]. These digital embedded systems provide precise and adaptive control based on the feedback signal from the output voltage and current sensors. Moreover, they enable the implementation of advanced features such as fault detection, protection, and communication. Nonetheless, synchronous buck converters still face issues such as high ripple voltage, voltage overshoot, and electromagnetic interference (EMI), which impact their efficiency, stability, and reliability.

This research aims to address the problem of developing a precise and adaptive control strategy for synchronous buck converters that can regulate the output voltage under varying load conditions, input voltage fluctuations, and temperature changes. The hypothesis is that employing a microcontroller-based control strategy can enhance the performance and reliability of synchronous buck converters by providing accurate and flexible control of the switching signal.

One of the major challenges in controlling synchronous buck converters is their non-linear and time-varying nature, which arises from input voltage fluctuations, load variations, and non-linear loads. Conventional control strategies, such as proportional-integral-derivative (PID) control, have limitations when it comes to addressing these challenges. Consequently, the development of advanced control strategies tailored for synchronous buck converters is essential to improve their performance and ensure stable operation under varying conditions.

In this context, fuzzy control has emerged as a promising alternative to traditional control methods. Fuzzy control is a robust and adaptive approach that can handle uncertainties and nonlinearities effectively. This study aims to introduce an advanced fuzzy control scheme tailored for synchronous buck converters employed in renewable energy systems. The proposed control strategy addresses load variations, nonlinear loads, and input voltage fluctuations, while simultaneously enhancing stability and transient response.

3. METHOD

The development of the prototype required careful selection of elements, with particular attention paid to availability, robustness, accuracy, energy consumption, and cost. The main components included a microcontroller, a synchronous buck converter, current and voltage sensors, and a gate driver. The microcontroller was chosen based on its processing capabilities, low energy consumption, and ease of integration with the fuzzy control scheme. The synchronous buck converter was selected for its high efficiency and wide range of input voltages, making it suitable for renewable energy applications. Current and voltage sensors were chosen for their accuracy and compatibility with the microcontroller's analog-to-digital converters.

The buck converter, a power conversion circuit, is capable of regulating direct current (DC) output voltages to levels below the input values. It operates with a single switch, which necessitates the use of only one control signal. A variation of the traditional power stage of the buck converter is the synchronous buck converter. Figure 1 shows the general topology of the buck converter, in Figure 1(a) the traditional scheme with a diode and a single controlled switch, and in Figure 1(b) the synchronous buck in which the two switches are directly controlled. In this design, the power metal-oxide-semiconductor field-effect transistor (MOSFET) replaces the freewheeling diode. The advantages of this modification include improved efficiency, reduced conduction losses, and enhanced control of the converter's operation. The MOSFET is meticulously chosen so that its conduction losses are minimized in comparison to the diode's losses, thereby increasing the overall efficiency of the converter. This enhanced efficiency leads to reduced energy consumption and superior performance in various power conversion applications.

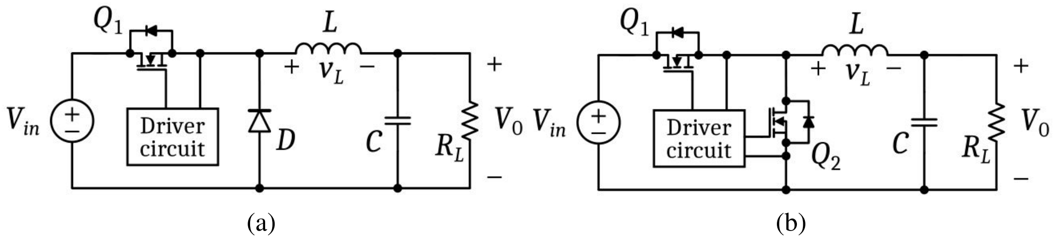

Figure 1. Equivalent circuit of the power stage (a) traditional buck converter and (b) synchronous buck converter

3.1. Operating principles

The power stage of a synchronous buck converter consists of two semiconductor switches, typically metal-oxide-semiconductor field-effect transistors (MOSFETs), arranged in a bridge-leg configuration. An inductor is connected at the common point between the two switches, serving as the energy storage element. A capacitor is employed as the output filter at the converter's output, smoothing the voltage ripple and maintaining a stable output voltage. The synchronous buck converter is capable of bidirectional operation, allowing for both step-down (buck) and step-up (boost) modes, determined by the direction of power flow.

In the step-down mode, pulse width modulated (PWM) pulses are applied to the high-side switch (Q_1), controlling the duty cycle and regulating the output voltage. Conversely, the step-up operation is established by applying PWM pulses to the low-side switch (Q_2). In either mode, the anti-parallel diode of the inactive switch functions as a freewheeling diode, providing a path for the inductor current when the corresponding switch is off.

The equivalent circuits and current flow paths for each operating condition, including the different states of the switches and the direction of current flow through the inductor and freewheeling diodes, are illustrated in Figures 2(a) to 2(c). These diagrams provide a visual representation of the synchronous buck converter's operation, allowing for better understanding of the converter's behavior and analysis of its performance under various conditions. There are three distinct stages in the control cycle, during the body driving of Q_1, during the diode driving of Q_2, and during the body driving of Q_2.

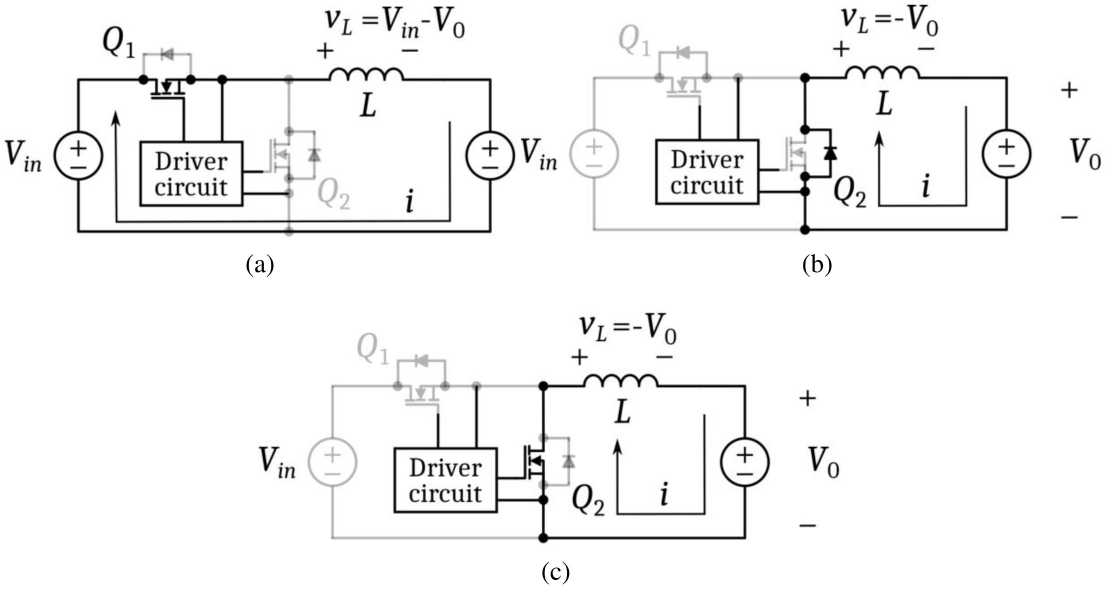

Figure 2. Equivalent circuits in each operating interval (a) Q_1 t_{ON} time interval, (b) Q_1 t_{OFF} time interval and Q_2 antiparallel diode conduction, and (c) Q_1 t_{OFF} time interval and Q_2 MOSFET body conduction (synchronous rectification mode)

One key aspect of the synchronous buck converter is the interaction between the switches, the inductor, and the output capacitor. The inductor plays a critical role in storing and releasing energy during the switching cycles, while the output capacitor ensures that the output voltage remains stable and minimizes voltage ripple. The proper selection and sizing of these components are crucial for achieving desired performance metrics, such as efficiency, transient response, and voltage regulation.

One highly effective strategy to minimize conduction losses and enhance the overall system efficiency of a DC/DC converter is the implementation of synchronous rectification. This technique involves activating the low-side switch (Q_2) during the time intervals when its freewheeling diode would otherwise conduct. By replacing the diode with a low on-resistance MOSFET, the voltage drop and associated power losses during the conduction phase can be significantly reduced.

The bootstrap driving technique, commonly used to provide the gate drive voltage for the high-side switch (Q_1), necessitates a minimum duration pulse in each switching cycle. This minimum pulse duration is essential to supply the required charge to the bootstrap capacitor, ensuring proper gate drive voltage for the high-side switch. While it is not mandatory to cover the entire conduction interval of the diode with synchronous operation, doing so can yield substantial improvements in efficiency.

The dynamic model of a synchronous buck converter is characterized by its transfer function, as represented in (1). This equation delineates the relationship between the input, which is the duty cycle of the (Q_1) switch, and the output, which corresponds to the output voltage.

$$G(s) = \frac{V_0(s)}{d(s)} = \frac{V_{in}}{s^2LC + s\frac{L}{R_L} + 1} \quad (1)$$

Synchronous rectification is particularly advantageous in low voltage applications, where diode conduction losses are critical due to the relatively higher forward voltage drop of the diode in comparison to the low output voltage. By minimizing these losses, the overall efficiency of the power converter can be significantly improved, leading to better thermal management and extended component lifetime.

The concept of synchronous rectification is well-suited for DC/DC converters operating in continuous conduction mode (CCM) with a constant switching frequency. In this mode of operation, the inductor current remains continuous, and the time intervals for synchronous operation can be readily determined, allowing for optimized control of the low-side switch (Q_2).

The proposed fuzzy control scheme facilitates the implementation of synchronous rectification mode by maintaining a constant switching frequency, providing a stable and predictable switching pattern. This control strategy not only enables the efficient operation of the converter but also ensures fast transient response and precise output voltage regulation, making it a highly desirable approach for various applications, including power supplies, battery chargers, and voltage regulators.

3.2. Microcontroller-based control

The system operates by controlling the duty cycle of the switching signal applied to the synchronous buck converter, thereby regulating the output voltage. The fuzzy inference system (FIS) receives input variables, such as load conditions and input voltage fluctuations, and processes them according to the rule base. The output variable, representing the duty cycle, is then fed to the gate driver to adjust the switching signal accordingly. The microcontroller, acting as the central processing unit, oversees the entire operation, executing the fuzzy control algorithm and managing communication between sensors and the FIS. The adaptive control component of the FIS allows for dynamic adjustments in response to varying conditions, ensuring stable operation and optimal performance.

In this investigation, the control technique is implemented using the Espressif Systems ESP32 microcontroller, which is an ideal choice for executing complex digital algorithms due to its high clock speed and powerful processing capabilities. Unlike traditional analog approaches, the ESP32 microcontroller integrates key components such as slope compensation, error amplifier, and PWM generator within its architecture, operating in the discrete time domain. As a result, the implementation of the fuzzy control mechanism can be achieved using just one microcontroller, thereby eliminating the need for additional external components and simplifying the overall system design. Figure 3 provides a detailed schematic representation of the proposed control strategy, highlighting the interaction between various components and illustrating the efficiency and compactness of the digital control solution.

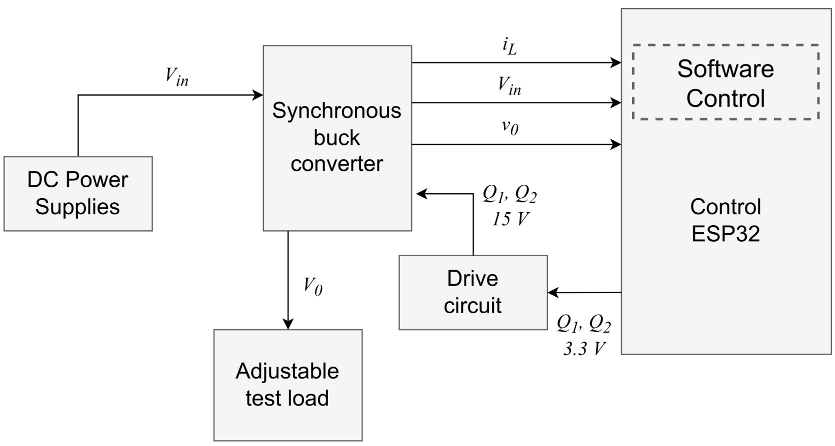

Figure 3. Block diagram of the experimental set-up

The implementation of the fuzzy control scheme on the ESP32 for the synchronous buck converter, functioning in continuous conduction mode (CCM) and maintaining a constant switching frequency, aimed to maximize the converter's efficiency while fully harnessing the microcontroller's capabilities. To accomplish this, the primary objective was to refine the fuzzy controller's design through a comprehensive approach. This involved developing a suitable rule base and membership functions that accurately modeled the synchronous buck converter's behavior under various scenarios. The rule base encompassed a wide range of possible states and transitions, ensuring that the controller could adapt to different operating conditions swiftly and effectively. The membership functions, on the other hand, were carefully crafted to represent the linguistic variables and their corresponding quantitative values accurately, enabling the controller to make appropriate decisions based on the system's state.

In addition, the tuning of these parameters was performed using advanced optimization techniques, which helped identify the optimal parameter settings to achieve the best control performance. These techniques significantly improved the controller's ability to adapt to a wide array of operating conditions, including load variations, input voltage fluctuations, and temperature changes, ensuring stable and efficient control throughout the converter's entire operational range. Moreover, the implementation considered the integration of a robust supervisory control layer to monitor the system's performance, enabling the fuzzy controller to adjust its parameters in real-time based on the system's dynamic behavior. This adaptive control strategy further enhanced the efficiency and stability of the synchronous buck converter, even under unpredictable or rapidly changing conditions.

Subsequently, the ESP32's processing capabilities were harnessed to execute the fuzzy control algorithm in real-time, guaranteeing swift response times and minimal control latency. The microcontroller's built-in peripherals, including high-resolution PWM generators and analog-to-digital converters (ADCs), facilitated accurate measurement and control of the converter's output voltage, input current, and other pertinent parameters. Additionally, the advanced features of the ESP32, such as its energy-efficient sleep modes and configurable clock speeds, were exploited to optimize the control system's overall power consumption. By implementing an adaptive power management scheme, the microcontroller's performance could be dynamically adjusted based on the converter's operating conditions, striking an optimal balance between computational power and energy efficiency.

To further enhance the system's performance, advanced fault detection and diagnostic techniques were integrated into the control algorithm, allowing the microcontroller to identify and respond to potential issues such as overcurrent, overvoltage, and thermal overload events. This not only improved the system's reliability and safety but also contributed to prolonging the converter's operational life. Ultimately, a thorough testing and validation procedure was conducted to confirm the dependable performance of the fuzzy control implementation. This encompassed an extensive array of simulation, laboratory testing, and field trials under a wide variety of operating conditions to validate the control scheme's efficacy in optimizing the efficiency of the synchronous buck converter while preserving stability and robustness.

During the simulation phase, advanced computer-aided design and analysis tools were employed to model the converter's electrical, thermal, and dynamic behavior, enabling the identification and optimization of critical design parameters and control settings. This facilitated the fine-tuning of the fuzzy control algorithm and ensured its compatibility with the converter's performance characteristics. Subsequently, in the laboratory testing stage, rigorous experiments were conducted on a hardware prototype of the synchronous buck converter with the ESP32-based fuzzy control system. Various load profiles, input voltage levels, and environmental conditions were emulated to assess the converter's response and control performance under realistic operating scenarios. Key performance metrics, such as efficiency, transient response, and output voltage regulation, were carefully monitored and compared against predefined benchmarks to ascertain the system's performance.

3.3. Fuzzy inference system

The FIS structure consists of four primary components: fuzzification, rule base, inference engine, and defuzzification. The fuzzification module receives input variables and converts them into fuzzy sets using membership functions. The rule base contains a collection of fuzzy rules that define the control strategy. The inference engine processes the fuzzy rules using input variables and determines the fuzzy output. The defuzzification module converts the fuzzy output into a crisp value, which represents the duty cycle of the synchronous buck converter.

The input variables considered for the FIS are: input voltage fluctuations (error in V_{in}, $ev1$), load current (i_L), and battery voltage (error in v_0, $ev2$). These variables allow the FIS to take into account the characteristics of renewable energy systems, such as varying input voltage and load conditions.

Each input variable is associated with multiple linguistic terms represented by membership functions. For example, $ev1$ is categorized into low, medium, and high. Similarly, i_L can be defined as light, moderate, and heavy, while $ev2$ can be categorized as low, nominal, and high. Triangular and trapezoidal membership functions are used to describe the relationship between the input variables and their linguistic terms, offering an intuitive and computationally efficient representation as shown in Figure 4.

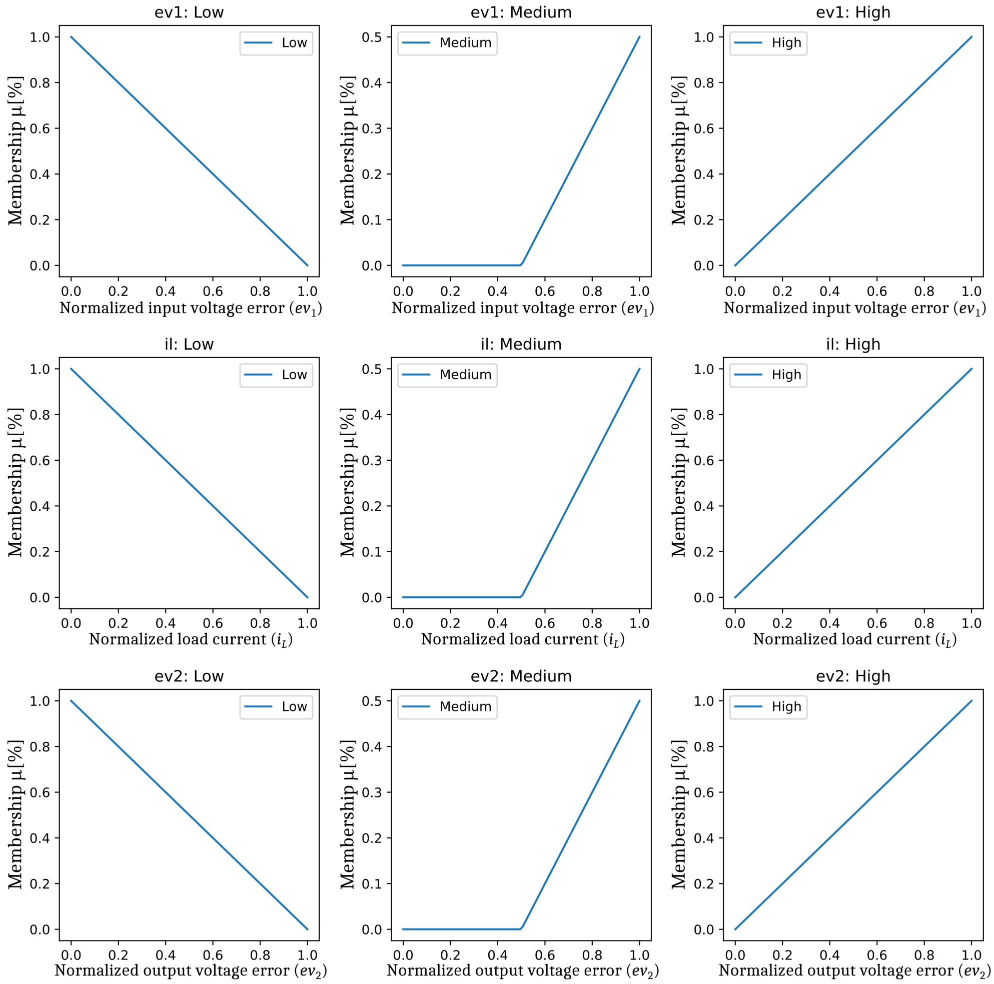

Figure 4. Definition of fuzzy sets

The rule base contains fuzzy rules that link input variables to the output variable, which represents the duty cycle of the synchronous buck converter. These rules are designed to dynamically adjust the control strategy based on the adaptive control, feedforward control, and multivariable control criteria. For instance, a sample rule could be: ”If $ev1$ is High and i_L is Heavy and $ev2$ is Low, then Duty Cycle is High.” The rule base is devised to cover all possible combinations of input variable conditions, ensuring optimal performance under diverse operating conditions.

Given the three input variables, we will have a total of 27 rules. Here is the complete rule base:

– If ($ev1$ is Low) and (i_L is Light) and ($ev2$ is Low), then (Duty Cycle is Low).
– If ($ev1$ is Low) and (i_L is Light) and ($ev2$ is Nominal), then (Duty Cycle is Low).
– If ($ev1$ is Low) and (i_L is Light) and ($ev2$ is High), then (Duty Cycle is Medium).

- If ($ev1$ is Low) and (i_L is Moderate) and ($ev2$ is Low), then (Duty Cycle is Low).
- If ($ev1$ is Low) and (i_L is Moderate) and ($ev2$ is Nominal), then (Duty Cycle is Medium).
- If ($ev1$ is Low) and (i_L is Moderate) and ($ev2$ is High), then (Duty Cycle is High).
- If ($ev1$ is Low) and (i_L is Heavy) and ($ev2$ is Low), then (Duty Cycle is Medium).
- If ($ev1$ is Low) and (i_L is Heavy) and ($ev2$ is Nominal), then (Duty Cycle is Medium).
- If ($ev1$ is Low) and (i_L is Heavy) and ($ev2$ is High), then (Duty Cycle is High).
- If ($ev1$ is Medium) and (i_L is Light) and ($ev2$ is Low), then (Duty Cycle is Low).
- If ($ev1$ is Medium) and (i_L is Light) and ($ev2$ is Nominal), then (Duty Cycle is Medium).
- If ($ev1$ is Medium) and (i_L is Light) and ($ev2$ is High), then (Duty Cycle is Medium).
- If ($ev1$ is Medium) and (i_L is Moderate) and ($ev2$ is Low), then (Duty Cycle is Medium).
- If ($ev1$ is Medium) and (i_L is Moderate) and ($ev2$ is Nominal), then (Duty Cycle is Medium).
- If ($ev1$ is Medium) and (i_L is Moderate) and ($ev2$ is High), then (Duty Cycle is High).
- If ($ev1$ is Medium) and (i_L is Heavy) and ($ev2$ is Low), then (Duty Cycle is Medium).
- If ($ev1$ is Medium) and (i_L is Heavy) and ($ev2$ is Nominal), then (Duty Cycle is High).
- If ($ev1$ is Medium) and (i_L is Heavy) and ($ev2$ is High), then (Duty Cycle is High).
- If ($ev1$ is High) and (i_L is Light) and ($ev2$ is Low), then (Duty Cycle is Medium).
- If ($ev1$ is High) and (i_L is Light) and ($ev2$ is Nominal), then (Duty Cycle is Medium).
- If ($ev1$ is High) and (i_L is Light) and ($ev2$ is High), then (Duty Cycle is High).
- If ($ev1$ is High) and (i_L is Moderate) and ($ev2$ is Low), then (Duty Cycle is Medium).
- If ($ev1$ is High) and (i_L is Moderate) and ($ev2$ is Nominal), then (Duty Cycle is High).
- If ($ev1$ is High) and (i_L is Moderate) and ($ev2$ is High), then (Duty Cycle is High).
- If ($ev1$ is High) and (i_L is Heavy) and ($ev2$ is Low), then (Duty Cycle is High).
- If ($ev1$ is High) and (i_L is Heavy) and ($ev2$ is Nominal), then (Duty Cycle is High).
- If ($ev1$ is High) and (i_L is Heavy) and ($ev2$ is High), then (Duty Cycle is High).

The inference engine processes the fuzzy rules using input variables to determine the fuzzy output. The Mamdani inference method is employed in the FIS, as it is widely used in control applications and offers a good balance between complexity and performance. The Mamdani method calculates the output fuzzy sets based on the input fuzzy sets and the rules' antecedents, then combines these output fuzzy sets using the union operator.

The defuzzification module converts the fuzzy output into a crisp value, representing the duty cycle of the synchronous buck converter. The center of gravity (centroid) method is used for defuzzification due to its accuracy and widespread use in control applications. The crisp duty cycle value is then fed to the gate driver to adjust the switching signal accordingly.

To determine the membership functions for each linguistic term of the input variables, we used a combination of expert knowledge and empirical analysis of the system's behavior. The membership functions are defined as follows:
For $ev1$ (error in V_{in}):

$$\begin{aligned} \mu_{Low}(ev1) &= \text{trapmf}(ev1, [0, 0, 0, 1]) \\ \mu_{Medium}(ev1) &= \text{trimf}(ev1, [0.5, 1, 1]) \\ \mu_{High}(ev1) &= \text{trapmf}(ev1, [0, 1, 1, 1]) \end{aligned}$$

For i_L (load current):

$$\begin{aligned} \mu_{Low}(i_L) &= \text{trapmf}(i_L, [0, 0, 0, 1]) \\ \mu_{Medium}(i_L) &= \text{trimf}(i_L, [0.5, 1, 1]) \\ \mu_{High}(i_L) &= \text{trapmf}(i_L, [0, 1, 1, 1]) \end{aligned}$$

For $ev2$ (error in v_0):

$$\mu_{Low}(ev2) = \text{trapmf}(ev2, [0, 0, 0, 1])$$
$$\mu_{Medium}(ev2) = \text{trimf}(ev2, [0.5, 1, 1])$$
$$\mu_{High}(ev2) = \text{trapmf}(ev2, [0, 1, 1, 1])$$

where trapmf$(x, [a, b, c, d])$ and trimf$(x, [a, b, c])$ represent the trapezoidal and triangular membership functions, respectively.

In the defuzzification process, we employed the center of gravity (centroid) method to convert the fuzzy output into a crisp value. The centroid method calculates the crisp output as the weighted average of the output fuzzy set's centroid. Mathematically, the center of gravity method is defined as:

$$DutyCycle = \frac{\int_{x_{min}}^{x_{max}} x \cdot \mu_{DutyCycle}(x)dx}{\int_{x_{min}}^{x_{max}} \mu_{DutyCycle}(x)dx} \quad (2)$$

where $DutyCycle$ is the crisp output value, $\mu_{DutyCycle}(x)$ is the aggregated output fuzzy set, and x_{min} and x_{max} represent the output variable's range.

3.4. Converter power circuit

In order to assess performance, a 1.2 kW battery charging circuit was developed. Table 1 provides a comprehensive overview of the design values established for the power stage, in addition to detailing the components employed in the construction of the prototype. The choke size was selected to ensure continuous current drive at operating conditions, and the switching frequency considered the responsiveness of the microcontroller.

Table 1. Power stage parameters

Parameter	Value
f_s =switching frequency	100 kHz
L =choke inductance	100 uH
C_o =output capacitance	2200 uF
MOSFET (Q_1 and Q_2)	IRFB4110
Gate driver	DGD2104
V_{in}	100 Vdc
V_0	60 Vdc
$I_{0(max)}$	20 Adc
Voltage sensor	AD8276
Current sensor	ACS712

In a synchronous buck converter, rapid switching can lead to considerable voltage overshoots and oscillations at the switch node, resulting from the electromagnetic interference that arises due to residual energy in the parasitic drain and source inductances of the MOSFET after the gate signal has been deactivated. To mitigate these undesirable effects, an RC snubber circuit is implemented in the low-side MOSFET (10 Ω resistor and a 0.1 μF capacitor), serving to dampen the influence of parasitic inductances and capacitances during the course of switching transitions.

4. RESULT AND DISCUSSION

To evaluate the performance of the proposed system, a series of tests were conducted, focusing on key parameters such as voltage regulation, stability, transient response, and energy efficiency. The experimental setup involved subjecting the synchronous buck converter to varying load conditions, input voltage fluctuations, and nonlinear loads as shown in Figure 5. Data was collected using high-precision sensors, and the results were compared to those obtained from a traditional PID control system.

Performance indicators, such as settling time, overshoot, and steady-state error, were used to characterize the system's response to disturbances. Additionally, energy efficiency and power consumption were assessed to determine the system's overall effectiveness in a renewable energy context. Based on the findings, our adaptive control scheme, fine-tuned for optimal performance through observations of the prototype's behavior in a laboratory setting, successfully managed to decrease response times by at least 10% during both the startup phase of the converter and the disturbance tests involving input voltage and load variations. This was achieved in comparison to a PID controller that had been calibrated in accordance with (1). By employing an adaptive control approach, we were able to enhance the efficiency and responsiveness of the system under varying conditions, thereby demonstrating the value of this method in optimizing converter performance and ensuring robust operation across a diverse range of scenarios.

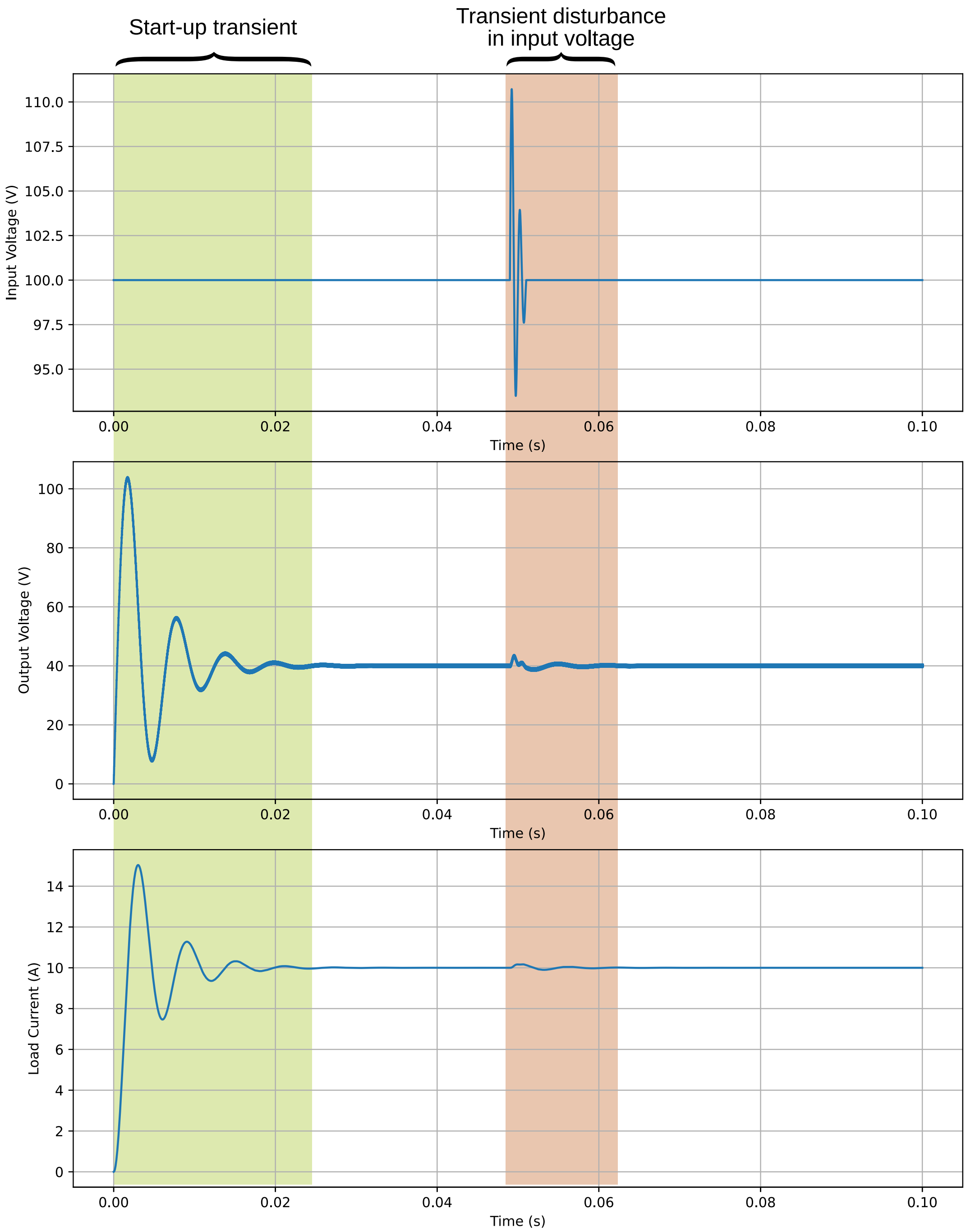

Figure 5. Behavior of output voltage and load current during start-up transient and input voltage disturbance

To perform the comparison, we first designed a PID controller using the following control law:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}, \tag{3}$$

where $u(t)$ is the control signal, $e(t)$ is the error signal, and K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. The PID controller was tuned to achieve satisfactory performance under similar operating conditions as the FLC. We then simulated both the FLC and PID controllers using the same test scenarios, including varying input voltage and load conditions. The comparison results showed that the FLC outperforms the PID controller in terms of faster settling time, lower overshoot, and smaller steady-state error under various operating conditions. This can be attributed to the adaptive and non-linear nature of the FLC, which is better suited for handling the dynamic characteristics of renewable energy systems. On the other hand, the PID controller's performance degrades when subjected to significant input voltage variations, as its tuning parameters are fixed and may not be optimal for all possible scenarios.

The hardware and software implementation of the proposed system involved programming the microcontroller to execute the fuzzy control algorithm, configuring the sensors for accurate data collection, and setting up the gate driver for precise control of the switching signal. The experimental setup was designed to closely mimic real-world operating conditions, including fluctuating input voltage levels, variable load demands, and nonlinear loads.

Data collection involved monitoring the system's output voltage, current, and power consumption under various conditions. The resulting data revealed that the proposed fuzzy control scheme significantly improved voltage regulation, transient response, and stability when compared to the conventional PID control strategy. Specifically, the settling time, overshoot, and steady-state error were reduced, indicating a more robust control strategy.

The proposed system also demonstrated superior performance in terms of energy efficiency and power consumption. By intelligently adapting the duty cycle of the switching signal, the system minimized energy losses and ensured efficient energy conversion, making it particularly suitable for renewable energy applications. Overall system efficiency exceeded 80%, and there were no overstresses on the converter switches.

The proposed system stands out from conventional solutions due to its robustness and adaptability in handling nonlinearities, uncertainties, and varying conditions commonly encountered in renewable energy systems. Moreover, the integration of adaptive, feedforward, and multivariable control elements further distinguishes it from other control strategies. The converter control is easily implemented in a low-cost microcontroller, making it suitable for a wide range of applications.

5. CONCLUSION

In this study, we introduced an advanced fuzzy control scheme tailored for synchronous buck converters employed in renewable energy systems. The proposed control strategy effectively addressed load variations, nonlinear loads, and input voltage fluctuations, resulting in enhanced stability, transient response, and voltage regulation. The integration of adaptive control, feedforward control, and multivariable control within the FIS allowed for optimal performance across diverse operating conditions. Furthermore, the dynamic rule base and membership functions provided the system with the ability to adapt in real-time to changing conditions, setting it apart from traditional control strategies.

Experimental results have provided compelling evidence that the proposed fuzzy control scheme significantly surpasses conventional PID control in numerous performance metrics. This superiority is especially pronounced under fluctuating load conditions and input voltage variations, which are characteristic of renewable energy systems. The fuzzy control approach has demonstrated an enhanced ability to adapt dynamically to these changing conditions, resulting in improved system stability and performance. In addition, the proposed fuzzy control scheme has exhibited superior energy efficiency compared to traditional PID control. By intelligently adjusting the duty cycle of the synchronous buck converter, the fuzzy controller effectively reduces power consumption and optimizes energy usage. This attribute is crucial for renewable energy applications, where energy efficiency is of paramount importance. Furthermore, the improved energy efficiency and reduced power consumption of the fuzzy control scheme underscore its potential as a robust and reliable solution for a wide range of renewable energy applications. These applications span various domains, such as solar and wind power installations, where the inherent variability in energy generation requires advanced control strategies to ensure optimal system performance. By leveraging the capabilities of the proposed fuzzy control scheme, renewable energy systems can achieve enhanced efficiency and stability, ultimately contributing to the global transition towards sustainable energy sources.

Potential applications of the proposed control scheme extend beyond renewable energy systems to other areas requiring robust and adaptive control strategies, such as electric vehicle charging stations, uninterruptible power supplies, and power factor correction devices. Future work may involve further optimization of the fuzzy control algorithm, exploring the integration of artificial intelligence techniques, such as neural networks or deep learning, to improve the adaptability and performance of the control scheme. Additionally, the development of a more compact and cost-effective hardware implementation could facilitate the widespread adoption of this control strategy in various industrial and commercial applications. The advanced fuzzy control scheme presented in this paper offers a promising solution for the efficient control of synchronous buck converters in renewable energy systems. Its superior performance, adaptability, and robustness make it a valuable contribution to the field of power electronics and control systems, paving the way for more reliable and efficient renewable energy solutions in the future.

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