Comparing fuzzy logic and backstepping control for a buck boost converter in electric vehicles

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ABSTRACT

Significant advances have been made in the control of DC/DC converters, owing to the effective combination of linear and nonlinear approaches. The above-mentioned approaches have greatly improved the efficiency as well as stability of the converter, even when faced with changing conditions. Nevertheless, the emergence of artificial intelligence has introduced new perspectives in the domain. The objective of the article is to examine two separate methodologies for controlling a boost-buck converter: using a nonlinear approach, especially backstepping, and utilizing artificial intelligence through fuzzy logic. The main aim of this work is to illustrate the inherent stability and robustness of fuzzy logic controllers compared to backstepping control in managing effectively various variations and challenges encountered in converter control.

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1. INTRODUCTION

Electric vehicles (EVs) have become prominent representations of sustainable and ecologically conscious transportation, attracting growing attention within the automobile industry. In order to address the increasing need for electrical power and improve energy efficiency, these vehicles frequently incorporate fuel cells, batteries, and supercapacitors as environmentally friendly sources of energy [1]–[4]. Nevertheless, the need to include various power sources has resulted in the need for DC/DC converters in order to effectively control energy inside the system.

In the given environment, DC/DC converters assume a pivotal role in facilitating the effective conversion of electrical energy, hence facilitating the adjustment of voltage and current levels in accordance with the unique requirements of individual components inside the electric vehicle [5]. The use of DC/DC converters in electric vehicles has resulted in the development of many designs, with the objective of using the benefits offered by different clean energy technologies. For example, the use of unidirectional DC/DC converters is necessary for fuel cells to provide power to the electrical system of a vehicle. On the other hand, supercapacitors need a connection to bidirectional converters in order to facilitate fast charging and energy discharge in accordance with the driving requirements. However, researchers and industry professionals are now exploring innovative approaches to enhance the efficiency of electric vehicles and to address challenges related to power management, energy efficiency, and the unpredictable nature of operating conditions. One potentially promising strategy is the use of artificial intelligence for controlling of these converters, which has the potential to provide significant enhancements in terms of overall both effectiveness and dependability [6].

The objective of this paper is to examine two different control methodologies that possess unique and possibly advantageous characteristics for the DC/DC converters used in electric cars. In this analysis, we will examine the principles and techniques of non-linear control, specifically focusing on the backstepping approach. The advanced control strategy presented herein has been designed to address complicated dynamic systems via the use of adaptive control laws and the consideration of system nonlinearities. The use of backstepping control exhibits the potential in substantially improve the operational efficiency of buck boost converters, particularly in situations characterized by variable and changing conditions. These aspects are of utmost importance in guaranteeing stability and dependability in a wide range of real-world contexts. Secondly, we will explore an alternative type of control that utilizes fuzzy logic, a technique based on artificial intelligence. The use of fuzzy rules as the foundation for this method provides enhanced adaptability and robustness in the implementation of control systems, leading to improved efficiency in the management of electrical energy. Fuzzy logic enables the management of changes and uncertainties that naturally occur during the functioning of electrical systems. This capability has significant potential for enhancing the robustness and energy efficiency of DC/DC converters used in electric vehicles [7].

2. PRESENTATION OF THE STUDIED SYSTEME

The buck-boost converter stands out for its ability to control the output voltage, whether at a lower level (buck mode) or at a higher level compared to the input voltage (boost mode). This feature enables efficient conversion from a direct current (DC) to a lower or higher direct voltage, providing remarkable flexibility of use [8]–[13]. The construction of the buck-boost converter is shown in Figure 1.

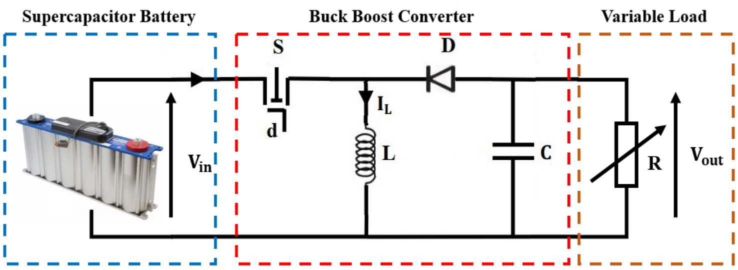


Figure 1. Equivalent circuit of a buck boost DC/DC converter

3. DESIGN OF CONTROL SYSTEM

This section introduces the control methods for the buck-boost converter, commencing with the use of the backstepping controller approach. Next, a second method is examined, involving the design and implementation of fuzzy logic. The implementation of this control methodology is of crucial importance in ensuring the stability and precision of the converter's output voltage. A comprehensive examination of these two approaches will provide a more profound comprehension of their use within this context [14], [15].

3.1. Nonlinear control of buck-boost converter using backstepping

The objective of this controller is to control the output voltage in order to closely follow the voltage of the DC bus. This objective is achieved by acting on the duty cycle of the buck boost converter [12], [16]. This advanced control approach optimizes the buck-boost converter's performance, ensuring effective regulation of output voltage in response to input voltage fluctuations, and thus contributing to the overall reliability and efficiency of the power system. The steps in this control process are explained in detail.

3.1.1. Averaged state-space modeling of the DC/DC buck boost converter

Given the initial condition when the switch is set to position S = 1, we can use Kirchhoff's rules to analyse the circuit and get the (1).

$$\begin{cases} \frac{di_L}{dt} = -\frac{r_L + r_s}{L} i_L + \frac{V_{in}}{L} \\ \frac{dv_{out}}{dt} = -\frac{v_{out}}{RC} \end{cases} \quad (1)$$

When the diode is in a conducting state, the switch is set to position S = 0, resulting in the outcome (2).

$$\begin{cases} \frac{di_L}{dt} = -\frac{r_L}{L} i_L - \frac{v_{out}}{L} \\ \frac{dv_{out}}{dt} = -\frac{i_L}{C} - \frac{v_{out}}{RC} \end{cases} \tag{2}$$

The state vector of the linear circuit encompasses the variable x, which includes the inductor current and the output voltage, as shown in (3).

$$\begin{pmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{pmatrix} = \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} -\frac{r_L+r_S}{L} d - \frac{r_L}{L}(1-d) & -\frac{1}{L}(1-d) \\ -\frac{1}{C}(1-d) & -\frac{1}{RC} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \frac{d}{L} \\ 0 \end{pmatrix} V_{in} \tag{3}$$

Let x_1 be the current passing through the inductor, and x_2 represent the voltage across the output capacitor. Additionally, the symbols r_s and r_L represent the ON resistance of the power switch and the corresponding series resistance of the inductor, respectively.

3.1.2. Design of backstepping controller

Using the backstepping control method, a nonlinear controller is designed for the buck-boost DC-DC converter to adjust the output voltage [17], [18]. The following steps are followed for this purpose.
Defining the output voltage error of the converter as (4):

$$\varepsilon = y - V_{ref} \tag{4}$$

V_{ref} represents the converter's output voltage reference. Utilizing in (3) and (4), we can obtain the time derivative of ε, which leads to (5)-(7).

$$\dot{\varepsilon} = \dot{y} - \dot{V}_{ref} \tag{5}$$

$$\dot{\varepsilon} = \dot{x}_2 - \dot{y}_{ref} \tag{6}$$

$$\dot{\varepsilon} = (d-1)\frac{x_1}{C} - \frac{x_2}{RC} - \dot{y}_{ref} \tag{7}$$

Selecting a Lyapunov function (8), for instance:

$$V = \frac{1}{2}\varepsilon^2 \tag{8}$$

The time derivative of V is given by (9):

$$\dot{V} = \varepsilon\dot{\varepsilon} = \varepsilon((d-1)\frac{x_1}{C} - \frac{x_2}{RC} - \dot{y}_{ref}) \tag{9}$$

As indicated in (9), the selected Lyapunov function should have a negative derivative. Alternatively, the expression for $\dot{V}$ can be given by (10):

$$\dot{V} = -k_1\varepsilon = \varepsilon\dot{\varepsilon} = \varepsilon((d-1)\frac{x_1}{C} - \frac{x_2}{RC} - \dot{y}_{ref}) \tag{10}$$

with: k_1 is a positive design parameter. the final control law d is obtained in (11):

$$d = \frac{C}{x_1}\left(-k_1\varepsilon + \frac{x_2}{RC} + \dot{y}_{ref}\right) + 1 \tag{11}$$

In order to determine the command to be transmitted to the switch, it is essential to measure in real time the output voltage, the current flowing through the inductance, and the variable impedance of the load. Since the load impedance varies depending on the consumed current, this recurrent measurement becomes crucial for generating the appropriate command. It is illustrated in the Figure 2.

3.2. Fuzzy logic controller for buck-boost converter

This technique employs fuzzy logic to develop a controller capable of dynamically and flexibly controlling the output voltage of the DC/DC converter. In contrast to conventional control techniques that depend on exact mathematical models, fuzzy logic enables the management of intricate and unpredictable systems via the use of language rules and a decision-making methodology that resembles human reasoning. The first step in the development of the fuzzy logic controller is doing an examination of a buck-boost converter. The selection of input and output variables for the fuzzy logic controller is contingent upon the unique characteristics of the system under consideration and the intended outcome [19]–[25]. The inputs often used for the controller consist of the voltage error ε(t) and the derivative of the error Δε(t), as stated in (12) and (13) correspondingly.

$$\varepsilon(t) = v_{out}(t) - V_{ref} \quad (12)$$

$$\Delta\varepsilon(t) = \varepsilon(t) - \varepsilon(t - T) \quad (13)$$

The error change $\Delta\varepsilon(t)$ measures the variation in voltage error between two consecutive instants. It can be calculated by subtracting the current voltage error from the previous voltage error. Figure 3 presents the block diagram of buck boost converter using a fuzzy logic controller.

The fuzzy logic controller consists of three essential components, namely a fuzzification module, a rule base module, and a defuzzification module. The primary function of the fuzzification block is to convert two input values. The first value corresponds to the error between the output voltage and the input voltage, while the second value reflects the previous value of the error, both of which are represented as fuzzy inputs. The rule-based block builds the connections between the fuzzy inputs and the fuzzy output. Finally, the defuzzification module converts the fuzzy output into a precise output value. Figure 4 illustrates the implementation of the fuzzy logic controller.

In relation to setting control rules for fuzzy control, a general interpretation can be outlined as: i) When the error value reaches an exact value of 0 and remains constant over a period of time, it is recommended to preserve the present setup without making any changes; ii) In situations when the error value is non-zero but steadily converging towards zero at an acceptable pace, it is advisable to maintain the current arrangement; and iii) When there is a rise or reduction in the error value, it is necessary to take appropriate action depending on the size and direction (positive or negative) of both the error value and the change in error. The primary aim of this endeavor is to facilitate the convergence of the error value towards the null value. Therefore, it is necessary to make appropriate modifications to the control signal. Table 1 shows the rule base used to generate the control signal.

Table 1. Fuzzy logic rule base

Output		Change error $\Delta\varepsilon(t)$				
		NH	NL	Z	PL	PH
Error $\varepsilon(t)$	NH	1	1	0.5	0.5	0.5
	NL	1	0.5	0.5	0.5	0
	Z	0.5	0.5	0	-0.5	-0.5
	PL	0	-0.5	-0.5	-0.5	-1
	PH	-0.5	-0.5	-0.5	-1	-1

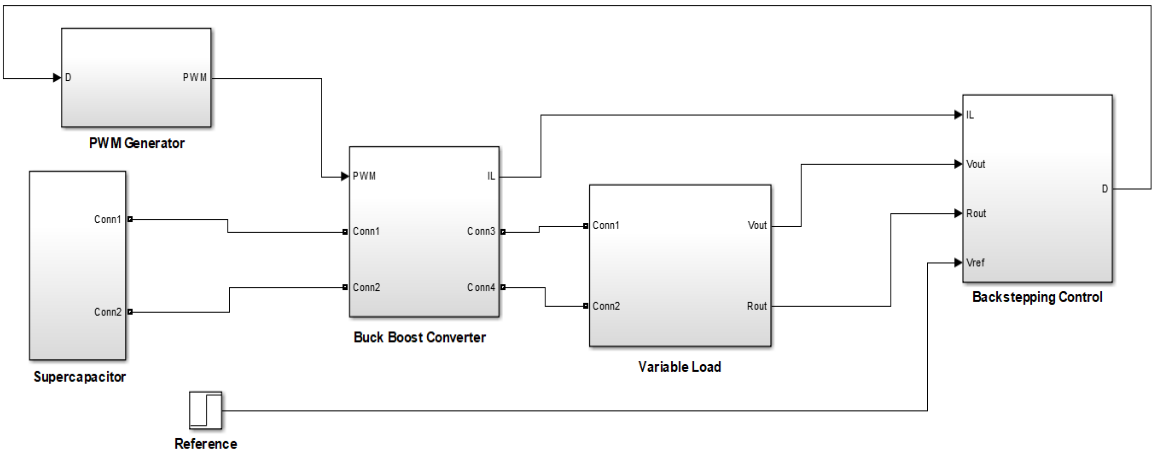


Figure 2. Block diagram of backstepping control for a buck boost converter

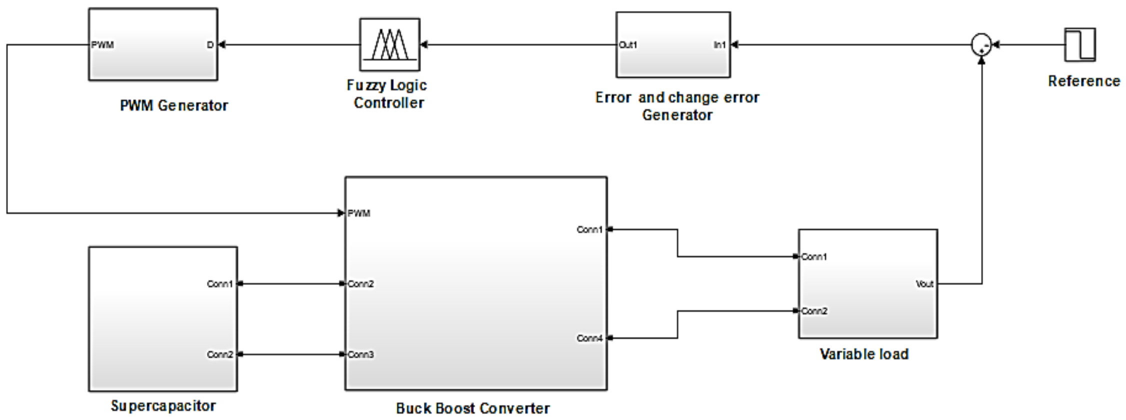


Figure 3. Block diagram of fuzzy logic control for a buck boost converter

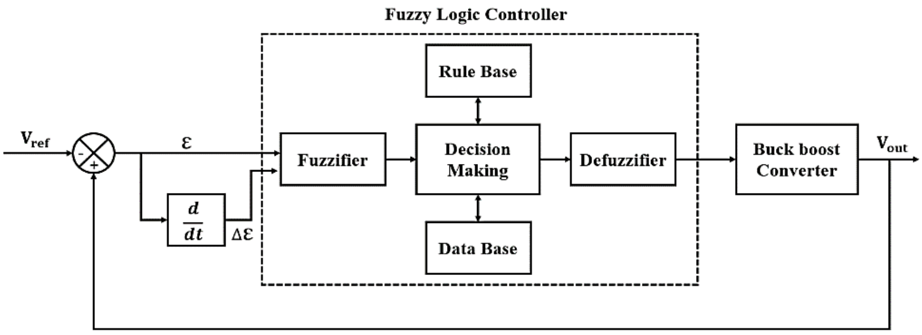


Figure 4. Components of a fuzzy logic controller

4. RESULTS AND DISCUSSION

Within the context of assessing the robustness of each controller, a technique has been used to quantify their efficacy when confronted with variations in load. The procedure entails the application of a load current that is created based on a changeable load profile. In order to conduct this assessment, a two-step approach was employed. During the first stage, the reference voltage (Vref) is maintained at a constant value of 150 V, specifically in the boost mode of operation. The controller is exposed to a load current that fluctuates in accordance with the predetermined profile. The answers of the controller were recorded and afterward analyzed in the present configuration. During the second stage, the reference voltage (Vref) is adjusted to a value of 80 V for a duration ranging from 2 seconds to 5 seconds, while operating in buck mode. During this temporal interval, the controller is required to effectively manage a rapid change in the setpoint, hence emulating real operational conditions. The assessment of the controller's performance inside this particular setup facilitates comprehension of its ability to promptly adapt to sudden alterations in setpoints. The tests were performed with a constant input voltage of 100 V. This methodology enables the simulation of specific conditions, facilitating the assessment of controller stability and efficiency within predetermined operating parameters.

The simulation results of two control strategies, namely backstepping control and fuzzy logic control, are shown in Figures 5 and 6 correspondingly. It is evident that in both cases, the output voltage closely follows the reference value, as illustrated in the Figures 5(a) and 5(b), even with a variable load, as seen in Figures 6(a) and 6(b). When using the backstepping technique, the resulting voltage shows an overshoot of roughly 225 V, equivalent to 50% of its final value. Additionally, it shows oscillations with an amplitude ranging from 0 to 7 V, as visually shown in Figure 5(a). The presence of these oscillations gives rise to some irregularities in the output voltage. In contrast, the use of fuzzy logic control results in the occurrence of oscillations in the output voltage as a consequence of variations in load current. However, these oscillations remain within a limit of 13 V, representing an approximate 8.66% deviation from the final value. Hence, this approach facilitates achieving of a more consistent output voltage as compared to the backstepping control technique. In conclusion, both control approaches have shown their capacity to accurately follow the desired reference value even in the presence of load variations. Nevertheless, it can be seen that fuzzy logic control has a somewhat higher level of efficacy in maintaining output voltage stability when compared to backstepping control.

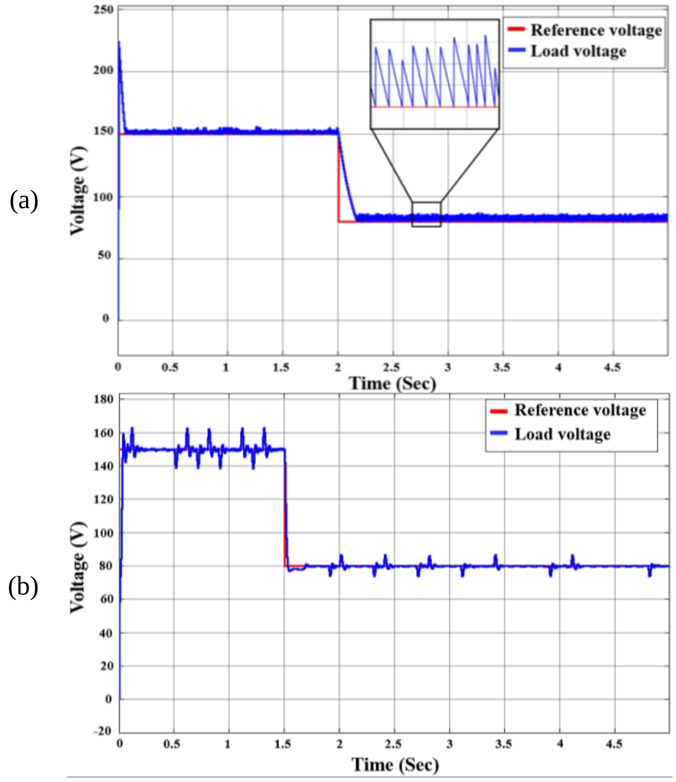


Figure 5. Simulation results of (a) the output voltage for a variable load using backstepping controller and (b) fuzzy logic controller

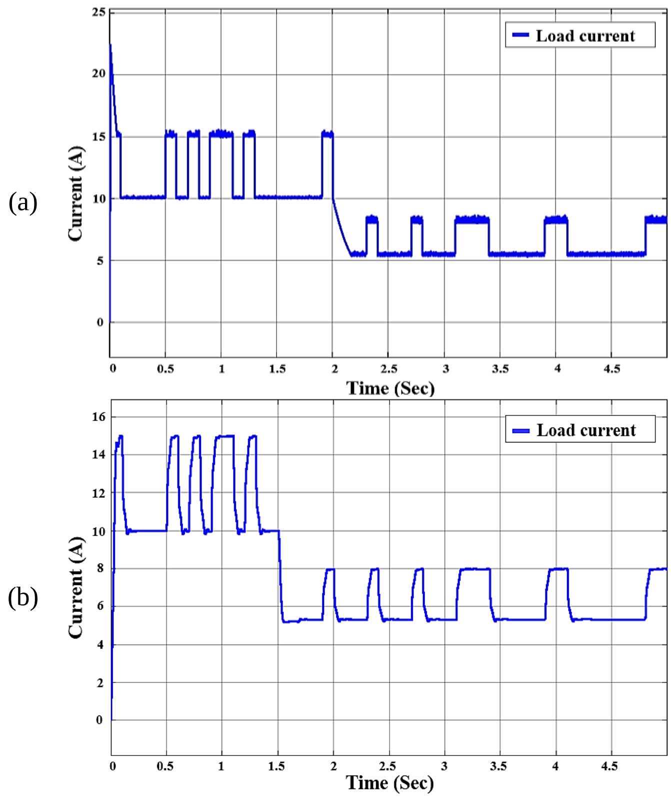
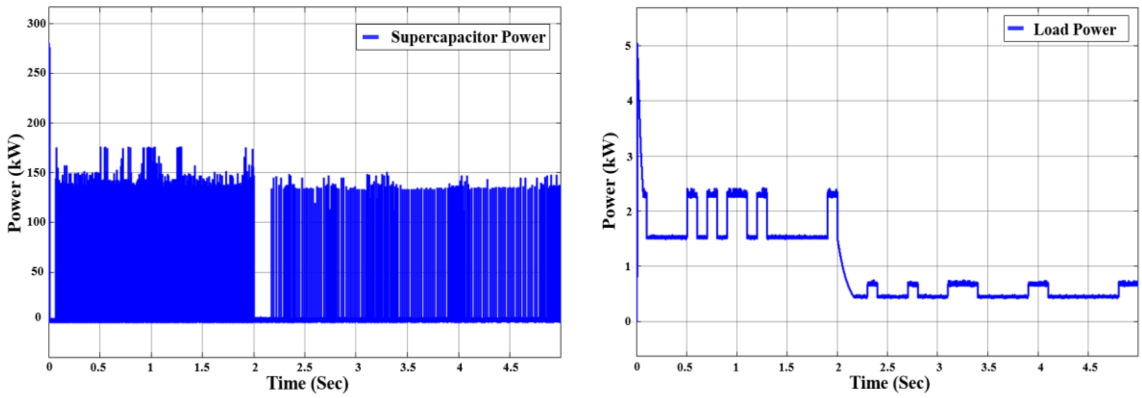


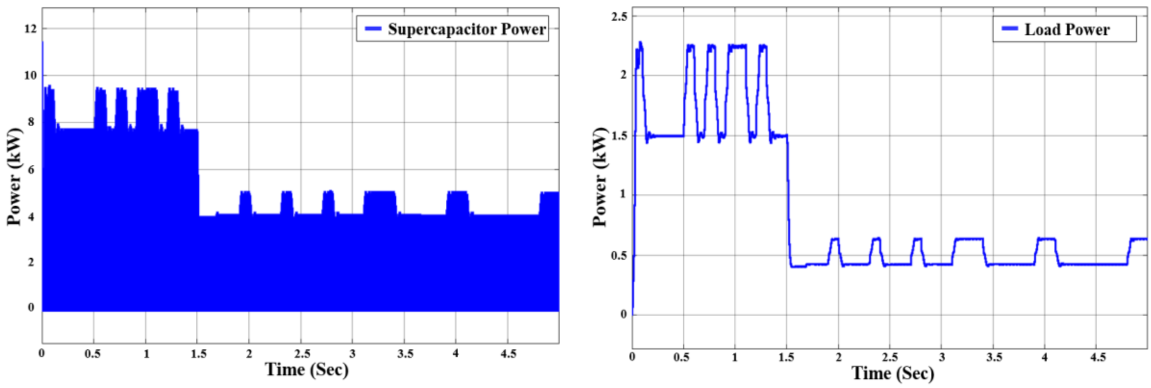
Figure 6. Simulation results of (a) the current load using backstepping controller and (b) fuzzy logic controller

The results are shown in Figure 7, illustrating the power supplied by the supercapacitor in Figure 7(a) and the power consumed by the load in Figure 7(b). The use of the backstepping control approach results in a yield of around 0.85, which corresponds to an energy conversion efficiency of 85%. In contrast, Figures 8(a) and 8(b) illustrates the power details that are both provided and used via the implementation of fuzzy logic control. The control methodology used in this study demonstrates a notable level of efficacy, achieving an approximate value of 0.96, which corresponds to a high energy conversion efficiency of 96%. The results mentioned above highlight the advantages of fuzzy logic, confirming its superior effectiveness in controlling power distribution in comparison to the backstepping control approach.



(a) (b)

Figure 7. Simulation results of (a) the power supercapacitor and (b) power load using backstepping controller



(a) (b)

Figure 8. Simulation results of (a) the power supercapacitor and (b) power load using fuzzy logic controller

5. CONCLUSION

The results of a comparative study of buck-boost converter control techniques revealed significant differences. Both control methods demonstrated their ability to follow the reference value despite load variations, but fuzzy logic proved superior in terms of output voltage stability and energy efficiency. With fuzzy logic, the output voltage showed less oscillation and reduced overshoot compared to backstepping, indicating better stability. In addition, fuzzy logic was able to deliver energy more efficiently, with an efficiency of around 96% compared with 85% for backstepping. Therefore, if the main objective is to obtain a more stable output voltage and improve the energy efficiency of the converter, fuzzy logic seems to be a preferable option. However, it is essential to take into account other factors such as system complexity, computational time constraints and available resources before making a final decision. In some cases, backstepping may still be a viable alternative, depending on the specific requirements of the application.

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