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A Control Strategy for Zeta Converter Adaptation in Photovoltaic Systems: Genetic Algorithm-Based PID Controller

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ABSTRACT

The demand for efficient and stable DC-DC converters has grown due to their widespread use in renewable energy systems, battery-operated devices, and switched-mode power supplies. The zeta converter, a unique type, offers benefits such as steady output current, low output voltage changes, and the ability to function as both a buck and boost converter. However, unpredictable behavior can lead to issues such as fluctuations in output, excessive overshooting, and instability, which can negatively impact sensitive devices. This paper proposes a method to model, simulate, and study a zeta converter in continuous conduction mode (CCM) to address voltage control problems caused by input changes. The proposed solution involves using a proportional-integral-derivative (PID) controller adjusted with a genetic algorithm (GA) to improve dynamic response and reduce output voltage ripple and peak overshoot in transient conditions. The simulation results show that the GA-improved PID controller significantly enhances converter performance by reducing voltage ripple and peak overshoot. The controller can maintain a fixed output voltage despite changes in input and load, making it an effective method for utilizing renewable energy and other sensitive power electronic devices.

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1. Introduction

The direct current to direct current (DC-DC) conversion is a fundamental component of power electronics that is currently advancing rapidly to meet the increasing demands of modern systems [1], [2]. DC-DC converters play an important role in supplying regulated voltage to loads, particularly where the input voltage is either unregulated or changing over time, as is usually the case with rectified line voltage sources or renewable energy systems. These converters are used in many areas, like solar power systems, battery-operated devices, DC motor controls, and switched-mode power supplies (SMPS), where having a steady and reliable output voltage is crucial for the equipment to work efficiently [3], [4].

The fourth-order converters, which consist of SEPIC, CUK, and zeta converters, represent one of the unique features that differentiate various types of DC-DC converters. The converters have characteristics like isolated output and a constant current output and are able to be used in buck-boost converter applications as well, hence making them perfect in specialized applications [5]–[7]. Specifically, the zeta converter has gained a lot of interest because it can deliver a regulated output voltage over changing input or loading conditions and smaller ripple output voltage levels, and it has no pulsating output current, an aspect that allows smaller output capacitors to be used. These benefits result in increased efficiency and reliability of the converter in a sensitive application, such as renewable energy systems, where variations in input voltage are common [8]–[11].

DC-DC converters are considered in broad terms to fall into two main families: these being buck converters, which lower the voltage; boost converters, which increase the voltage; and buck-boost converters, which can either increase or decrease the voltage. Special topologies like SEPIC, CUK, and zeta converters further expand these functionalities, imposing flexibility that meets more specific application needs. Applications primarily consider these converters based on their suitability for different loads with varying voltage control and response requirements [12]–[14].

Even though DC-DC converters are commonly used, they have nonlinear features that can cause issues like big fluctuations in output voltage, high peak overshoot, and unstable performance during changes [15], [16]. Such problems are particularly troublesome in those applications where very stable and tight regulation of voltage is needed, as in the case of PV systems, where input voltage drifts constantly with environmental changes. Complex control strategies can overcome these limitations by improving the dynamic response, reducing ripples, and preventing transient overshoot. PWM is the most common switching technique because it efficiently regulates by varying the duty cycle of the converter's switches. Nevertheless, traditional control techniques tend to be unable to entirely correct the nonlinear behavior of the system when there is a rapid rate of change within its operating environment [17]–[21].

To handle these issues, the combination of intelligent optimization techniques and traditional control has become a common phenomenon. An example of this is the tuning of proportional-integral-derivative (PID) controllers with the help of optimization algorithms. The PID controllers have been considered simple and effective for controlling system dynamics, whereas they strongly rely on the optimal parameter tuning of proportional, integral, and derivative parameters [22]–[34]. Conventional tuning, Ziegler-Nichols (ZN), can lead to less than optimum tuning operation, particularly in nonlinear regulators like the DC-DC converters. Particle swarm optimization (PSO), fuzzy-logic controller, and genetic algorithm (GA) are compared in [35]. Accordingly, it is seen that GA is superior for PID controller adaptation. Similarly, GA, PSO, simulated annealing (SA), and surrogate-based optimization (SBO) are adapted to the PID controller in [36] with the conclusion of GA’s faster response and moderate overshoot. Research [37] suggests implementation of GA with PID controller has good performance on system stability, static, and dynamic indices. As stated in [35]–[37], genetic algorithms (GA), which are a type of advanced optimization method, can be used to determine the best PID settings for improved response time, reduced fluctuations, and fewer sudden spikes.

The given study is devoted to modeling simulations and the performance of a zeta converter in continuous conduction mode (CCM). Its application is in PV, where there can be wide variations in the applied input voltage but where a fixed output voltage is needed to reliably convey power to the load [38]–[45]. A GA-optimized PID controller is recommended to improve the zeta converter's efficiency by minimizing voltage fluctuations and the highest voltage spikes during sudden changes. The zeta converter is represented using the state-space analysis (SSA) method, which shows how the input voltage, state variables, and output voltage are mathematically separated from each other [46]–[55]. The system is simulated using MATLAB and Simulink, which also allows us to compare how the zeta converter works with and without the new GA-based PID controller. This work has three goals defined as follows

- The objective of this project is to design a zeta converter that will produce continuous output from various types of input, particularly for photovoltaic applications.
- GA-optimized PID controller is developed to improve the transient response and stability of the zeta converter.
- The converter's performance is evaluated and compared in terms of output voltage ripple and peak overshoot during transient situations, both with and without the optimized controller.

This research focuses on designing and simulating the zeta converter in Continuous Conduction Mode (CCM) using MATLAB/Simulink, implementing a GA-based PID controller, and analyzing how the system performs under different load conditions. A GA-based PID controller is applied to the proposed system because of its advantages over other control techniques as presented in [35]–[37]. The Zeta converter topology is implemented due to its advantages over other DC/DC converter topologies, which are compared in Section 2 and Section 3, including low switching losses, superior step-down/up capabilities, reduced output voltage ripple, and improved overshoot performance. The conclusion is that using the GA-optimized PID controller can greatly improve how quickly the zeta converter responds and keeps the voltage stable, making it a suitable choice for solar power and other renewable energy sources.

The remainder of the paper is organized as follows: Section 2 covers types of DC/DC converters and the advantages of the zeta converter in detail. In Section 3, details of outstanding control techniques applied to the zeta converter topology are analyzed. Section 4 presents the zeta converter design and selection of parameters, the basis of the GA-based PID control technique, and MATLAB coding details. Performance assessment with efficiency evaluation follows in Section 5. Conclusions are presented with the highlights of the paper in Section 6.

2. Types of DC-DC Converters

DC-DC converters play a significant role in power electronics by converting uncontrolled input direct current voltages into stable and controlled output voltages. These converters are normally non-isolated and characterized using switching transistors (usually power transistors, like MOSFETs). Here are the features and uses of traditional DC-DC converter types (buck, boost, buck-boost, CUk, SEPIC, and zeta converters) listed in Table 1.

Table 1. Comparison between the DC-DC converters

	Buck	**Boost**	**Buck-Boost**	**Cúk**	**SEPIC**	**Zeta**
Settling time	Worst	Worst	Worst	Medium	Medium	Good
Output voltage polarity	Same	Same	Inverse	Same	Same	Same
Switching losses	Low	Medium	High	High	Medium	Low
Step up	No	Yes	Yes	Yes	Yes	Yes
Step down	Yes	No	Yes	Yes	Yes	Yes
The cost	Low	Low	High	High	High	High
Output voltage ripple	Worst	Worst	Worst	Worst	Worst	Good
Overshoot	Worst	Worst	Worst	Medium	Medium	Good

- Buck converter (Step-Down): A buck converter decreases a greater input supply to a smaller output supply. It finds a broad application in charging batteries, in welding equipment, and in devices that need lower regulated voltages. With power delivered in continuous conduction mode (CCM), it delivers smooth output current with an output inductor [38], [48].
- Boost Converter (Step-Up): It multiplies an input signal (which is typically low) into an amplified signal (which is usually high), and so it is appropriately used in batteries and solar panels. In the ON state, it collects energy in the inductor and then dumps that energy to the output capacitor in the OFF state; however, it experiences high switching losses and low efficiency at high duty cycles [6], [8], [17], [45].
- Buck-Boost Converter: An inverting flyback converter can step up as well as step down voltage, but the output has inverted polarity. It is applied in places where the regulated negative voltages are needed [34], [42].
- Cuk Converter: A fourth-order non-isolated converter, which can either step up or step down, has an output of reverse polarity. It provides constant input and output current but is difficult to model since it is non-linear and of higher orders [3], [32], [40]–[47].
- SEPIC Converter (the Single-Ended Primary Inductance Converter): The topology also has positive polarity output and can be used to step up and step down. It uses coupled inductors and capacitors, so it works well where a stable voltage with the same polarity as the input is needed [12], [15], [25], [49]–[65].
- Zeta Converter (Dual SEPIC): The Zeta converter is a fourth-order converter that utilizes two SEPIC stages, enabling it to either step up or step down while maintaining the output's polarity about the input. It provides low ripple and low switching stress, and this makes it an economical solution in regulated power supply applications like renewable energy systems [3], [5], [14], [20], [22].

3. Control Techniques of Zeta Converters

Zeta converters are a well-studied form of converter because they can output a regulated DC with the polarity of the input, which has led to their use in renewable energy systems and sensitive electronic systems. Many different methods have been suggested to create mathematical models that describe how zeta converters behave, especially since they mainly operate in continuous conduction mode (CCM) [56]–[58].

The state space analysis (SSA) method is the most widely followed method of small-signal analysis and transfer function derivation of zeta converters. Researchers showed that SSA provides accurate modeling, stable output voltage regulation, and quick response to changes, even when line conditions and load vary. Nevertheless, to maintain a steady production, duty cycles need to be changed as the parameters change. The comparison between open-loop control systems and closed-loop control (especially with PID compensators) showed that closed-loop control does a better job of keeping the voltage stable and managing quick changes.

Other modeling procedures include Leverrier Algorithms combined with SSA for improved dynamic response, Fuzzy Logic and Particle Swarm Optimization (FLC-PSO) controllers enhanced for better voltage regulation and ripple avoidance and Switching Flow Graph (SFG) techniques that use Mason's gain formula to derive transfer functions, poles, zeros, and frequency response for improved modeling and controller design.

Conventional controllers have been combined with optimization techniques like genetic algorithms (GA) to improve performance, particularly in dynamic conditions. Many kinds of DC-DC converters, like zeta converters, have greatly reduced output voltage changes, lessened overshoot, and improved system stability when using GA-based PID controllers [2], [14], [22], [23], [31], [53], as shown in Table 2.

Overall, SSA is a popular modeling approach because it reduces non-linearity and can manage nonlinear situations, while GA-based PID controllers are very efficient at providing stable voltage outputs with few temporary issues.

Table 2. Summary of modelling techniques of the zeta converter

Authors	Modelling techniques of zeta converters	Comments
[2] H. Ahmad & N. Saleh Sultan (2014)	The study focuses on fuzzy logic controller-based particle swarm optimization (FLC & PSO)	- The zeta converter utilized FLC and PSO for its switching process - The goal is to improve the output voltage regulation and performance of the zeta converter - It is proposed that the converter displayed significant improvements in this regard
[14] V. P. Dhote & G. P. Modak (2017)	State space analysis (SSA) technique	- Simulated open- and closed-loop systems in MATLAB/Simulink - Observed that the closed-loop system is more efficient than the open-loop system while using a PID controller for a constant output voltage
[22] M. M. Garg, Y. V. Hote & M. K. Pathak (2015)	State space technique and the Leverrier algorithm are two important methods in control theory	- Used the state-space analysis technique along with the Leverrier algorithm - Observed that the compensated zeta converter performed remarkably well, providing good dynamic response and steady-state behaviour
[23] E. Davaran Hagh, E. Babaei & L. Mohammadian (2015)	The technique involves switching the flow graph	- This research highlighted the efficiency of the proposed PID controller, which features special tuning for control purposes
[31] G. P. Modak & V. P. Dhote (2017)	State space analysis (SSA) technique	- The research stated that there is a deviation of 1 V in the solar panel's output voltage with every 5°C variation in the temperature - Highlighted that the zeta converter provided a constant output voltage throughout the operation - The output voltage regulation is excellent
[53] E. Vuthchhay & C. Bunlaksananusorn (2008)	State space analysis (SSA) technique	- The output voltage throughout the zeta converter operation is a constant 5V - The proposed zeta converter, in conjunction with a PI compensator, demonstrated a fast transient response to a step load

4. Basis of GA-based PID Control for Zeta Converter

This chapter clarifies the presented methodology for modeling, controlling, and enhancing a zeta DC-DC converter to maintain a stable output voltage despite variations in input. The method uses state-space modeling, PID control, and genetic algorithm (GA) optimization to enhance both quick responses and stable performance.

In Continuous Conduction Mode (CCM), the operational principles of the zeta converter are considered on the two possible switching conditions: (i) switch ON and diode OFF, and (ii) switch OFF and diode ON. Using Kirchhoff's current and voltage laws, we derive mathematical relationships to find the duty cycle, the current changes in an inductor, and the voltage changes in a capacitor, which help us understand the electrical features of the converter.

The state space analysis (SSA) method is used in dynamic analysis because it effectively predicts how the system will respond over time, allowing for the precise determination of the currents in inductors and voltages in capacitors. A PID controller is developed to control the output voltage, and the genetic algorithm is used to best tune the PID parameters (Kp, Ki, Kd) to cut the overshoot, enhance the settling time, and reduce the voltage ripples.

Finally, the findings from MATLAB/Simulink validate the approach that integrates a photovoltaic (PV) module with a zeta converter as the input source. The system's performance is explained under various input conditions, showing that the suggested method can provide a steady output voltage and a fast response to changes, as illustrated in Fig. 1.

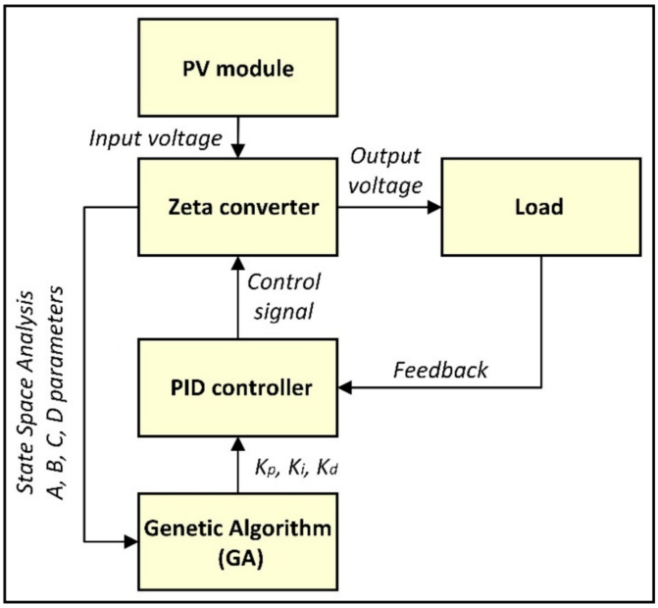


Fig. 1. Block diagram for GA-based PID control for the proposed system

4.1. Zeta Converter in Continuous Conduction Mode (CCM)

The zeta converter working in continuous conduction mode (CCM) is controlled by a switch (MOSFET or BJT) that changes its state, causing the diode to switch between ON and OFF at the same time. Two inductors (L_1 and L_2) are employed to mitigate the input current ripple, as illustrated in Fig. 2. Two capacitors (C_1 and C_2) are present, presumed to be sufficiently sized, with the voltage across C_1 equal to V_{Out} as shown in Table 3.

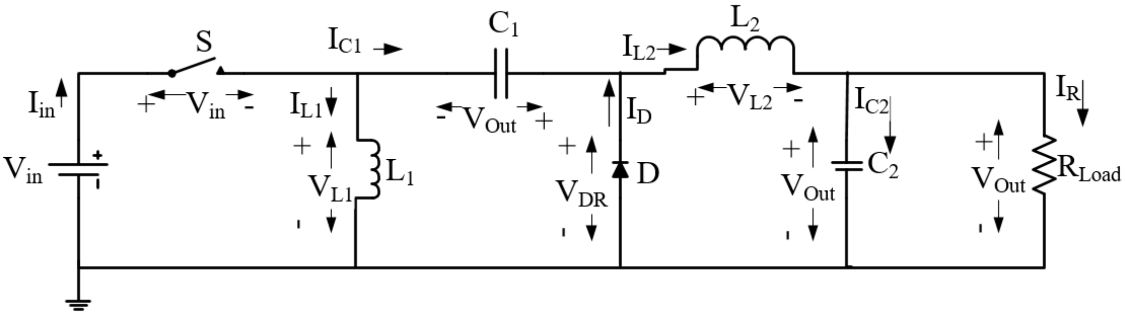


Fig. 2. Design for the Zeta DC to DC converter

4.1.1. Step 1: Duty Cycle Calculation

The relationship between the input and output voltages is defined by the duty cycle. In the case of a zeta converter in CCM, the duty cycle D is calculated by using (1) and as in (2):

$$D = \frac{V_{out}}{V_{out} + V_{in}} \tag{1}$$

Substituting:

$$D = \frac{13}{13 + 38} = 0.4194 \tag{2}$$

The on-time of the switch is therefore about 41.94 % of the total switching time.

Table 3. System specifications for the zeta converter

Parameters	Symbol	Value
PV Module Output Voltage	V_{in}	38 V
Zeta Converter Output Voltage	V_{out}	13 V
Switching Frequency	f_{SW}	25 kHz
Load Resistance	R	10 Ω
Inductor Ripple Current (limit)	$\Delta I_{L1}, \Delta I_{L2}$	0.15 A
Capacitor Ripple Voltage (limit)	$\Delta V_{C1}, \Delta V_{C2}$	0.2 V
Overshoot Limit		1%

4.2. Full Design Methodology of Zeta Converter

The zeta converter is designed by determining important factors like the duty cycle, inductance values, and capacitor values to ensure that it operates well in continuous conduction mode (CCM), has minimal ripple, and delivers a stable output voltage. Its design is a combination of the specifications provided in Table 4.

Table 4. Operating conditions and design aspects of the zeta converter in CCM

Aspect	Condition 1: Switch ON & Diode OFF	Condition 2: Switch OFF & Diode ON
Switch State	Switch (S) is **ON** (closed)	Switch (S) is **OFF** (Open)
Diode State	Diode (D) is **OFF** (reverse-bias)	Diode (D) is **ON** (forward-bias)
Inductor Voltages	$V_{L1} = V_{in}\ V_{L2} = V_{in}$	$V_{L1} = -V_{out}\ V_{L2} = -V_{out}$
Inductor Currents	I_{L1} & I_{L2} **increase linearly** $\frac{dI_L}{dt} = \frac{V_{in}}{L}$	I_{L1} & I_{L2} **decrease linearly** $\frac{dI_L}{dt} = -\frac{V_{out}}{L}$
Energy Flow (Inductors)	Both inductors **store energy** (charging)	Both inductors **release stored energy** (discharging to capacitors & load)
Capacitor Behavior	C_1 **discharges** energy to V_{out} C_2 supports the load partially	L_1 **charges** C_1 L_2 **charges** C_2 and supplies load
Current Through Switch / Diode	Switch current: $I_s = I_{L1} + I_{L2}$ **increases**	Diode current: $I_D = I_{L1} + I_{L2}$ **decreases**
Voltage Across Diode	Reverse-biased: $V_D = -(V_{in} + V_{out})$	Forward-bias: $V_D \approx 0$ (short circuit)
Time Interval	$0 < t \leq D \cdot T$	$D \cdot T < t \leq T$
Duty Cycle (Design)	Defined as $D = \frac{V_{out}}{V_{out}+V_{in}}$ (for CCM operation)	Complements ON time: $1 - D$
Inductor Design	Designed to maintain **continuous current mode**: $\Delta I_L = \frac{V_{in} \cdot D}{f \cdot L}$	$\Delta I_L = \dfrac{V_{out} \cdot (1-D)}{f \cdot L}$
Capacitor Design	Ripple voltage: $\Delta V_{C1} \approx \frac{I_{out} \cdot D}{f \cdot C_1}$	$\Delta V_{C2} \approx \dfrac{I_{out} \cdot (1-D)}{f \cdot C_2}$

4.2.1. Step 2: Inductor Calculation

The inductor values are chosen to maintain CCM and limit current ripple. L_1 and L_2 can be calculated by using (3) and (4).

$$L_1 \geq \frac{V_{in} \cdot D}{\Delta I_{L1} \cdot f_{SW}} \tag{3}$$

$$L_2 \geq \frac{V_{out} \cdot (1-D)}{\Delta I_{L2} \cdot f_{SW}} \tag{4}$$

With the design parameters presented in Table 1, L_1 and L_2 are obtained as 2 mH as stated in (5) and (6).

$$L_1 = \frac{38 \times 0.4194}{0.15 \times 25 \times 10^3} \approx 2\, mH \tag{5}$$

$$L_2 = \frac{13 \times (1 - 0.4194)}{0.15 \times 25 \times 10^3} \approx 2\, mH \tag{6}$$

4.2.2. Step 3: Capacitor Calculation

Capacitors are designed to limit the output voltage ripple. C_1 and C_2 can be calculated by using (7) and (8). I_{out} parameter is needed for the calculation of capacitors and is given in (9).

$$C_1 \geq \frac{I_{out} \cdot D}{f_{SW} \cdot \Delta V_{C1}} \tag{7}$$

$$C_2 \geq \frac{I_{out} \cdot (1 - D)}{f_{SW} \cdot \Delta V_{C2}} \tag{8}$$

$$I_{out} = \frac{V_{out}}{R} = \frac{13}{10} = 1.3\, A \tag{9}$$

With the design parameters presented in Table 1 and 1.3 A I_{out} value, C_1 and C_2 are obtained as 750 μF and 25 μF as stated in (10) and (11).

$$C_1 = \frac{1.3 \times 0.4194}{25 \times 10^3 \times 0.03} \approx 750\, \mu F \tag{10}$$

$$C_2 = \frac{1.3 \times (1 - 0.4194)}{25 \times 10^3 \times 0.03} \approx 25\, \mu F \tag{11}$$

4.2.3. Step 4: Final Designed Parameters

All parameters are calculated with (3)–(11) and presented in Table 5.

Table 5. Final designed parameters of the zeta converter

Parameters	Symbol	Value
Input Voltage	V_{in}	38 V
Output Voltage	V_{out}	13 V
Duty Cycle	D	0.4194
Switching Frequency	f_{SW}	25 kHz
Load Resistance	R	10 Ω
Inductor 1	L_1	2 mH
Inductor 2	L_2	2 mH
Capacitor 1	C_1	750 μF
Capacitor 2	C_2	25 μF

4.3. Optimization of PID Controller using Genetic Algorithm

A PID controller is used to maintain the output voltage of the zeta converter under different input and load requirements. But here, the choice of the best parameters of PID (K_p, K_i, K_d) is very important to attain lower rise time, less overshoot, and smaller steady-state error. To this end, a genetic algorithm (GA) is used as a tool of optimization because it has favorable global search properties and is applicable to nonlinear systems.

4.3.1. Genetic Algorithm Overview

Genetic Algorithm is an effective stochastic optimization tool based on natural selection and evolution. GA converges on a set of candidate solutions (chromosomes) iteratively to achieve optimal control parameters using selection, crossover, and mutation in each step. The procedure for PID optimization is outlined as

- Initialization—Generate a random initial population of chromosomes, each representing a set of (K_p, K_i, K_d).
- Fitness Evaluation—Assess each chromosome with the predetermined objective (fitness) function.
- Selection—Choose the most meritorious chromosomes selected using the performance value.
- Crossover and Mutation—make new chromosomes by combining and slightly altering parent chromosomes.
- Termination—Repeat until an optimal PID parameter is achieved or a maximum number of generations has occurred.

4.3.2. Initial Population and Best Chromosome Selection

An initial random population is generated as shown in Table 6. Each row represents a chromosome.

Table 6. Initial population for GA-based PID optimization

Chromosome	K_d	K_p	K_i	Fitness (J)
1	0.0815	0.0103	165.605	1,226,657.10
2	0.0906	0.0038	157.795	1,364,818.68
3	0.0127	0.0071	154.8338	36,744.45

The third chromosome is identified as the fittest, having the minimum objective function value.

4.3.3. GA Convergence and Final PID Parameters

The GA iteratively improves the population over several generations. Table 7 presents the optimal PID parameters obtained after running for 1000 generations.

Table 7. Parameters of optimized PID controller

Controller	K_p	K_i	K_d
PID (GA-optimized)	0.0079	150.0001	0.0794

4.3.4. System Stability Using Nyquist Criteria

Research [18] chose the MATLAB GUI (Graphical User Interface) to evaluate the system's stability after completing the discussed parameters. The basic template of this GUI is shown in Fig. 3. Using the PID controller, stability is checked by the following steps:

a. Executing the system parameters with a MATLAB script, firstly.

b. Putting plant numerator and plant denominator in expressions in the respective blocks, as shown in Fig. 3.

   i. num = [0 0 8.38e6 -1.1639e-10 32.466e11]

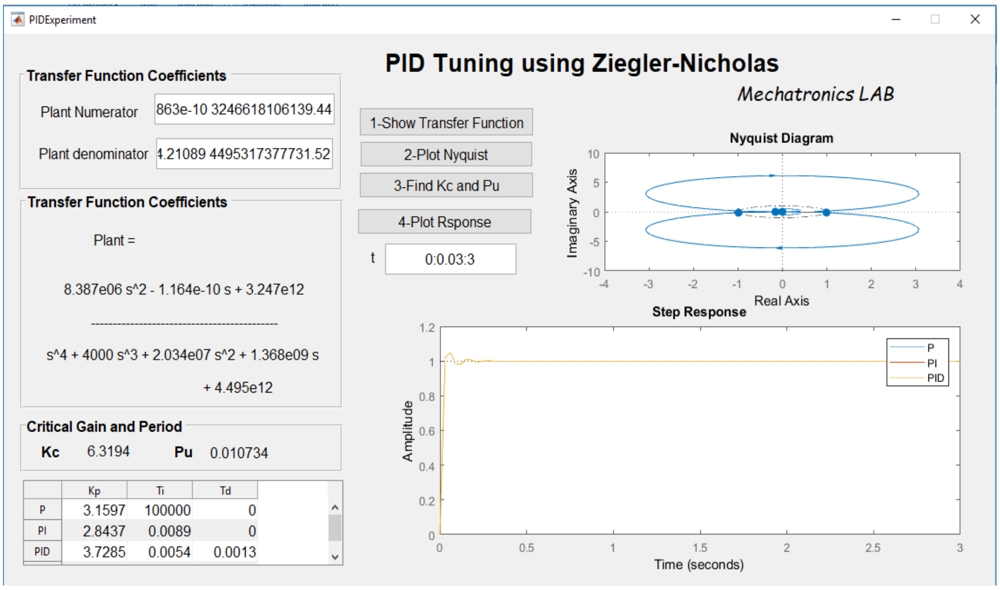
   ii. den = [1 4e3 20.34e4 13.68e8 449.53e10]

c. Showing the transfer function (sys) given in (12):

$$sys = \frac{8.387e06s^2 - 1.164e - 10s + 3.247e12}{s^4 + 4000s^3 + 2.034e07s^2 + 1.368e9s + 4.495e12} \tag{12}$$

d. Plotting the Nyquist, as shown in Fig. 4, along with the system's poles.

e. Plotting the Nyquist; as shown in Fig. 5 and Fig. 6 illustrating the zeroes of the system in detail.



Transfer Function Coefficients

Plant Numerator 863e-10 3246618106139.44

Plant denominator 4.21089 4495317377731.52

Transfer Function Coefficients

Plant =

```
  8.387e06 s^2 - 1.164e-10 s + 3.247e12

  ----------------------------------------

s^4 + 4000 s^3 + 2.034e07 s^2 + 1.368e09 s

                        + 4.495e12
```

t 0:0.03:3

Critical Gain and Period

Kc 6.3194 **Pu** 0.010734

	Kp	Ti	Td
P	3.1597	100000	0
PI	2.8437	0.0089	0
PID	3.7285	0.0054	0.0013

Fig. 3. Stability and instability for control system

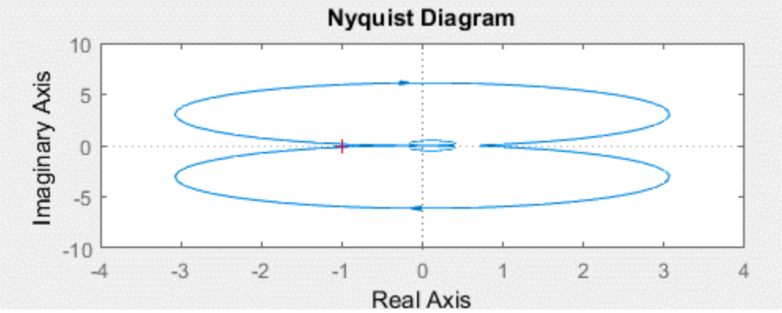


Fig. 4. Poles of the system in the Nyquist diagram

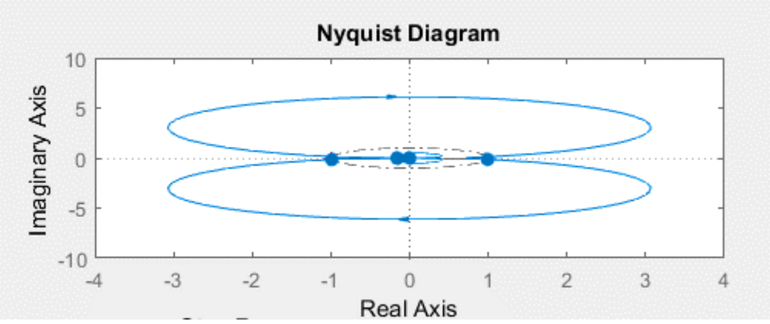
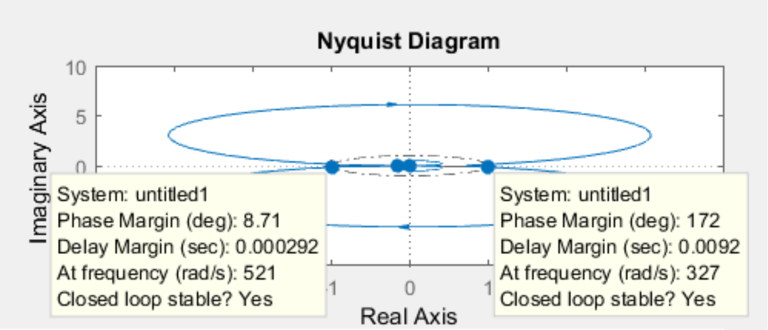


Fig. 5. Zeros of the system in the Nyquist diagram



System: untitled1
Phase Margin (deg): 8.71
Delay Margin (sec): 0.000292
At frequency (rad/s): 521
Closed loop stable? Yes

System: untitled1
Phase Margin (deg): 172
Delay Margin (sec): 0.0092
At frequency (rad/s): 327
Closed loop stable? Yes

Fig. 6. Zeros of a stable system in the Nyquist diagram

The study of this Section offered the analysis and design of the Zeta converter along with MATLAB Simulink implementation. The obtained results of the simulation are promising and added valuable information to theoretical knowledge on the Zeta converter working and its usage in Simulink. The flowchart of the proposed GA-based PID controller for Zeta converter is presented in Fig. 7.

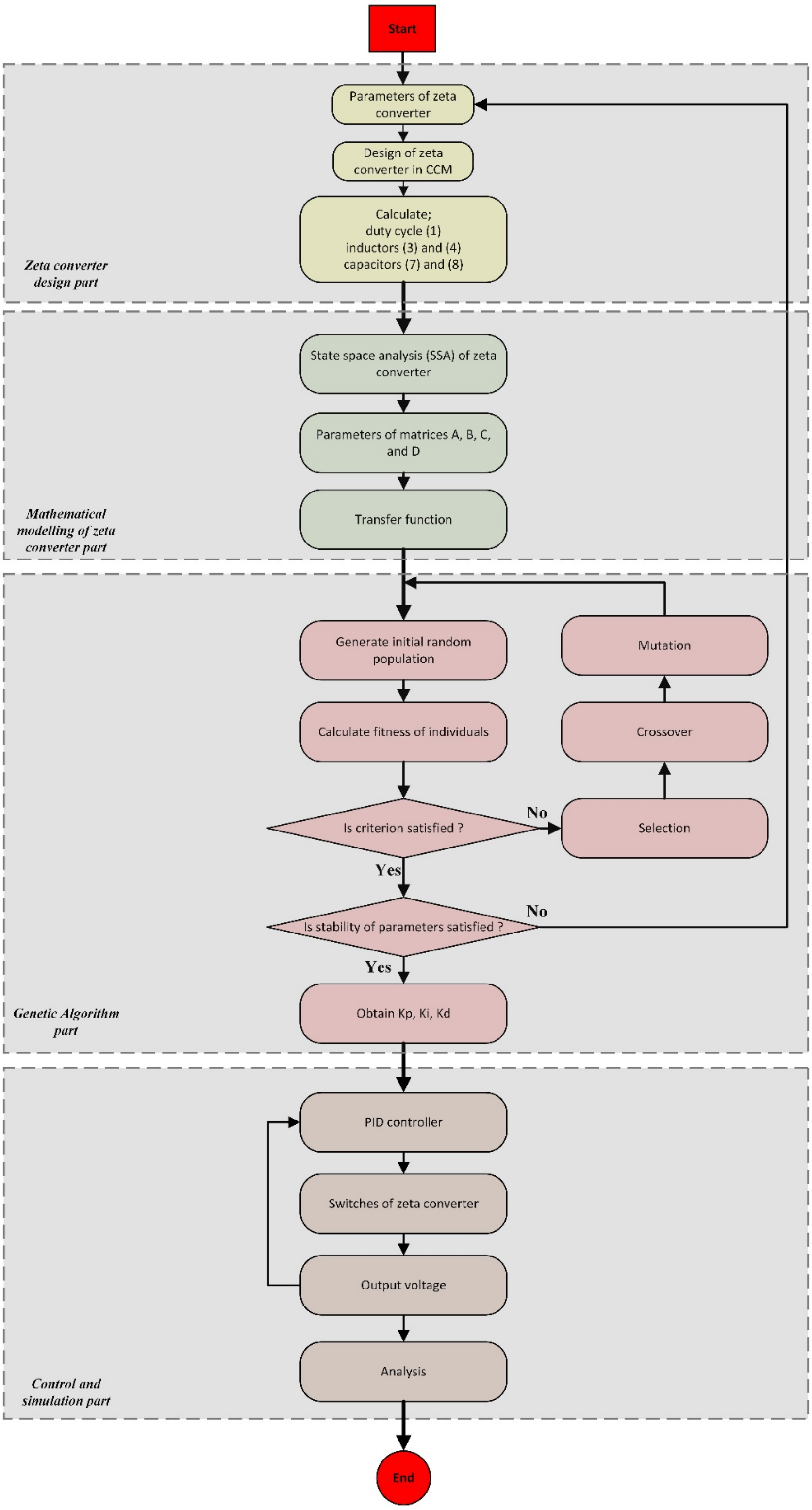


Fig. 7. Flowchart of the design procedure of the zeta converter and GA-based PID control

After the control configuration of the Zeta converter is completed, the efficiency of the PID controller is also tested with the Simulink block PID and the corresponding circuit parameters as represented in Fig. 8.

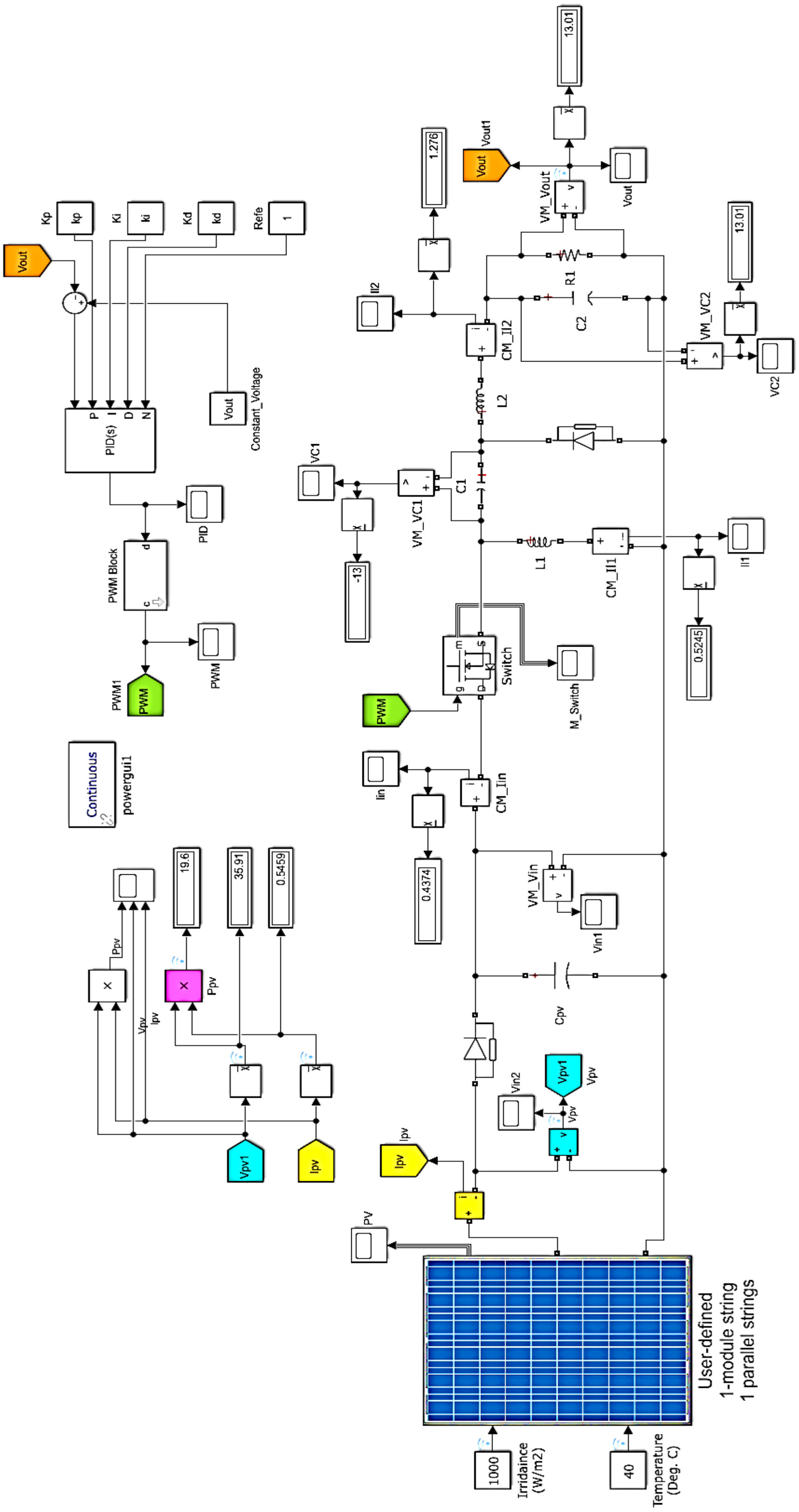


Fig. 8. Circuit for zeta converter in Simulink/MATLAB

The simulated converter can maintain a steady output voltage while the input voltage is dynamically changing to reflect the output of a photovoltaic (PV) model. The PV power is conditional on irradiance, temperature changes, and parameters of the PV model. One of the major issues in the simulation is the assumption of a constant resistive load, which may not accurately reflect real-life situations. Furthermore, the simulation considered temperature variations, making certain differences between the results and the experiment probable. The implementational process can be discussed as being slightly more optimized, and performance rates can be enhanced after further optimization and verification of the Zeta converter simulations under conditions that are closer to the real ones.

4.4. MATLAB Coding

The MATLAB coding procedure can be explained in the following steps:

a. Using MATLAB to design the zeta converter.

b. Using MATLAB to find the transfer function (state space analysis) of the zeta circuit.

c. Design a PID controller using a genetic algorithm.

d. Check the stability of the system.

e. Check its performance with the transfer function of the zeta converter in MATLAB.

After obtaining satisfactory results, check them in Simulink MATLAB.

5. Simulation Results

The simulation of the Zeta converter is carried out in MATLAB Simulink. It is to calculate its transfer and state-space analysis (SSA) to assess the system dynamics. Analysis of system stability is then done, resulting in the design of an optimized PID controller using a Genetic Algorithm (GA). This process also validates the functionality of the transferred data.

The Zeta converter is modeled in the form of a Simulink block, and the parameters of the PID controller are calculated with the help of the GA-based optimization methodology, which presupposes the use of predetermined system parameters. Performance assessment is done by recording the resulting PID parameters.

The voltage response is shown in Fig. 9 and the input voltage is supplied as 18 V. In its findings, a measurable increase in voltages and a proven negligible ripple is obtained as the voltage resonances at 0.022 mV, resulting in 0.022 V.

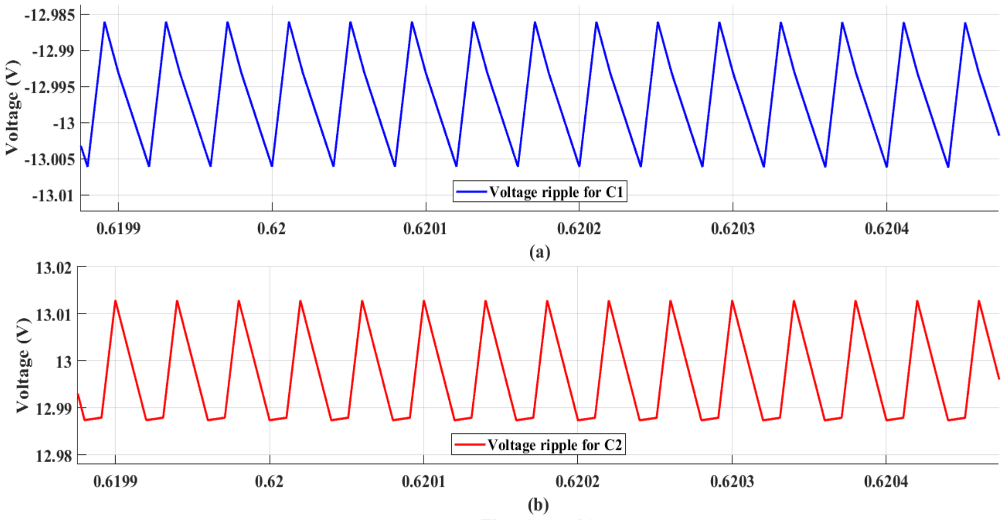


Fig. 9. Voltage ripple for: (a) C_1 and (b) C_2

Fig. 10 shows the simulated converter's response in terms of the current output of the Zeta converter. The converter with an input voltage of 18 V produced an output voltage of 13.01 V. The ripple that both inductors (IrippleL1 and IrippleL2) are measured to be around 1.561 x 10 (-1) A, which shows similar and contiguous ripple current in both inductors.

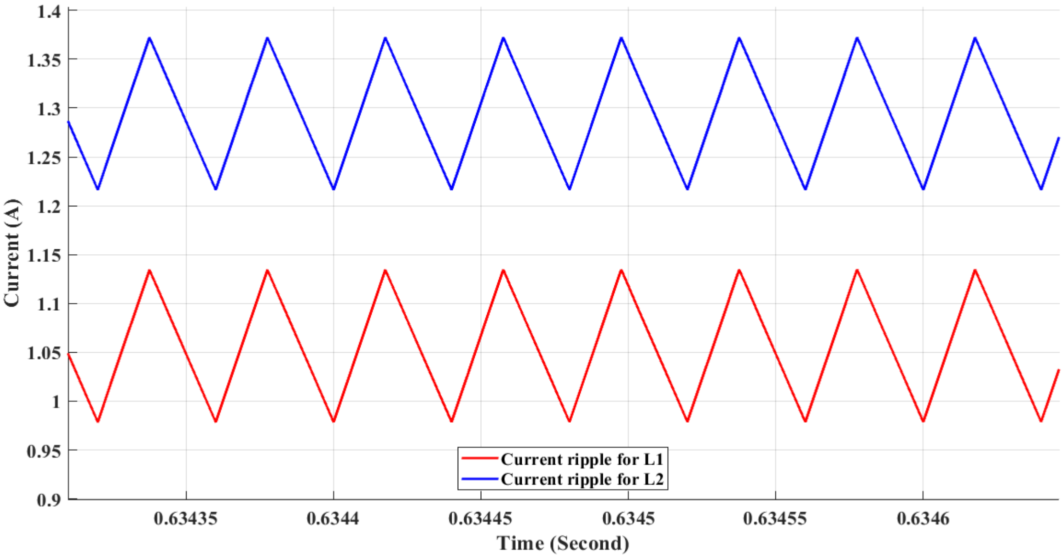


Fig. 10. Current ripple for L_1 and L_2

Fig. 11 indicates all electrical properties of the converter, including input voltages, output voltages, input currents, output current, inductor current ripple, capacitor voltages ripple, and switch switching behavior of the PWM-controlled switch.

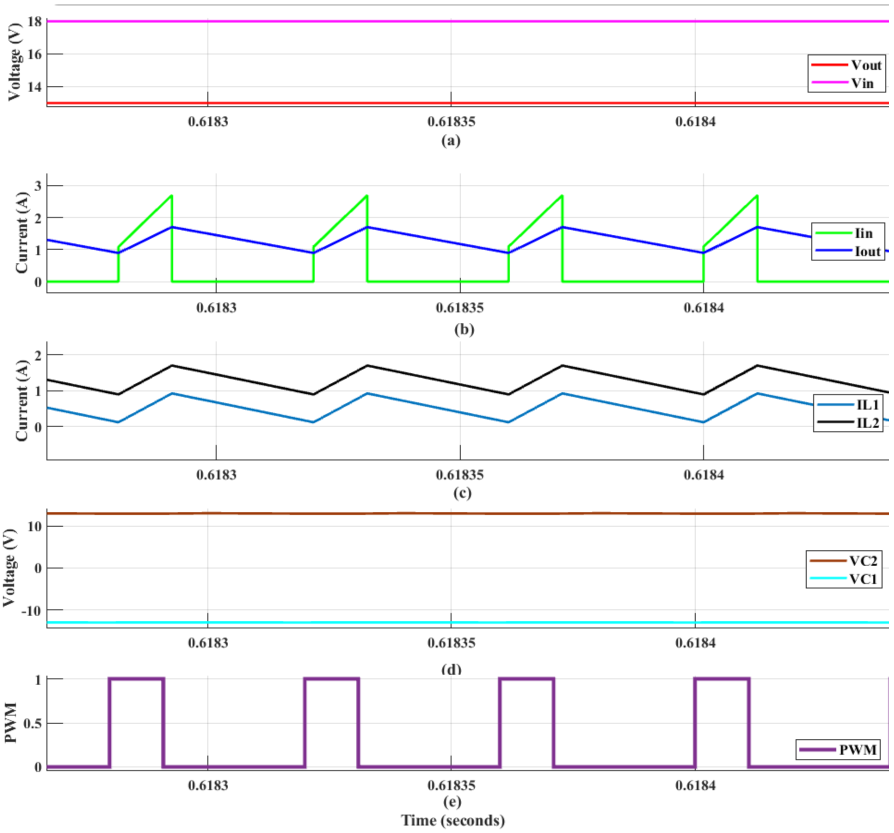


Fig. 11. (a) Input and output voltage; (b) Input and output current; (c) Current ripple across the inductor; and (d) Voltage ripple across the capacitor and switch (PWM) of the zeta converter

The Zeta converter is controlled with Pulse Width Modulation. The amount of the current flowing in the circuit depended upon opening and closing the PWM switch: when the latter is closed, current flows in the circuit; when the switch is opened, the input current of the converter is 0 A.

6. Conclusion

This paper proposes a control technique, which is to reduce the amount of voltage ripple and peak overshoot under transient conditions. To find the optimal parameters of the PID controller of the Zeta converter, the Genetic Algorithm (GA)-based optimization method is used. MATLAB identified the converter and modeled and simulated it in continuous conduction mode and analyzed its performance in detail.

The findings indicate that the proposed GA-based PID controller has the potential to reduce the output voltage states of lag and peak overshoots of the open-loop system significantly. The Zeta converter can sustain a controlled output voltage of about 13 V, with changes in input voltage of the photovoltaic (PV) module and the load parameters. Moreover, the system is subjected to controlled changes in irradiance and temperature, which enabled the study to certify the system to be robust.

The suggested control algorithm succeeds in providing a stable 13 V DC output at a dedicated laboratory setting. A further evaluation of the system on real-life environmental changes can be done, such as changes in temperature and dynamic operating environments. Additionally, the converter can be characterized across a wide range of DC loads with different load resistances, allowing for an assessment of its dynamic response and error compensation capabilities. Other optimization algorithms may be investigated as well to maximize the performance of the systems further.

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