Improving Switching Efficiency with a Step-Up/Step-Down Hybrid Buck-–boost Converter Using Fuzzy Logic Control

Kapcsolási hatékonyság javítása step-up/step-down hibrid buck–boost átalakítóval fuzzy logikai vezérlés alkalmazásával

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Abstract — **This paper presents a novel hybrid buck–boost DC–DC converter controlled using fuzzy logic to enhance switching efficiency in photovoltaic (PV) energy systems. The proposed topology integrates separate step-up and step-down converter blocks connected via a DC link capacitor, enabling flexible voltage regulation across a wide input range. A fuzzy logic controller dynamically adjusts the duty cycles based on real-time PV input voltage and current, ensuring optimal power conversion under varying environmental conditions. It is hypothesized that combining fuzzy logic control with dedicated converter structures significantly reduces output ripple, improves voltage stability, and increases overall efficiency compared to conventional buck-–boost designs. Simulation results validate the proposed system's performance, showing superior dynamic response, reduced oscillations, and enhanced efficiency. The step-down converter demonstrates an average improvement of 4.24% and the step-up converter, 2.63% in charging efficiency over the conventional design. The architecture is particularly suitable for renewable energy applications such as electric vehicle (EV) battery charging, where stable and efficient power regulation is critical.**

Keywords: buck–boost converter, fuzzy logic control (FLC), PV system, efficiency, MPPT, MATLAB.

Összefoglalás — **Ez a tanulmány egy újszerű hibrid buck–boost DC–DC konvertert mutat be, amelyet fuzzy logika vezérel, hogy növelje az átalakítási hatékonyságot fotovoltaikus (PV) energiarendszerekben. A javasolt topológia különálló step-up és step-down (feszültségnövelő- és csökkentő) konverter blokkokat integrál, amelyek DC-link kondenzátoron keresztül csatlakoznak, lehetővé téve a rugalmas feszültségszabályozást széles bemeneti tartományban. Egy fuzzy logikai vezérlő dinamikusan állítja be a kitöltési tényezőt a valós idejű PV-bemeneti feszültség és -áram alapján, biztosítva az optimális teljesítményátalakítást változó környezeti feltételek mellett. Feltételezzük, hogy a fuzzy logikai vezérlés és a dedikált konverterstruktúrák kombinációja jelentősen csökkenti a kimeneti feszültségingadozást, javítja a stabilitást és növeli az összhatékonyságot a hagyományos buck–boost kialakításokhoz képest. A szimulációs eredmények igazolják a javasolt rendszer teljesítményét, kiváló dinamikus választ, csökkent oszcillációt és fokozott hatékonyságot mutatva. A step-down konverter átlagosan 4,24%-os, a step-up konverter pedig 2,63%-os javulást mutat a töltési hatékonyságban a hagyományos kialakításhoz viszonyítva. Az architektúra különösen alkalmas megújulóenergia-alkalmazásokhoz, például az elektromos járművek (EV) akkumulátorainak töltéséhez, ahol a stabil és hatékony teljesítményszabályozás különösen fontos.**

Kulcsszavak: buck–boost konverter, fuzzy logikai vezérlés (FLC), napelemes rendszer, hatásfok, MPPT, MATLAB

1 INTRODUCTION

A hybrid buck–boost DC–DC converter is designed to convert a variable input voltage into a constant or variable output voltage. The term "hybrid" refers to the integration of both buck and boost functionalities within a single circuit, enabling it to either step up or step down the voltage as needed. This means that if a consistent output voltage is required, the converter can adjust to changes in the input voltage. The hybrid buck–boost DC to DC converter is widely used in electrical power supplies for electronic devices, battery charging systems, and renewable energy systems such as solar and wind power systems.

Its high efficiency, low noise, and ability to handle a variety of input voltages make it preferred over other converter types [1]. The hybrid buck–boost converter's circuitry consists of an output filter, a switching circuit, and an input PV solar array. The switching circuit receives the pulsed DC voltage produced by the solar array. Two power switches (transistors or MOSFETs) are used in the switching circuit, and they alternately operate to control the voltage level. The output filter receives the input voltage when the switches are on; and when the switches are off, the energy stored in the filter's inductor and capacitor is used to maintain the output voltage [2]. The output filter is used to remove high-frequency noise or ripple from the signal and to smooth the output voltage. Typically, it consists of a capacitor and an inductor connected in series with the load.

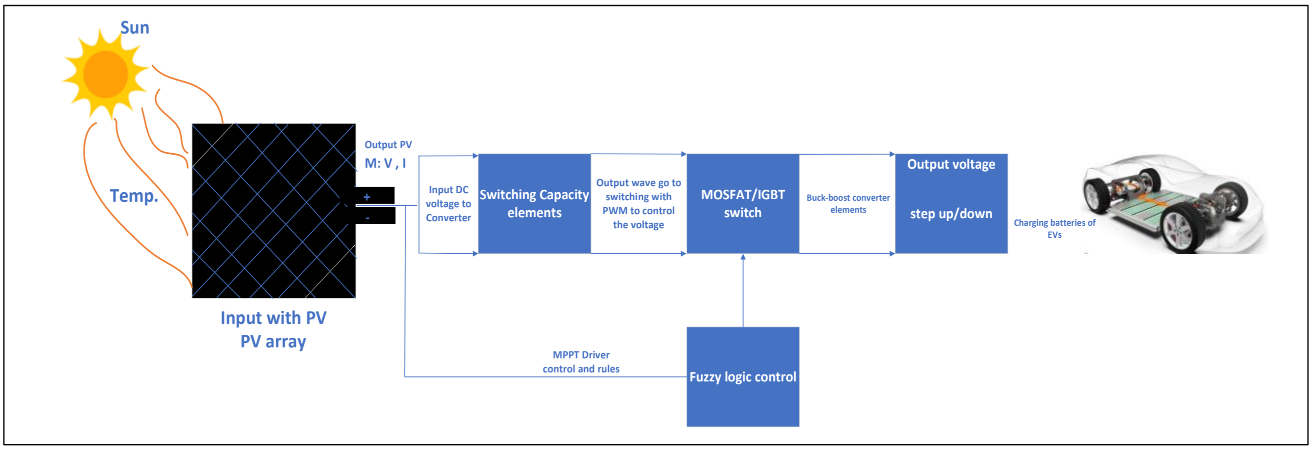

Figure 1: Schematic diagram of the system operation

In conclusion, the hybrid buck–boost converter is a flexible and effective power converter that is frequently utilized in a variety of applications like EV battery charging. It can handle a wide range of input voltages and integrates the capabilities of both buck and boost converters into a single circuit [3]. One of the main advantages of the hybrid buck–boost converter is its ability to provide a regulated output voltage even when the input voltage varies widely or remains constant. This is due to the converter's dual ability to step up and step down the input voltage, which enables it to keep the output voltage steady even while the input voltage fluctuates [4].

The hybrid buck–boost converter has relatively high efficiency when compared to other converter types. This is because it transfers energy directly from the input to the output, doing away with the need for a transformer, which can result in losses. The switching circuit of the converter is also highly efficient and reduces losses [5]. Additional advantages of the hybrid buck–boost converter include its small size and low weight. This is because of its high-power density, which allows it to deliver significant power in a very small container. Because of this, it is ideal for usage in systems with limited weight and space, such as portable electronic devices or automotive systems [6].

The fundamental DC–DC converters, including the buck (whose duty cycle determines the ideal input-to-output voltage ratio), boost, buck–boost, Cuk, Sepic, and Zeta converters, cannot significantly step-down or step-up the input voltage, which is required for many contemporary applications. This study introduces a fuzzy logic–controlled hybrid buck-–boost converter with separate step-up and step-down blocks to improve switching efficiency and voltage regulation under varying PV conditions.

2 Step-up and Step-down Buck–Boost Converter Design for Optimized Switching Capacity

In this paper, a new method for easily switching dual structures—which consist of two capacitors and two to three diodes, or two to three inductors and two to three-diodes—is presented. As shown in [7], these circuit topologies have the ability to either step up or step down the input voltage. With only a few disadvantages, they can be incorporated into a conventional buck–boost converter to attain a high voltage conversion ratio while preserving all the advantages of a topological converter.

A PV solar array with a fuzzy logic controller (FLC) and a switching-capacity block for the step-up and step-down circuit will help to reduce the ripple and output overshoot caused by the output of the conventional buck–boost converter, whose ripple increases power loss in the main circuit that affects the load [8]. As evidenced by its voltage gain, this converter architecture permits a larger step-down, and step-up, depending on the input voltage, than the conventional buck–boost topology.

This topology introduces a single switching capacitor block for use in both step-up and step-down modes in separate circuits. By utilizing an input PV-solar array with an FLC strategy, the design reduces both cost and weight. Additionally, the proposed topology is expected to offer higher efficiency by eliminating hysteresis and potential energy losses associated with transformer magnetization.

2.1 *Switching capacity of step-down buck boost operation*

Fig. 2 shows a buck–boost converter diagram that includes a square-block capacitance, designed to enhance the performance output of the converter. This configuration can be connected to batteries or other types of loads, allowing control of the load to operate at high efficiency of step-down converter.

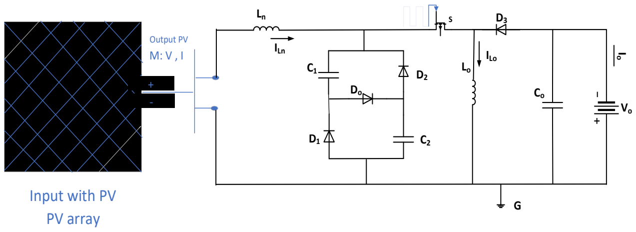

Figure 2: Step-down buck boost converter with square block switching

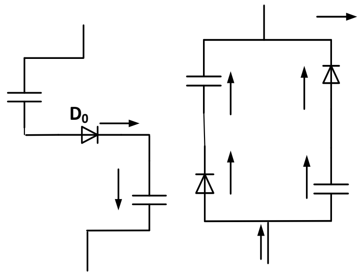

Figure 3: Switching on and off operation of the square block

According to the Fig. 3, the parallel and series operation of the square-block buck boost converter, can be described as follows:

1. When switch S is off, the converter operates as two separate circuits. The input circuit, which includes a rectifier, converts the PV input to a DC output and charges the capacitors through the square-block configuration and the current will be pass through the L_n and, in series, through the square block to charge the capacitors C_1 and C_2. The second circuit, connected to the output, uses inductors to supply current in the reverse direction to charge the output load, such as a battery.
2. When the switch S is operating the square block causes the two-capacitor discharge in parallel and with the support of the L_n which used to charge the output inductors L_o. These inductors use as the supplier to the output to charge the load or control the load with the helping of output capacitor C_o.

By using the voltage second balance method on the inductors, based on the average voltage across the inductors over a full switching cycle, which must be equal to zero in steady state operation [9].

1. Voltage across input inductors

When S is on, the voltage across L_n is

$$V_{Ln-on} = V_S - V_c.$$

When S is off, the voltage across the L_n is

$$V_{Ln-off} = V_S - 2V_c.$$

According to the equations for the voltage across input inductors at the on and off state equations the balance input voltage will be,

$$(V_S - V_c)t_{on} + (V_S - 2V_c)t_{off} = 0.$$

Then, for the times, $t_{off} = t - t_{on} = t(1-d)$, and $d = t_{on}/t$.

Hence the balance equation of the inductor voltage reads

$$(V_S - V_c)d\,t + (V_S - 2V_c)(1-d)t = 0,$$
$$(V_S - V_c)d + (V_S - 2V_c)(1-d) = 0,$$
$$V_S d - V_c d + V_S - V_S d - 2V_c + 2V_c d = 0,$$
$$V_S - V_c d - 2V_c + 2V_c d = 0.$$

Therefore the input voltage will be:

$$V_S = V_c(d + 2 - 2d),$$

and the voltage across the capacitor is

$$V_c = \frac{V_S}{2-d}.$$

2. The Voltage balance across the output inductors

When S is on, the voltage across L_o is

$$V_{Lo-on} = V_c,$$

and when S is off, the voltage across the L_o is

$$V_{Lo-off} = V_o,$$

therefore the balance equations for the output inductor should be equal to zero:

$$V_c t_{on} + V_o t_{off} = 0.$$

In this case, for the times equation:

$$V_c\,d + V_o\,(1-d) = 0.$$

Hence t the balance equation for the output inductor is

$$V_o = \frac{-V_c\,d}{(1-d)}.$$

According to the capacitor voltage of the input balance equation, the output voltage of the whole circuit can be calculated as

$$V_o = \frac{-V_S\,d}{(2-d)(1-d)}.$$

Therefore, as comparing to the conventional diagram of the converter without step-down block and filters inductance is *(2-d),* which increases the performance of the converter.

The efficiency of the switching step down buck boost converter is given by the following equations,

$$p_i = V_S\ i_S,$$

and

$$p_o = V_o\ i_o = \frac{V_S\,d}{(2-d)(1-d)}\ i_o.$$

The related input and output current for the balanced voltages are

$$i_S\,d = i_o(1-d),$$
$$i_o = \frac{i_S\,d}{(1-d)}.$$

Hence the output power of the converter will be:

$$p_o = V_o\ i_o = \frac{V_S\,d}{(2-d)(1-d)}\ i_o$$
$$= V_S\,i_S\,\frac{d^2}{(2-d)(1-d)^2}.$$

Then the efficiency of the step-up block hybrid buck boost converter reads

$$\mu = \frac{p_o}{p_i} = \frac{d^2}{(2-d)(1-d)^2}.$$

Since the equation of (2 - d) is consistently greater than one, the efficiency of the proposed converter surpasses that of the conventional buck–boost converter for all duty cycle values.

2.2 Switching capacity of step-down buck boost operation

According to Fig. 4, the performance of the converter increases due to the step-up block which is connected at the output stage of the converter, that has the capacitance due to the small resistance through the capacitance, the losses are reduced [10]. To increase the output voltage with lower losses, the step-up converter is better than the step-down converter, in order to make the batteries charging more slowly for protection.

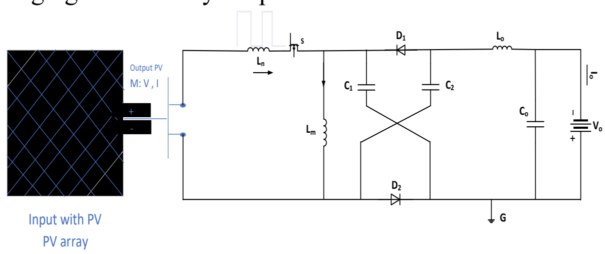

Figure 4: Step-up buck boost converter with square block switching

During operation, the X-block-based buck–boost converter functions in two distinct modes depending on the switching state:

1. When switch S is off, the inductor L_m supplies energy to the load circuit. At this time, the two diodes are forward-biased, allowing both capacitors to charge in parallel from the PV source which makes the two capacitors C_1 and C_2 connected in parallel, those capacitors will charging energy that coming from L_m and L_o to make the operation in balance through the operator work.
2. When switch S is on, the diodes become reverse-biased, and the capacitors C_1 and C_2 are connected in series. They discharge together to supply a higher voltage to the output.

The two capacitances connected in the X-block gives the converter high gain, enabling control of the output voltage, making it higher than the input power supply, which is useful when the solar energy is used as the input to charging the batteries. To derive the equations for the converter using the voltage-second balance method a systematic approach is used, that is similar to the one we used for basic converters but adapted to the hybrid converter topology. For the input stage which include the L_n is intended to improve performance, such as reducing ripple in the output voltage and current. These components will improve the dynamic performance by smoothing out voltage and current transients, in steady-state operation, the output voltage of the step-up converter is as follows.

According to the second stage of the converter which contains the inductor L_m, the voltage balance across this inductor when the switch is operating with inputvoltage with duty cycle d also under the switching is open, the output corresponds to the time duration $(1-d)$, the equation of the voltage balance for the inductors should equal to zero.

For S in operation L_m and L_o:

$$V_{lm\ on} = V_S, V_{lo\ on} = V_o.$$

For S not in operation L_m and L_o:

$$V_{lm\ off} = V_o - V_s\ ,$$

$$V_{lo\ off} = V_o.$$

Hence the balance voltage across the L_m,

$$V_s\, d + (1-d)\,(V_o - V_s) = 0,$$

$$V_o = \frac{-2d\, V_s}{(1-d)}.$$

For L_o the dynamic behavior is thesame as for L_m which additionally contributes energy to the output.

The output voltage of the step-up hybrid buck–boost converter has double the gain compared to the conventional one, thus increasing the performance of the converter for step-up operation.

The efficiency of this converter is given by:

$$p_o = V_o\ \ i_{o,}$$

$$p_s = V_s\ \ i_s,$$

$$\mu = \frac{p_o}{p_i} = \frac{V_o\ \ i_o}{V_s\ \ i_s} = \frac{V_o}{V_s}\,\frac{(1-d)}{2d}.$$

Compared to conventional and step-down converters, the efficiency is improved when the duty cycle is higher than 0.5.

3 VOLTAGE GAIN COMPARISON

The converters that are used for applications focus on the gain of the components inside the converter which have the responsible for improving the operation of the converter. Regarding the output voltage of the three converters which are the conventional, hybrid step-down and step-up converters. The hybrid converters are designed to improve the performance of the converter achieve high output performance, decreasing ripple, and the total losses that can affect the load. Then the step-down used to control the output voltage to be less than the input voltage, the step-up converter used to control the output voltage to be greater than the input voltage, the conventional converter can perform both, but with higher losses and ripple.

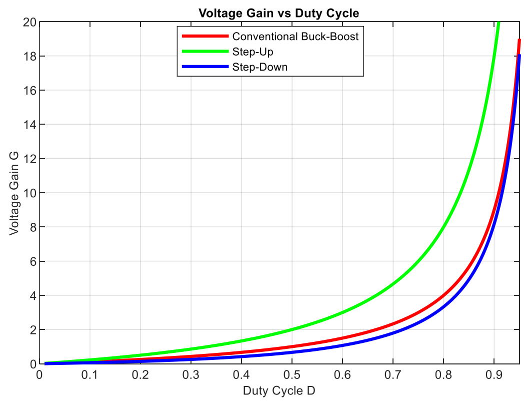

Figure 5: Voltage gain with duty cycle

With regard to the voltage gain shown in Fig. 5, the conventional buck–boost converter is appropriate for applications needing a wide voltage range because it can both step up and step down with a high voltage gain, although it often has larger ripple and poorer efficiency. Applications requiring a large voltage rise benefit greatly from the step-up converter, which performs best at high duty cycles ($d \geq 0.5$) and offers higher gain and efficiency at the expense of increased ripple. Because it offers smaller ripple and higher efficiency, the step-down (buck) converter is perfect for situations where voltage reduction is required, especially when duty cycles $d \leq 0.5$. Filters are applied in order to reduce ripple and losses for both step-up and step-down. However, at high duty cycles, the step-down will have more ripple and overshoot, whereas at lower duty cycles, the step-up will have more ripple.

Based on the design and voltage gain analysis, the square-block buck–boost converter achieves lower voltage gain compared to the X-block configuration. It is suitable for low voltage output control, whereas the X-block design offers higher voltage gain, making it ideal for applications requiring high output voltage such as fast battery charging. For high performance and lower losses, the square-block and X-block buck boost converters are used to control the load, such as forbattery chargers when the supplier is solar array used for EV low voltage applications.

Table 1: Key points of the three converters

Converters	Square-block converters	X-block converters	Conventional converters
Voltage gain	$V_o = \frac{-V_S\, d}{(2-d)(1-d)}$	$V_o = \frac{-2d\, V_s}{(1-d)}$	$V_o = \frac{-d\, V_s}{(1-d)}$
Efficiency	$\mu = \frac{p_o}{p_i} = \frac{d^2}{(2-d)(1-d)^2}$	$\mu = \frac{p_o}{p_i} = \frac{V_o\ i_o}{V_s\ i_s} = \frac{V_o}{V_s}\frac{(1-d)}{2d}$	$\mu = \frac{p_o}{p_i} = \frac{V_o\ i_o}{V_s\ i_s} = \frac{V_o}{V_s}\frac{(1-d)}{d}$

4 Fuzzy logic control strategies for the output voltage

DC–DC power converters in photovoltaic (PV) systems are well-suited for fuzzy logic control, a computational intelligence technique that simulates human reasoning to make control decisions. Unlike traditional PID controllers, which need an exact mathematical model, FLC is a rule-based control strategy that can handle nonlinear and complex systems [11].

Output voltage control is essential in PV-powered applications because solar energy is intermittent. The performance of traditional controllers deteriorates due to their inability to handle temperature and irradiance changes. FLC offers a reliable substitute by dynamically modifying control parameters according to input conditions, ensuring steady voltage output under variable solar conditions [12][13].

To increase the safety of the converters that using to charging of EVs fuzzy logic is a numerical control strategy capable of regulating the output signal with high performance and lower lossesthereby enabling safe operation compared to other types of control. In photovoltaic (PV) systems, maximum power point tracking (MPPT) is crucial for maximizing energy output. Artificial Intelligence (AI) techniques can greatly improve the efficiency and effectiveness of MPPT algorithms [13]. FLC is a type of AI-based control used to track voltage in PV systems operating with MPPT algorithm.

4.1 The system operation with fuzzy logic control

This system regulates the output voltage of aPV system using FLC, dynamically controlling both a step-up and a step-down buck-–boost converter. Since the PV voltage fluctuates due to changing sunlight and temperature conditions, the system employs aMPPT algorithm to extract the maximum available power while maintaining a stable output voltage [14][15].

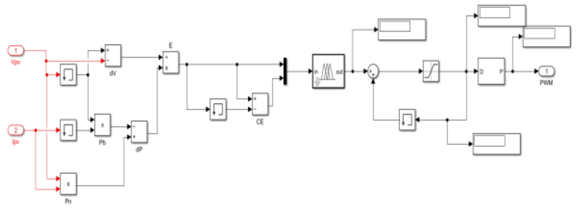

Figure 6: FLC system

The FLC-based MPPT system is designed to enhance the efficiency of PV energy harvesting by continuously monitoring the PV voltage (V_{pv}) and current (I_{pv}) to determine the optimum operating point. The controller calculates the power output and evaluates both the error (E) and the change in error (ΔE), which are then used as inputs to the fuzzy inference system. Implemented using the Mamdani-type fuzzy logic approach, the controller applies a set of intuitive rule-based decisions to generate a PWM (Pulse Width Modulation) signal. This PWM output adjusts the duty cycle of the DC–DC converter, thereby regulating the PV operating voltage. Depending on the input voltage level, a switching control unit activates either the step-up or step-down buck–boost converter to maintain operation at the maximum power point (MPPT). The fuzzification, rule application, and defuzzification processes allow the system to respond dynamically to changing environmental conditions, and the control rules used to achieve MPPT are summarized in Table 2, with the FLC interface illustrated in Fig. 7.

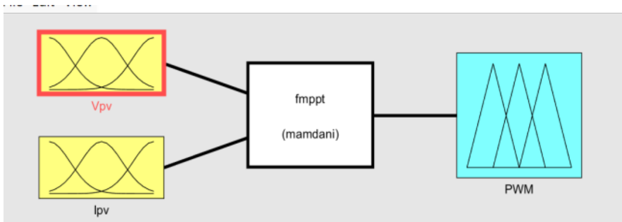

Figure 7: FLC interface

Table 2: Fuzzy control rules for PWM output

ΔE/E	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	PB	PS	NS	NS	Zero
NS	PS	PS	NB	NS	NS
ZE	NS	NS	PB	Zero	PB
PS	NS	PB	PS	NB	PB
PB	NB	NB	Zero	Zero	Zero

The inputs to the FLC are the PV voltage and current, each characterized by five linguistic terms: negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB). These linguistic terms are represented using triangular membership functions, chosen for their simplicity and computational efficiency. The output, which is the PWM signal used to control the converter, is also described using the same five linguistic terms and triangular membership functions. Fig. 8 illustrates the PWM output surface generated from fuzzy rules. As shown, when both V_{pv} and I_{pv} are low (NB), the PWM output peaks positively, correcting the converter toward maximum power. The surface confirms the smooth, nonlinear mapping of fuzzy rules across variable PV conditions.

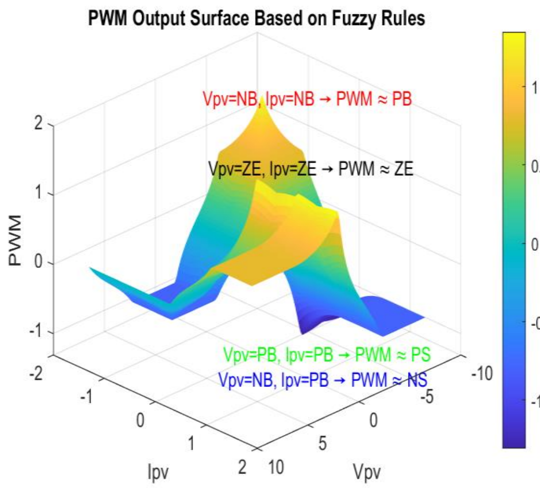

Figure 8: 3D surface plot showing FLC for PWM output as a function of V_{pv} and I_{pv} based on fuzzy rules

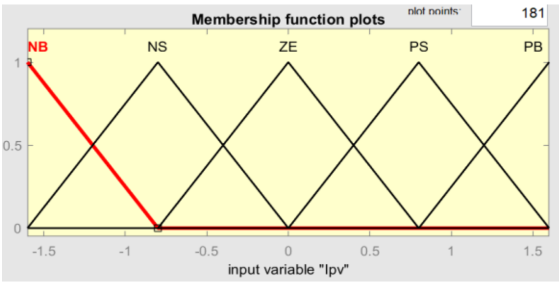

Figure 9: Membership functions of the PV current (I_{pv})

As shown in Fig. 9 the horizontal axis represents the range of I_{pv} values from -1.5 to +1.5, while the vertical axis shows the degree of membership from 0 to 1. Each triangle represents a fuzzy set: NB, NS, ZE, PS, and PB. These functions are symmetrically arranged, allowing smooth transitions between fuzzy states. Similarly to the current input, V_{pv} is described over a range of -8 to +8, and divided into five fuzzy sets with corresponding triangular shapes. These fuzzy sets enable the system to capture the behavior of the voltage under varying conditions effectively. The output fuzzy sets (NB to PB) correspond to the control signal that adjusts the duty cycle of the converter to maintain optimal operation of the PV system. This approach ensures fine-grained control and robust response to input variations as shown in Fig. 10.

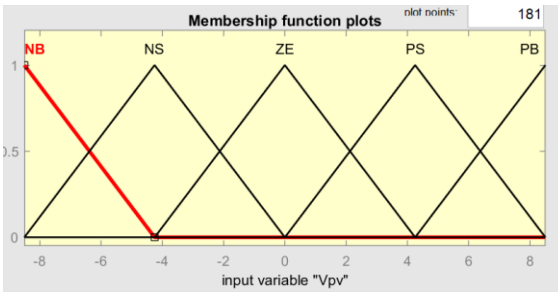

Figure 10: Membership functions for the PV voltage (V_{pv})

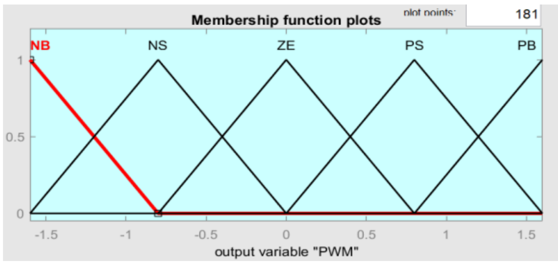

Figure 11: The membership functions of the PWM output

The fuzzy rule base includes 25 control rules that determine the PWM output based on various combinations of PV voltage and current. These rules are derived from expert knowledge and are designed to respond effectively to dynamic solar conditions by adjusting the converter's duty cycle. For instance, when both $V_{pv}$and I_{pv} are in the NB region (low voltage and low current), the output PWM is also NB, implying a strong correction to increase power extraction. Conversely, if both inputs are PB, indicating high voltage and current, the controller maintains the output in the PB region to sustain efficient operation. Below a brief description of some of the fuzzy rules is given:

- If V_{pv} is NB and I_{pv} is NB, then PWM is PB.
- If V_{pv} is NB and I_{pv} is NS, then PWM is PS.
- If V_{pv} is NB and I_{pv} is ZE, then PWM is NS.

This pattern continues for all 25 combinations, creating a control surface that handles varying operating conditions. The fuzzy operators used include the minimum (MIN) method for the AND operation and implication, the maximum (MAX) method for aggregation, and the centroid method for defuzzification, which calculates the center of gravity of the aggregated output membership functions to produce the final PWM signal.

5 Case Study : Simulation of Buck–Boost Converter with FLC

A simulation of a PV system with a buck–boost converter controlled by an FLC was performed in MATLAB/Simulink. The FLC successfully tracked the maximum power point under varying irradiance levels by adjusting the PWM signal based on the error and change in power error. The system responded quickly to changes in sunlight and stabilized the output voltage and power with minimal oscillation. Compared to conventional methods, the FLC showed improved efficiency and dynamic performance.

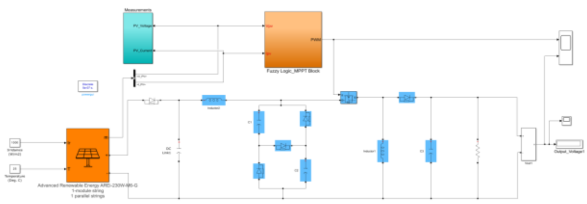

Figure 12: Step-down buck–boost model with FLC

If the PV voltage is higher than required, the step-down buck–boost converter reduces it by adjusting the switching duty cycle to regulate the output, as shown in the output of Fig. 13 the input voltage will be in between 30 and40 V but the output voltage will be with a smooth 10 V output, which is used to slowly charge EV batteries due to the lower output voltage.

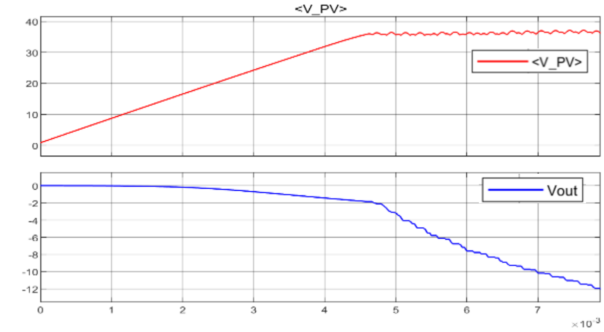

Figure 13: Output voltage of step-down buck–boost with FLC

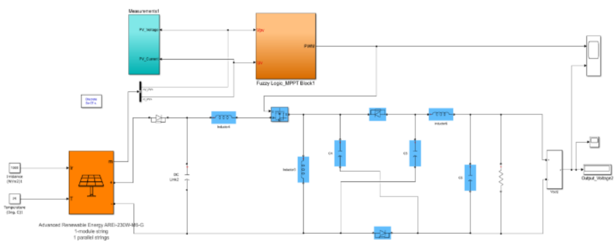

Figure 14: Step-up buck–boost model with FLC

When the PV voltage is lower than the desired output, the step-up buck–boost converter increases the voltage by controlling the energy stored and released by the inductor. As shown in Fig. 15, this results in an output voltage that exceeds the input, with low ripple and improved efficiency – ideal for fast EV battery charging.

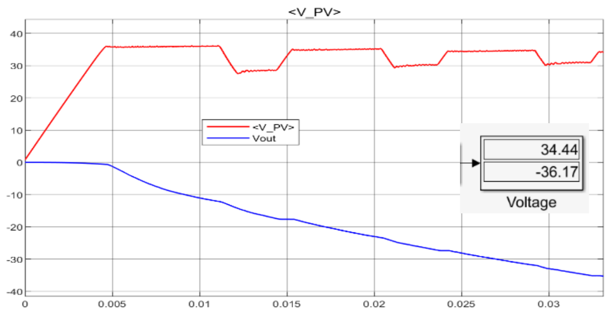

Figure 15: Output voltage of step-up buck–boost with FLC

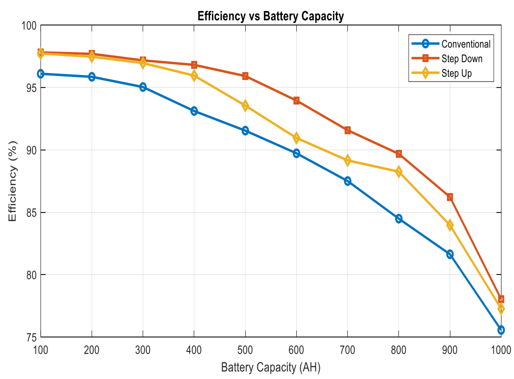

Figure 16: Efficiency comparison of converters

Fig. 16 illustrates the efficiency comparison among three converter configurations: a conventional buck–boost converter, a fuzzy logic–controlled step-down hybrid converter, and a fuzzy logic–controlled step-up hybrid converter. The graph plots battery capacity (in ampere-hours, Ah) against charging efficiency (in percent). Across all tested capacities (100–1000 Ah), both fuzzy logic–controlled converters consistently outperform the conventional topology. The step-down FLC converter achieves the highest efficiency values, with an average gain of 4.24%, while the step-up FLC converter shows an average improvement of 2.63% over the conventional approach. This demonstrates the effectiveness of fuzzy logic control in reducing ripple, enhancing voltage regulation, and optimizing power flow during the charging process. The performance advantage becomes more noticeable at lower battery capacities, which are more sensitive to switching and control losses, further supporting the suitability of the proposed converter for variable renewable energy systems such as solar-powered EV charging.

By continuously selecting the appropriate mode, this system ensures maximum power extraction, efficient voltage regulation, and adaptability to environmental changes. Compared to traditional MPPT methods, fuzzy logic improves response time and reduces oscillations, making this approach highly effective for renewable energy applications. Compared to conventional buck–boost converters, the proposed hybrid design integrates separate step-up and step-down stages, improving both voltage regulation and efficiency. Traditional methods struggle with ripple and slow dynamic response, especially under variable irradiance. Additionally, the use of distinct X-block and square-block topologies allows tailored optimization for high and low voltage scenarios, which is not observed in previous approaches.

6 Conclusion

This paper investigates hybrid buck–boost DC–DC converter topologies using fuzzy logic control (FLC) for efficient photovoltaic (PV) system operation. The hybrid converter, combining step-up and step-down configurations, enhances efficiency, reduces size, and improves reliability by adjusting the duty cycle based on input voltage fluctuations. The FLC-based MPPT algorithm dynamically tracks the maximum power point, optimizing power extraction from the PV system while maintaining a stable output voltage. The step-down buck–boost converter operates effectively when the PV voltage is higher than the required output, regulating the voltage to a smooth 10 V output, ideal for electric vehicle (EV) battery charging applications. On the other hand, the step-up buck–boost converter is employed when the PV voltage is lower than the desired output, boosting the voltage to achieve higher output (up to 40 V), with low ripple, improving charging speed and efficiency. Compared to traditional methods, the fuzzy logic controller enhances response time, minimizes voltage oscillations, and adapts more effectively to changing environmental conditions. This makes the system highly suitable for renewable energy applications such as electric vehicle (EV) charging.

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