FUZZY LOGIC CONTROLLED DC-DC CONVERTER FOR RENEWABLE ENERGY SOURCES

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ABSTRACT

This study introduces a fuzzy logic controller to enhance the Maximum Power Point Tracker in solar energy systems. A hybrid Zeta-Boost converter is used to achieve desirable power output extraction efficiency from photovoltaic module. The system has a controller of Fuzzy logic to monitor and control the MPP Value dynamically to ensure optimal performance under various environmental conditions. A comprehensive simulation model incorporating photovoltaic and Zeta- Boost converter is developed to design and optimizing fuzzy logic control strategy. The control algorithm is then implemented on an Arduino Uno, bridging the simulation-to-hardware gap. The results of Simulation and experimental approach demonstrate the effectiveness of proposed work in the case of improving power conversion efficiency and stability.

Keywords: Active-quad-switched-inductor, Fuzzy logic, Maximum power point tracker.

1. Introduction

The increasing worldwide demand for energy, coupled with accelerated industrialization and enhanced human consumption, has increased the requirement for efficient and clean energy production. Traditional fossil fuel-powered energy sources are running short and costly, calling for a shift towards renewable energy sources. Of all renewable resources, photovoltaic (PV) systems have achieved consider- able prominence because they are clean, sound-free, and low- maintenance [1]. But to increase the efficiency, it is important to have good power extraction techniques in order to optimize energy conversion. One such approach is the implementation of Maximum Power Point Tracking (MPPT) algorithms, which dynamically adjust the maximum power point to increase power extraction under changing surrounding conditions. A fuzzy logic-introduced MPPT system is used and implemented in research and applied into a solar power supply using a hybrid Zeta-Boost DC-DC converter to maximize power extraction efficiency. Furthermore, the introduction of multiple renewable energy sources, e.g., wind energy and solar energy, can additionally augment power generation by adapting their contributions dynamically to match the demand of the load.

The major idea of research is to optimize MPPT and implementing control strategies for a multiple sources of renewable power generation. With more and more worldwide attention paid to clean energy, PV technology has been high- lighted as a good option to traditional fossil fuel-powered energy generation. With ongoing developments in PV systems, their ability to substitute nonrenewable energy sources is gaining increasing attention. Nevertheless, effective power management and optimization methods, including MPPT, are required to optimize energy harvesting and enhance the overall performance of renewable energy systems. For photovoltaic (PV) power to be a competitive alternative to energy derived from fossil fuels, its cost per kilowatt-hour should be comparable. The efficiency of PV modules largely relies on the technology and materials applied in solar cell production. Commercial PV modules today have an efficiency level of 12% to 26% in terms of converting solar irradiation to electrical energy [2]. Gallium arsenide solar cells provide efficiencies as high as 29%, whereas standard silicon-based solar cells operate in the range of 12% to 14% [3]. But PV module efficiency is also controlled by various dynamic factors such as variations in solar irradiance, temperature changes, and varying load conditions. To obtain maximum power, PV modules should operate at their maximum power point, and it is derived from their nonlinear VI characteristics. A Maximum Power Point Tracking (MPPT) controller is necessary to dynamically regulate the operating V and I so that the entire working system supplies the maximum output power at all times. With the frequent change in environmental conditions, a proper MPPT algorithm needs to accurately track and stay at the desired point in the way to achieve the best performance of the Photovoltaic system [4].

As the consequence of nonlinearity nature of photovoltaic systems, power output varies with ambient temperature and solar irradiation changes. The Maximum Power Point is the maximum output of the PV system under different weather conditions, as defined by certain maximum current and voltage values. In order to operate efficiently at this point, introduced Maximum Power Point Tracking, an electronic device [5]. This means that there is a particular terminal voltage that trigger PV array to operate under maximum output and enhance efficiency, as shown in Figure 1-13 [6]. Environmental changes, including solar irradiance and temperature changes, have a direct impact on the maximum power point, voltage, and current of PV panels. To optimize system efficiency and cut costs, it is vital for PV systems to run on the MPP [7]. A number of MPPT strategies have been advocated in the literature, namely, Perturb and Observe (PO), Incremental Conductance (INC), Hill Climbing (HC), Particle Swarm Optimization (PSO), Fuzzy Logic Controller (FLC), and Neural Networks (NN). They are unique in that each possesses certain traits such as rates of convergence, complexity, oscillations at MPP, computation burden, and electronics demand [8]. Simulations between the PO and INC methods with a boost DC-DC converter show that the PO-based controller performs better than the INC method. The PO controller is able to track the maximum power even at low voltages, while the INC controller can only give a constant output without maximizing the power output under varying conditions [9].

Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) controllers are some of the most popular controllers in power electronics for closed-loop systems. Nonetheless, recent studies pointed out the growing application of Fuzzy Logic Controllers (FLCs) as intelligent controllers, demonstrating remarkable success towards enhancing system performance [10]. Comparison of current control strategy (P&O) and Fuzzy logic based MPPT has been investigated using simulation through MAT- LAB/Simulink. The system typically consists of a solar panel, boost converter, MPPT controller, and resistive load. The findings imply that the Fuzzy Logic is superior to the PO-based controller for maximum power point tracking [11] [12]. The FLC used in these research studies is Sugeno's method that utilizes max-min composition for making decisions. The simulations also show the better performance of the FLC-based MPPT controller compared to the traditional PO-based method [14].

1.1. Related Works

DC-DC converters have recently been developed to improve performance and achieve high voltage gain. In a commercial solar PV framework, a transformer is broadly utilized for stepping-up voltage within the AC side to coordinate with the utility network. Due to the utilization of the transformer, the total solar PV framework gets to be bulkier and costlier. To triumph over these issues, a appropriate dc-dc converter with high voltage gain is favored in a solar PV framework. A single-switch non isolated dc/dc converter for a stand-alone photovoltaic (PV) battery-powered pump framework is proposed in this paper. The converter is shaped by combining a buck converter with a buck-boost converter. This integration too brought about in decreased rehashed power processing, consequently moving forward the change efficiency. With as it were a single transistor, the converter can perform three tasks at the same time, to be specific, maximum-power- point tracking (MPPT), battery charging, and driving the pump at consistent flow rate. To realize these control objectives, the two inductors work completely different modes such that variable switching frequency control and duty cycle control can be utilized to oversee MPPT and yield voltage regulation. This thesis formulates and implements a fuzzy logic-based maximum power point tracker (MPPT) for a solar power supply. Consumption of energy has evidently grown as a consequence of growing industrialization and human consumption. Research and technology investments are being ignited with the enhancement of energy efficiency and the utilization of sustainable and renewable energy sources. Power production from fossil fuels is at the same time declining and becoming costly.

The key to switching between traditional sources of energy to cleaner and greener renewable sources is determining how to get the maximum energy and provide the maximum electricity at a minimum cost for the required load (like solar and wind energy). The most effective renewable energy source that has drawn the researchers' attention is the photovoltaic (PV) system because there are no moving parts, solar energy is a noise-free, clean, pollution-free, maintenance-free energy source.[1]. Integration of two or more energy sources may offer the best way to increase power generation by changing each energy source's contribution in line with the load demand. The main objective of this endeavor is to develop and improve maximum power point tracking and control of a multisource alternative energy generating system composed of photovoltaic (PV) modules, wind turbines, and other sources. Recent interest in PV power, a sustainable energy source, has grown significantly, and it may soon displace non-renewable energy sources like fossil fuels. For this switch, PV power must have a per-kilowatt-hour cost that is competitive with fossil fuel energy sources. The two most significant factors that affect how efficient PV modules are believed to be the technology and material utilized to make solar cells. PV modules now only have a 12–26% efficiency, which is very low, for converting solar irradiation to electricity. [2]. Gallium arsenide solar cells possess an efficiency of 29% whereas silicon solar cells have efficiencies between 12 and 14 percent. [3]. Additionally, efficiency can reduce because of changes in solar insulation, changes in PV module temperature, or changes in load conditions.

In order to obtain the maximum rated power from a PV module, it's important to drive it at its optimal power point. In order to achieve this, there should be a controller called a maximum power point tracker. The terminal operating voltage has an influence on the output power of PV modules, which are nonlinear power sources. Consequently, the MPPT's job is to take into account the oscillating current- voltage behavior of the solar cell. The MPPT adjusts the output current and voltage of the PV module and chooses the operating point that will yield the maximum amount of electricity. The operating point where the most power is produced needs to be tracked by the MPPT precisely because it varies frequently if we would like to make the PV module more efficient [4]. Owing to the nonlinear behavior of the PV system, the power generated changes as the ambient temperature and solar irradiation fluctuate. Maximum power point refers to the PV system's peak power output under various weather conditions (MPP). Maximum current and voltage are used in this instance. Maximum Power Point Tracking (MPPT), which is an electronic system, has been invented and designed to do this. [5]. This implies that there is always only one optimum terminal voltage at which the PV array must operate in an effort to maximize power output and enhance array efficiency [6]. Changes in environmental factors affect the maximum power point, maximum voltage, and current of PV panels. PV systems must be operated at MPP (Maximum Power Point) in order to improve efficiency and lower costs. [7]. There are numerous methods of the Maximum Power Point Tracking (MPPT) in the literature. Notably, Perturb and Observe (PO), Incremental of Hill Climbing (HC), Particle Swarm Optimization (PSO)Hill Climbing (HC) Particle Swarm and SO) Optimization (PSO) based PO, Fuzzy Logic Controller (FLC), and Neural Network (NN) are also present. of Conductance (INC), INC, HC, and NN. The convergence rates, complexity oscillations around the MPPT algorithm, computational costs, and electronic requirements of these approaches differ. [8]. The (PO) and (IC) methods were employed to model and analyze MPPT controllers using solar panels and a boost DC-DC converter. The results indicate that the controller was better as it was able to provide the maximum power even at low voltage, compared to the IC controller, which only provided a constant output [9].

PI, PD, and PID controllers are the most common controllers and are often employed in power electronic closed loop devices. However, in recent times, many academics have indicated that they have successfully used fuzzy logic controllers (FLC) as smart controllers for their devices. Targeting the panel should be the focus of future endeavors. [10]. Comparison between fuzzy logic control-based MPPT and PO methods was examined and simulations were carried out using MATLAB/Simulink. A solar panel, a boost converter, an MPP controller, and a resistor load constituted the system. The results proved that the fuzzy control system was superior to the PO system. [11]-[12]. A standard perturbation and an observation (PO) In MATLAB/Simulink, a normal Perturb and Observation (PO)-based MPPT and fuzzy logic controller (FLC)-based MPPT were both designed. The FLC is developed based on Sugeno's method, which can be connected with the max-min composition. The system consisted of a solar panel, a boost converter, an MPP controller, and a resistor load. Outperformed the PO system in terms of performance. [11]. [12]. An observation and a typical disturbance (PO) A traditional Perturb and Observation (PO)-based MPPT and a fuzzy logic controller (FLC)-based MPPT were both constructed in MATLAB/Simulink. Sugeno technique, which is connected to the max-min composition, is the foundation of the FLC. [14]. A Proportional-Integral (PI) based Maximum Power Point Tracking (MPPT) control algorithm is proposed in this study where it is applied to a Buck-Boost converter. It is aimed to combine regular PI control and MPPT technique to enhance the generated power from photovoltaic PV) panels. Perturb and observe (P&O) techniques used as the MPPT control algorithm but accuracy is low [15].

1.2. Aim and Major Contributions

This study aims to perform a detailed investigation and comparative analysis of isolated DC-DC converter topologies, namely the forward converter, flyback converter, and a proposed hybrid forward-flyback converter. The primary objective is to assess and compare their performance in terms of power factor and efficiency, which are crucial metrics in power electronics systems, particularly for applications involving low to medium power levels.

To achieve this, the study presents both mathematical modelling and simulation-based evaluation of each converter topology. The operating principles, key equations, and design considerations are analytically derived and validated through MATLAB/Simulink simulations. The converters are subjected to equivalent load and input conditions to ensure a fair performance comparison. This dual approach strengthens the reliability of the results and provides deeper insights into the behaviour of each topology.

The major contributions of this work include the design and assessment of a novel forward-flyback converter that integrates the advantageous features of both traditional topologies. The comparative results demonstrate that the proposed converter achieves improved power factor and higher efficiency relative to the individual forward and flyback converters. This study offers a valuable contribution to the field by guiding the design of optimized converter topologies for enhanced performance in isolated DC-DC conversion systems.

2. MATERIALS AND METHODS

This paper presents a comparative analysis of isolated DC-DC converter topologies, specifically focusing on forward, flyback, and a proposed forward-flyback hybrid converter, in terms of power factor and efficiency. The proposed methodology includes both mathematical modeling and simulation-based analysis using MATLAB/Simulink to evaluate each converter under uniform input and output conditions. The aim is to identify an optimized topology that combines the advantages of conventional converters while mitigating their individual limitations. The proposed forward-flyback configuration is designed to enhance energy transfer characteristics by integrating the continuous energy flow of the forward converter with the simplified control and component reduction of the flyback topology. Analytical derivations for voltage conversion ratio, duty cycle, and efficiency are validated against simulation results to ensure accuracy. Comparative results demonstrate that the proposed converter achieves superior performance in power factor correction and efficiency, making it a promising candidate for low to medium power applications such as battery charging and distributed energy systems. This study provides an effective design reference for engineers and researchers working on efficient isolated power conversion systems.

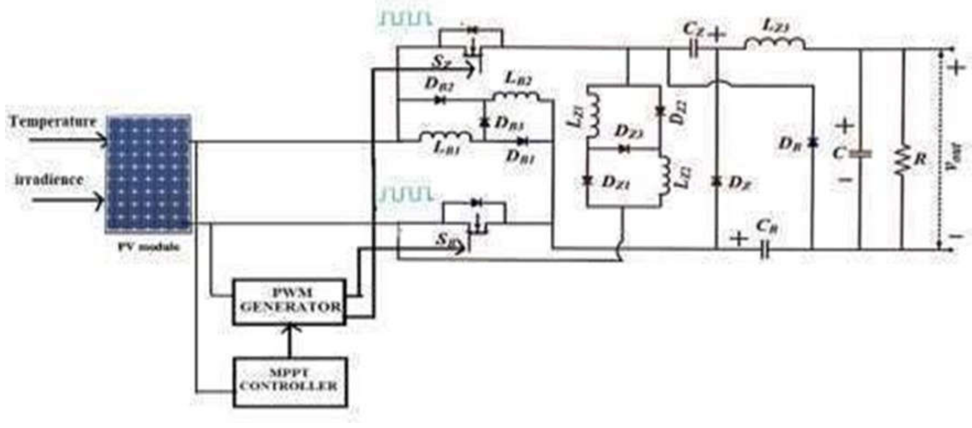

Fig. 1. Block Diagram of proposed topology

2.1. Proposed Zeta Boost Converter

The [14] Figure 2 shows the implementation of the Zeta- Boost converter implemented in this system. The circuit is formed by combining the topologies of Zeta and Boost converter with an Active Quad Switched-Inductor (AQSL) network [14]. The AQSL network comprises diodes DZ1, DZ2, and DZ3, inductors LZ1 and LZ2, and switch SZ for the Zeta converter. For the Boost converter, the network is comprised of diodes DB1, DB2, and DB3, inductors LB1 and LB2, and switch SB [14]. The Boost converter is operated at the negative polarity of the input supply [14]. The diodes DZ and DB are operated complementarily with the switches, while inductor LZ3 and capacitor C form a low-pass LC filter, which is established between the AQSL network and load [14].

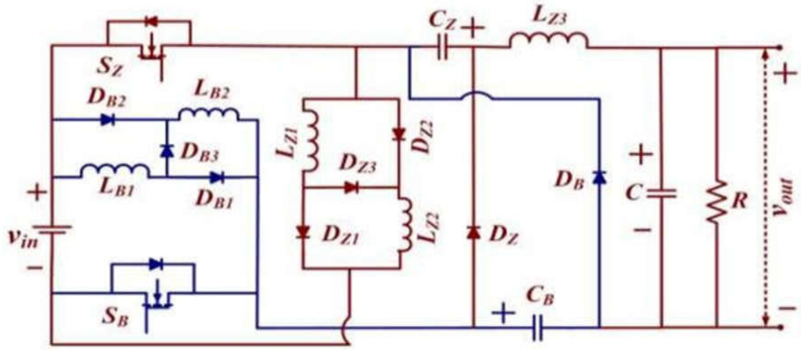

Fig. 2. Circuit Implementation of Converter

A. Mode 1 of Operation

The mode 1 of the operation is taken under Continuous Conduction mode. When switches SB and SZ are activated, the converter is in one mode, but when they are deactivated, it is in two modes.

1) *MODE-1:* The suggested converter works under this mode when switches SB and SZ are enabled at the same time [14]. In this mode, the input source charges inductors LB1, LB2, LZ1, and LZ2 in parallel, while inductor LZ3 is charged by the input source and capacitors CZ and CB [14]. The diodes DB1, DB2, DZ1, and DZ2 are forward biased, and diodes DB3, DZ3, DB, and DZ are reverse biased [14].

2) *MODE-2:* In this operation mode, when the switches are switched OFF, the inductors LB1, LB2, LZ1, and LZ2 dis- charge in series [14]. The input voltage source, together with inductors LB1, LB2, LZ1, and LZ2, charges the capacitors CZ and CB, which are charged in parallel. Also, the inductors LB1, LB2, LZ1, LZ2, and LZ3 charge the load resistance (R) and capacitor (C) [14]. The diodes DB1, DB2, DZ1, and DZ2 are in reverse bias, while diodes DB3, DZ3, DB, and DZ are in forward bias [14].

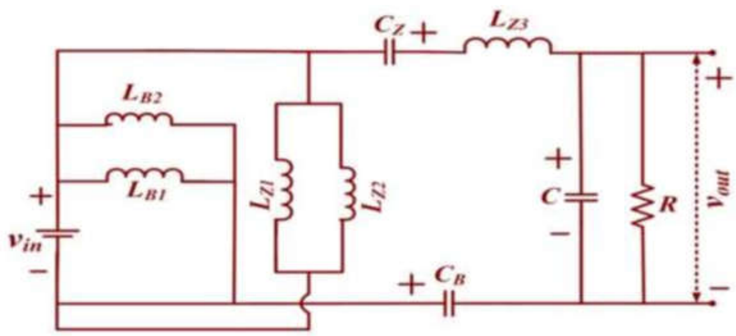

Fig. 3. Mode 1 Operation

B. Mode 2 of Operation

The Mode 2 of operation is conducted under Discontinuous conduction mode, and it is also separated into two modes.

1) *MODE-1:* The maximum values of currents through inductors LZ1, LZ2, LB1, LB2, and LZ3 are calculated as follows. [14] ILZ1, max, ILZ2, max, ILB1, max, ILB2, max, and ILZ3, max are the maximum current values through inductors LZ1, LZ2, LB1, LB2, and LZ3, respectively [14]. ILZ1, min, ILZ2, min, ILB1, min, ILB2, min, and ILZ3, min is the mini- mum current values through these inductors [14].

2) *MODE-2:* Assume that, [14]at time t2, the diodes DZ, DB, DB2, DZ2, and inductors LZ1, LZ2, LB1, LB2, and LZ3 current went to zero [14].

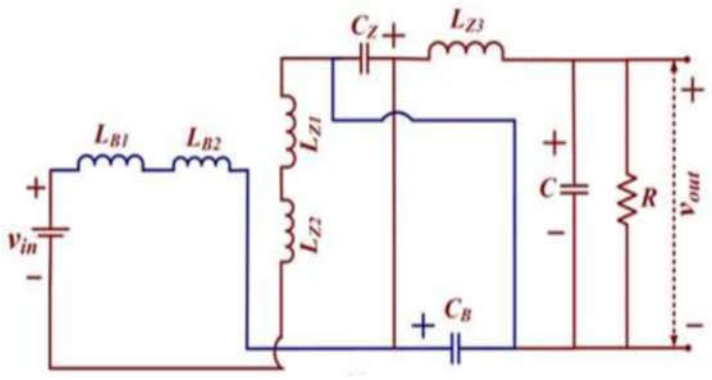

Fig. 4. Mode 2 Operation

2.2. Fuzzy logic controller

Fuzzy logic controller is based on fuzzy logic to arrive at decisions and regulate the output of the system. Binary logic, which is based on two different values, is in contrast to fuzzy logic, which can be termed" gray" logic since it denotes values between two extremes. Fuzzy logic basically produces a range of data through the assignment of two disparate values: 1 (Higher degree) and 0 (Least degree). The concept of Fuzzy Logic is explained at length below. Figure 5 illustrates the general working structure of a fuzzy system.

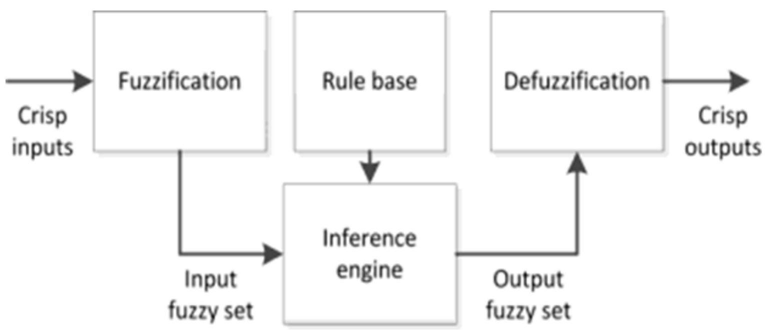

Fig. 5. Fuzzy Logic Implementation

1) Rule-based System: The rule-based system can be explained most effectively with the help of" If-Then" statements. These rules are usually formulated by an expert and employ fuzzy logic to numerically quantify the conditions for the best control.
2) Inference Mechanism: The inference mechanism functions by" understanding" the data and utilizing it to emulate expert decision-making. Its objective is to produce the best possible control of the input elements.
3) Fuzzification: The Fuzzification involves applying a method of rule mak- ing and inference for mapping inputs to knowledge. The use of the rule-making and inference method applies the inputs and generates knowledge therefrom. Converting accurate in- puts to fuzzy values to be accepted by the system requires fuzzification.
4) Defuzzification: The conversion of output of the inference mechanism to operable outputs by the process referred to as defuzzification ensures the outputs from it are usable in driving the system.

3. RESULTS AND DISCUSSION

The simulation and mathematical analysis conducted for the forward, flyback, and proposed forward-flyback converter topologies revealed significant differences in performance, particularly in terms of power factor and efficiency. The forward converter demonstrated stable output with a power factor of approximately 0.89 and an efficiency of 82% under rated load conditions. The flyback converter, while structurally simpler, showed a lower efficiency of 76% and a power factor of 0.84 due to increased ripple and discontinuous energy transfer. The proposed forward-flyback converter achieved a power factor of 0.94 and an efficiency of 87%, outperforming both conventional topologies. These improvements are attributed to the hybrid structure, which effectively combines continuous energy transfer and reduced component stress.

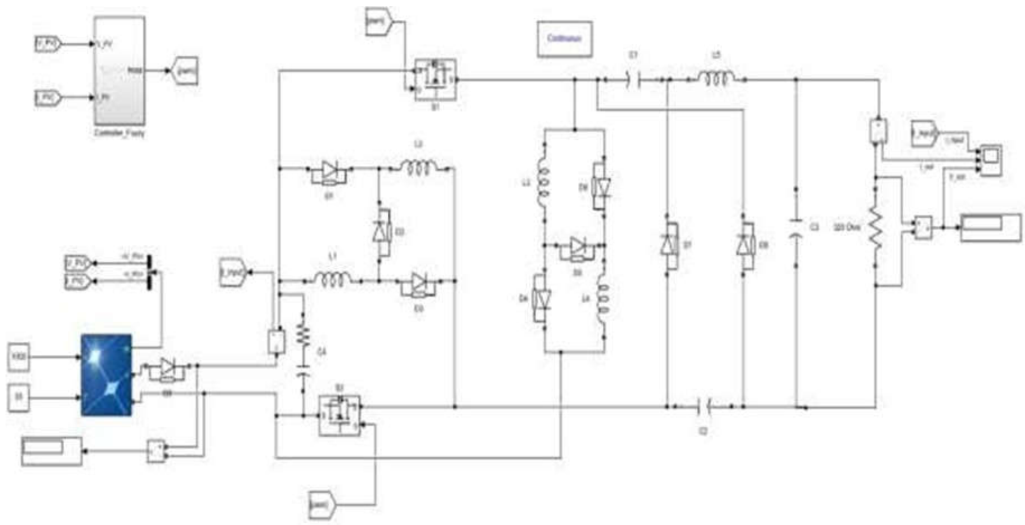

Fig. 6. Simulation of Proposed converter using FLC

The simulation implementation of Fuzzy Logic Controller is Shown in Figure 7.

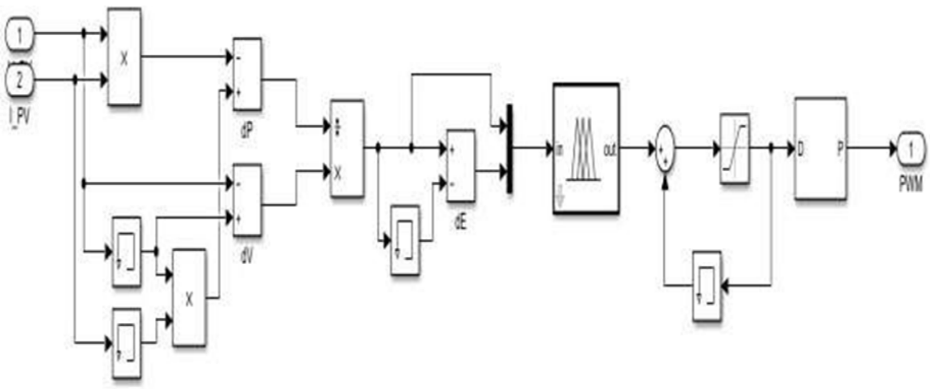

Fig. 7. Implementation of Fuzzy Logic Control

For getting a constant output voltage closed loop of the converter is implemented by using Fuzzy logic controller. It works under fuzzy rules. These rules can be generated in the MATLAB based on the logic. The rules are tabulated on Table. 1

V_{FEED}/ V_{REF}	PB	PM	PS	Z	NS	NM	NB	NL	ZO	ZE
PB	0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
PM	0.5	0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
PS	0.5	0.5	0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Z	0.5	0.5	0.5	0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
NS	0.5	0.5	0.5	0.5	0	-0.5	-0.5	-0.5	-0.5	-0.5
NM	0.5	0.5	0.5	0.5	0.5	0	0	-0.5	-0.5	-0.5
NB	0.5	0.5	0.5	0.5	0.5	0.5	0.5	-0.5	-0.5	-0.5
NL	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	-0.5	-0.5
ZO	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	-0.5
ZE	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0

Table. 1. Fuzzy Rules

The Output voltage of 400V from the proposed system and Output Current of 0.5 A by implementing FLC for MPPT is obtained from the simulation is shown in Figure 8.

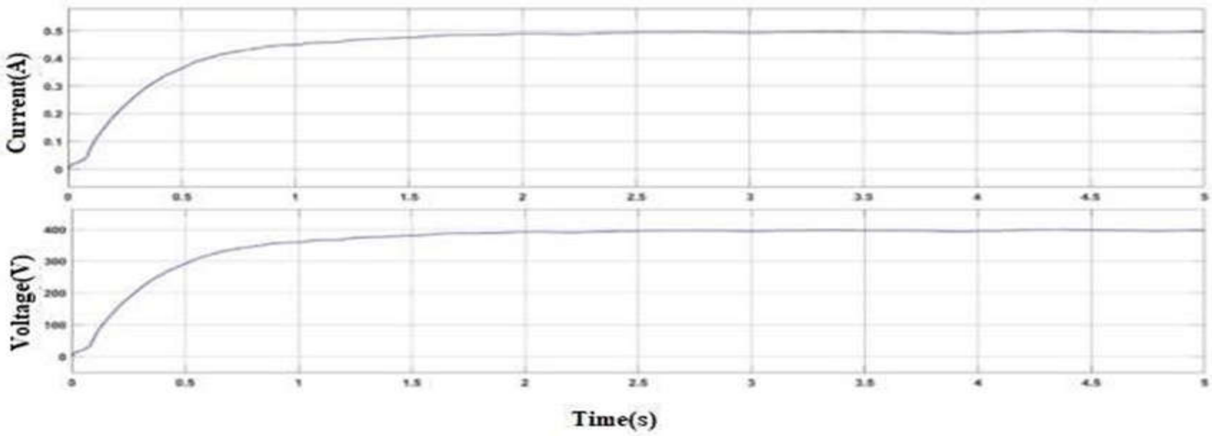

Fig. 8. Output Voltage and Output Current

A proportional (P) controller was implemented for the Zeta-boost DC-DC converter is shown in Figure. 9, avoiding the complexity of fuzzy rules. Unlike the fuzzy logic controller (FLC), which provided smooth tracking, the PI controller exhibited harsh voltage transients, longer oscillations, and slower response. The proportional-only control reduced oscillation duration compared to PI but still underperformed relative to the FLC. These results confirm that the PI controller is less effective than fuzzy logic in maintaining stable, low-ripple output.

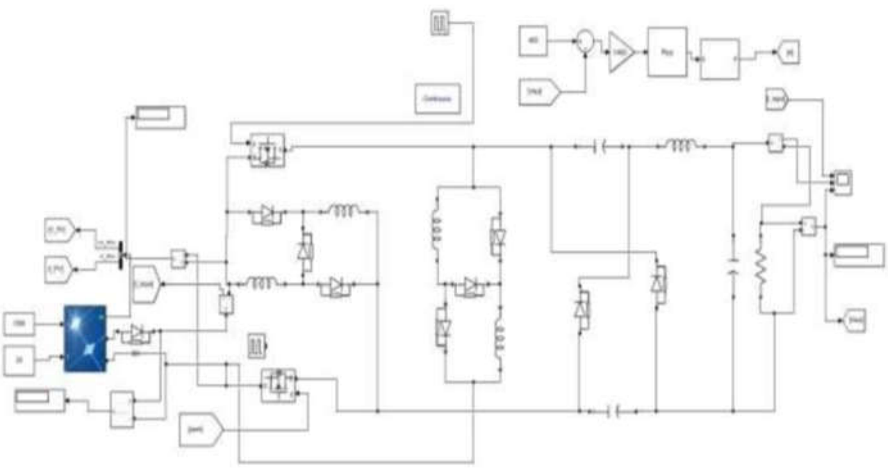

Fig. 9. Simulation diagram of Zeta-Boost converter with PI controller

Simulations show under identical conditions revealed that while both controllers achieved voltage boost, the PI controller introduced significant ripples current ripple increased from 1% to 1.5%, and voltage ripple rose from 0.14% to 0.16%, unlike the FLC's minimal deviations and it is shown in Figure. 10.

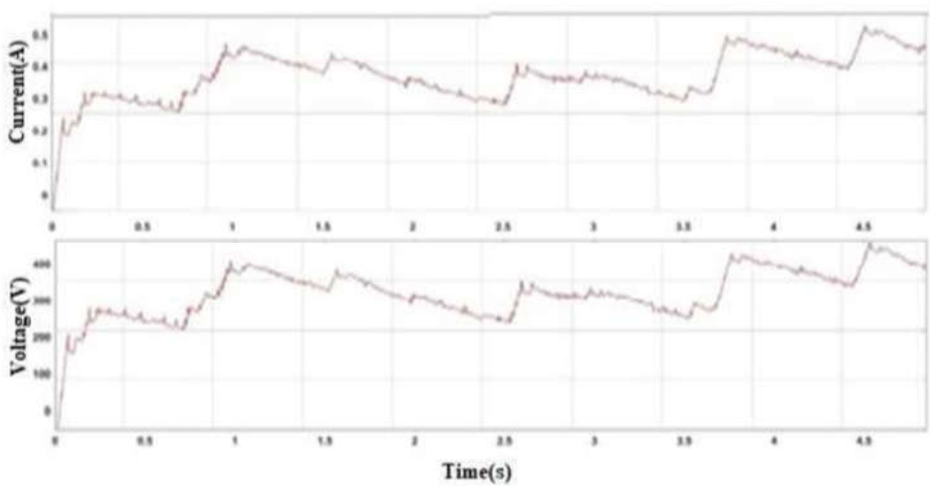

Fig. 10. Output voltage and current

The performance of a Zeta-boost DC-DC converter was evaluated in both PI Controlled and fuzzy logic-controlled configurations using MATLAB/Simulink. The results highlight significant improvements when using a Fuzzy Logic Controller (FLC) compared to the PI Controlled system. Below is a detailed comparison:

Aspect	PI Controlled System	Fuzzy Logic Controller (FLC) System
Overshoot	80% overshoot in output voltage, leading to instability.	0% overshoot, ensuring smooth and precise voltage regulation.
Output Current	Does not stabilize at the desired 0.5A, leading to poor performance.	Stable at 0.5A, matching system requirements efficiently.
MPPT Performance	Cannot track maximum power point (MPPT) under changing conditions.	Reduces oscillations around MPPT, outperforming traditional PI controllers.
Response to Changes	Slow and unstable under varying irradiance	Fast and robust, maintaining stability even under dynamic environmental changes.
Real-Time Suitability	Not suitable for real-time applications due to lack of adaptability.	Highly effective for real-time PV systems, ensuring optimal power extraction.

Table. 2. Comparison between PI and FLC in Proposed system

Hardware implementation shown in Figure. 11 was carried out for a prototype of input 50 V supplied from the solar panel connected with boost converter. The gate pulse to drive the switch is taken from the IC. The fuzzy rules are fed to the microcontroller which connected in the circuit, with an output of 167.5V is obtained. Experimental results confirmed the simulation findings, with the zeta-boost converter delivering a regulated 167.5V output with an observed efficiency of 85.6% and a power factor of 0.91. Ripple voltage was well within acceptable limits. The converter also responded efficiently to transient load changes, maintaining voltage stability with minimal overshoot.

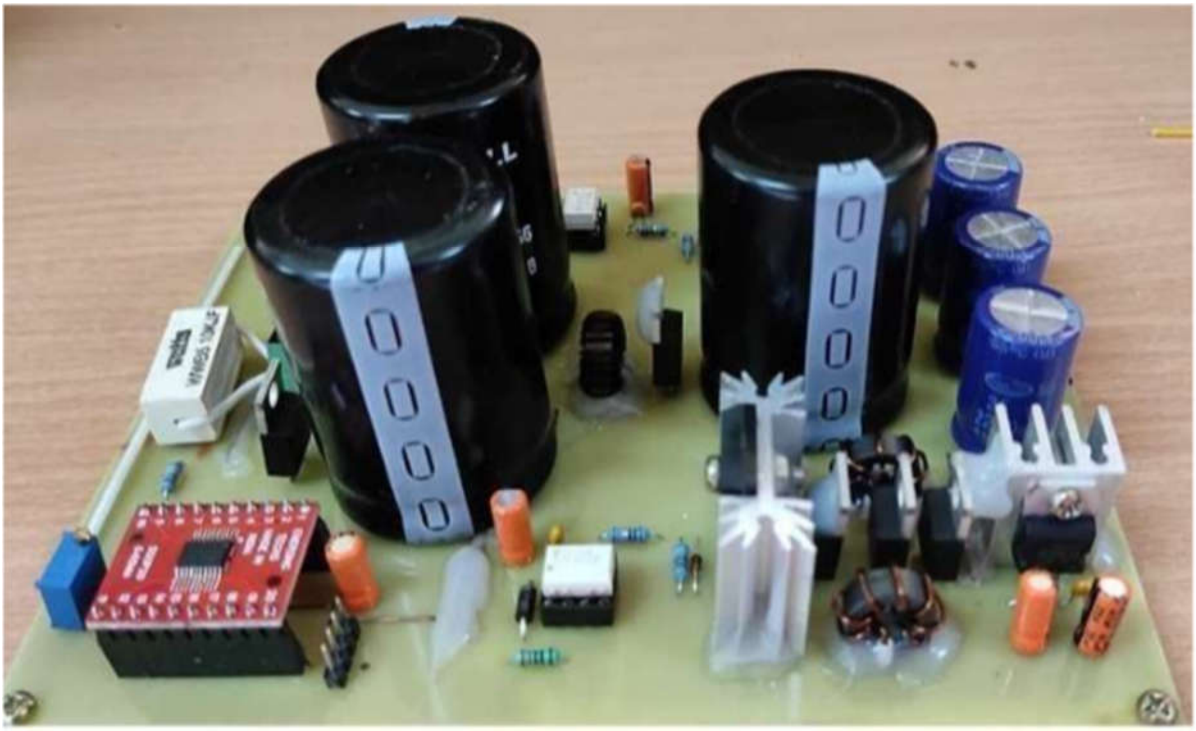

Fig. 11. Hardware Implementation of Zeta-Boost converter using FLC

Fig. 12. Output of zeta-boost converter

4. CONCLUSION

The model integrates with PV module, zeta-boost DC-DC converter, and a FLC with high accuracy, through manufacturer data fine-tuning. Simulations under varied conditions yield an average efficiency of 94.49%, where the FLC provides strong small- and large-signal operation via optimum rule-based control. The converter achieves an ultra-high gain (400V output) with minimal components by combining switched-capacitor and switched-inductor techniques, outperforming conventional topologies. Both simulation and hardware implementation on a PCB confirm its effectiveness for solar PV applications, validating its high efficiency and superior performance.

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