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Comparative Analysis of Conventional and Metaheuristic-Tuned PI Controllers for PV-Powered SEPIC Converter

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ABSTRACT: In modern years, solar energy has developed as the leading Renewable Energy Source (RES) and is widely utilized across various applications. Photovoltaic (PV) system built rapidly when compared with other conventional electrical plants because of its cost saving, less maintenance, ease of installation and long-term investment. Therefore, this research focuses on a PV system powered by Single Ended Primary Inductor Converter (SEPIC) regulated using Proportional Integral (PI) controller optimized through metaheuristic-algorithm. The proposed SEPIC converter step-up and step down the input voltage with same polarity to produce a stable output with higher efficiency and better performance. In order to normalize the output voltage from the converter, PI controller is applied by eliminating steady state error. The error signal fed to Pulse Width Modulation Generator (PWM) which generates pulses to attain high efficiency. The performance of PI is enhanced using a Grey Wolf Optimized (GWO)-based method, where the metaheuristic algorithm by tuning the PI parameters to solve optimization challenges in the system, resulting in superior performance effortlessly compared to the conventional PI controller. Simulation results obtained through MATLAB demonstrates superior performance in maintaining stable outputs of the system. The proposed converter achieved higher efficiency of 94% compared to other DC-DC converters. The proposed GWO achieves less rising and settling time as $0.04s\ and\ 0.1s$ compared to PI.

Key words: Photovoltaic, SEPIC converter, PI controller, GWO-PI algorithm, PWM generator

1. Introduction

In recent days Photovoltaic energy resource is most widely used technology compared to other (RES) such as, wind, hydro and biomass [1, 2]. The PV holds special importance owing to less maintenance, minor service prices, dependable, soundless as well as very humble to install. The developments in PV technology, have faster the acceptance of solar power in domestic, industrial, and transport areas.[3] The active price of electricity for solar PV structures is prominently partial by the act of power conditioning unit [4]. Even though it has drawback of low conversion proficiency and dependence on atmospheric conditions [5]. As a consequence, power electronic component is essential for boosting the PV voltage.

To address the limitations of PV and achieve higher output voltage, various DC-DC converters like boost, buck, buck-boost, cuk are commonly employed [6]. Boost converter efficiently step-up the voltage which has fast dynamic response, simple structure, and highly robust against disturbances. However, it has less efficiency and slow transient response. [7-8] Buck converters is widely designed for its greater efficiency and simplicity of control where it operates on both continuous and discontinuous mode. It seems difficulty, switching sound and generate heat during operation. The buck-boost converter makes rise or fall the magnitude of the input voltage by modest circuit and control loops, as it is unable to produce maximum efficiency. Cuk converter is step-up or step-down converter down voltages, which has less count of components, reduced conduction loss. Although it has more power loss, output voltage chattering.

The converters stated above, exhibits some break of operation, thus to overcome those drawbacks in the existing converters, in this work implemented a SEPIC converter for enhancing voltage level, improved efficiency, voltage versatility and a steady output voltage.

Moreover, the controller is essential for to regulate the voltage output. In [9] PI controller sustains speed transient response, easiness and capability to produce outstanding stable voltage, widespread major feature from other voltage controls. [10] Because of its ease of tuning, it is moderately simple operating logic, and precise empathetic of its act limitations. Thus, the proper tuning is a challenge for the controller. Similarly the controller has overshoot, system error etc. In order to overcome such abnormalities optimized algorithm is applicable to maintain parameter performance.

Algorithm	Advantages	Disadvantages
Particle Swarm Optimization Algorithm(PSO) [11]	It is implemented in digital and analog form and it does not require a brief mathematical explanation with fewer parameters.	It is cosmic and compound while allocating high dimensional spaces. Leads to weaker local search capability
Grasshopper Optimization Algorithm(GOA)[12]	It is easy to develop and implement and obtain good solution to problems.	It exist slow convergence speed and prone to getting stuck in local optima.
Whale Optimization Algorithm(WOA)[13]	It is cost effectiveness, leads to faster task completion and increased efficiency.	Low convergence speed, easily falls into local optimal value.

Table 1 shows the various types of algorithms according to their drawbacks and benefits. Among all of them GWO-PI one of the recently developed metaheuristic algorithm which is suited for optimal tuning of PI parameters. It simulates the social pyramid and hunting strategies of grey wolves to solve optimization problems as it is faster convergence, robustness and minimal need for gain adjustments.

2. Recent Works

Reza Asgarnia *et al* (2023) [14] have proposed novel DC–DC converter with SEPIC soft-switch for extraordinary voltage gain. The converter confirming diodes off in Zero Current Switching (ZCS) conditions, and rejects reverse recovery losses. Nevertheless, the quantity of devices applied is extensive, causing a major rise in loss and price. Also, using several components is the weakness of this converter.

Ahmed Shawky *et al* (2024) [15] have introduced grid-connected SEPIC variance mode inverter for improving efficiency by hybrid Demilitarized Zone (DMS), Zero Voltage Switching(ZVS), and Pulse Width Modulation(PWM) with in-depth mathematical model. Simultaneously five counts of buck-boost converter topologies are supported and equated to progress a three-phase DMI for grid-connected applications. However, the deviation and control scheme need more improvement to empower further efficient power conversion across numerous tasks.

R. Dhanasekar *et al* (2024) [16] have implemented Permanent Magnet DC Motor (PMDC) performance enhancement with SEPIC converter over high-order downhill surface. It is works in low ripple current applications and most of renewable sources, and proposes Proportional derivative integral sliding surface (PIDSS) for a PMDC motor. The system is applicable for renewable energy systems, medical devices, industrial automation, electric vehicles, and so on. Even though challenges in tuning the parameters, physical clarity reduction and execution difficulty takes place.

Binxin Zhu *et al* (2023) [17] have developed family of coat circuit with high step-up SEPIC converters which has less input current ripples and easy to control. The converter has the foremost weaknesses of complex structure and challenging appliance, SEPIC converter is most probable in industrial applications corresponding PV power generation and FC systems. Nonetheless, active switches distressed high voltage stress and low conversion efficiency.

K S Kavin *et al* (2023) [18] have proposed SEPIC converter for PV based PMBLDC in Electric Vehicles (EV).The converter associated with BLDC through inverters where its switching is controlled by PI controllers. The specialization is, it supplies power from grid to vehicles through converter during night time. Although it is cost free and simple design results with less efficiency.

3. Proposed System Description

To maintain better efficiency and to achieve stable output voltage, the proposed system incorporates SEPIC converter with metaheuristic tuned PI controllers.

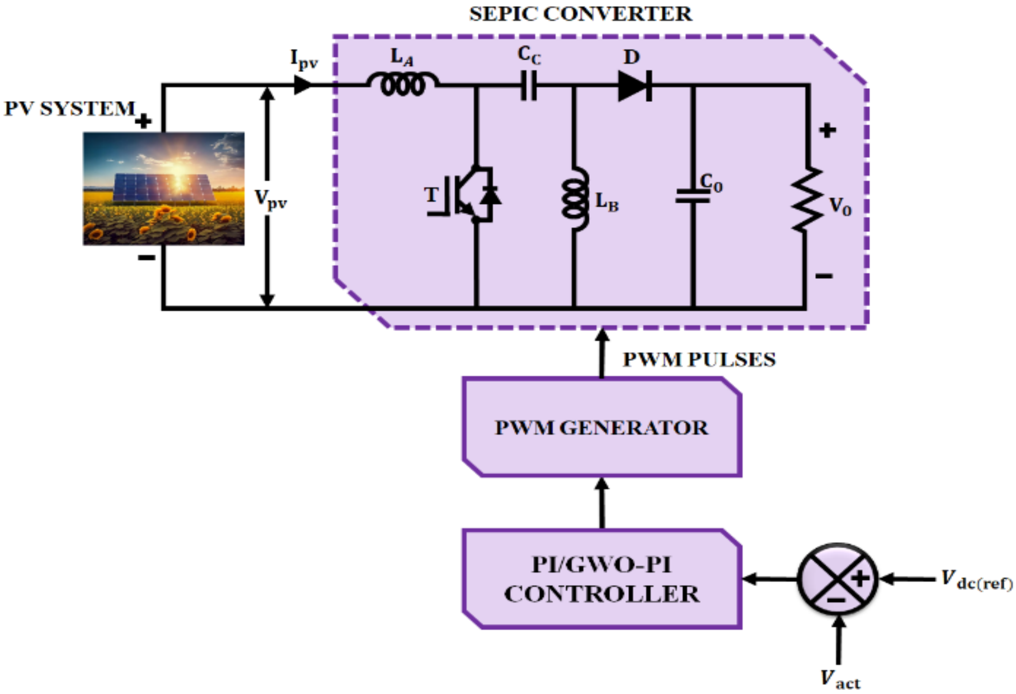


Figure 1: *Proposed Block diagram of PI-tuned SEPIC*

The PV system is utilized as major source, where the low DC voltage from PV is boosted using SEPIC converter. For regulation of converter, the research incorporates PI and GWO-PI controller. The PI controller compares the reference voltage (V_{dc}) with an actual voltage (V_{act}) and the error signal is fed to PWM generator for generation of pulses. In order to attain improved response, the PI controller parameters are tuned utilizing GWO algorithm which mimics the hunting strategy of grey wolves. As a consequence, improved converter performance is accomplished. Henceforth, stabilized DC supply is fed to load for various applications.

3.1 PV system

PV system conventionally converts solar energy into electric energy using unified several apparatuses especially PV module (solar panels) for conversion of photons into DC electricity. The corresponding circuit of PV module is signified with a single diode to photo-generated current. Here the elements are mentioned as photo-generated current I_{ph}, diode current I_d, and module output current is I_{PV} shown in Figure.2

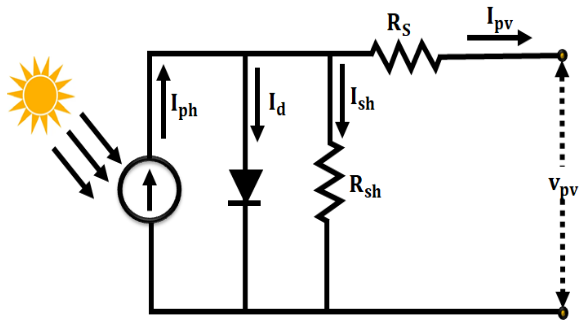


Figure 2: *Equivalent circuit for PV*

According to Kirchoff's Current Law (KCL), the output from PV module is derived in equation (1)

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

From the above equation

$$I_d = I_0 \left[exp \left(\frac{V_{PV} + I_{PV} \; R_s}{n_s V_T a} \right) - 1 \right] \tag{2}$$

I_0 is the saturation current in diode, n_s represent the amount of series cells in the module, V_{pv} is the output voltage from the module, R_{sh} and R_S are the equivalent series and shunt resistance and considered by equation (3).

$$V_T = \frac{kT}{q} \tag{3}$$

k is constant ,T is Kelvin temperature and q is the charge of electron. Thereby module's current leakage is termed as (4)

$$I_{sh} = \frac{V_{pv} + I_{pv} \, R_S}{R_{sh}} \tag{4}$$

From equation (1), (2) & (4), output from PV is derived to be :

$$I_{ph} = I_{pv} - I_0 \left[exp \left(\frac{V_{pv} + I_{pv} \, R_S}{n_s V_T a} \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_S}{R_{sh}} \tag{5}$$

Consequently to rise the voltage generated by PV system, SEPIC converter is introduced in this research, which is discussed below.

3.2 SEPIC Converter

SEPIC converter is a DC-DC converter applied in PV systems which is capable for step-up and step-down process, maintaining a stable output voltage. The polarity of output voltage will be same as input voltage compared to other converters. The current flowing from source to load takes the path through capacitor. Therefore adequate capacitance and current handling capacity is required .The circuit diagram for SEPIC is shown in Figure.3

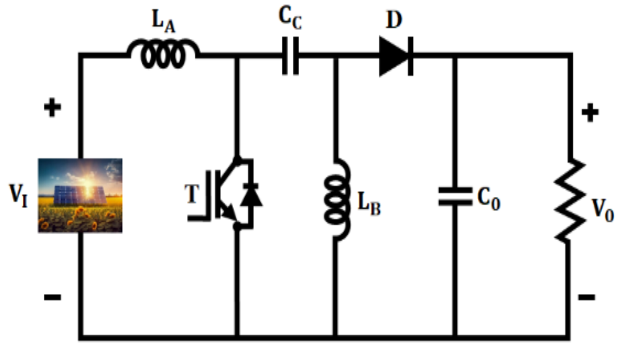


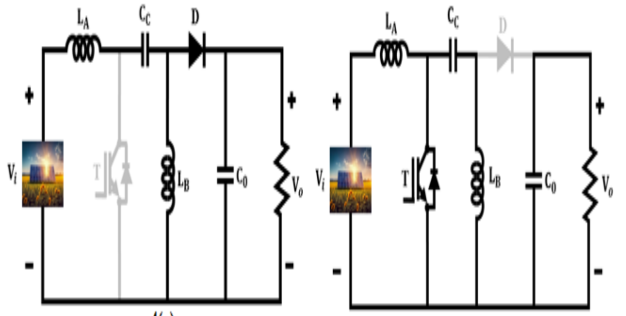
Figure 3: *Circuit of SEPIC Converter*

Consider capacitors C_c C_o, diode D , inductors as L_A , L_B and switch s ,Whereas input voltage is considered as V_i and output voltage is V_o. The modes of operation is resultant by two modes as reversed biased and forward biased condition.

3.2.1 Modes of Operation

Mode 1 (Forward Biased Mode):

Whenever the switch s, in OFF state diode D, operates as in forward biased condition where the capacitor C_c gets charged by the inductor L_A. Thereby passing the energy to the load through inductor L_B. The circuit for mode 1 is given in Figure. 4(a)



4(a) 4(b)

Mode 2 (Reversed Biased Mode):

The diode D operates as reverse biased condition when the switch s, in ON state. Here the component C_c discharges and therefore the inductors L_A and L_B gets charged by the voltage V_i and V_o respectively. The circuit for mode 2 is shown in Figure 4 (b)

The voltage factor is given by,

$$\frac{V_o}{V_i} = \frac{D}{1-D} \tag{6}$$

Normal voltage across the inductor L_A has given by,

$$L_A \frac{diL_1}{d_t} = DV_{i(ON)} + (1-D)V_{L_{A(OFF)}} \tag{7}$$

Voltage during ON and OFF state,

$$V_{L_{A(ON)}} = V_i \tag{8}$$

$$V_{LA(OFF)} = V_i - V_{C_c} \tag{9}$$

Similarly normal voltage across the inductor L_B is written as:

$$L_B \frac{di}{dt} L_B = D_{L_{B(ON)}} + (1-D)L_{B(OFF)} \tag{10}$$

Voltage during ON and OFF state,

$$V_{L_B(ON)} = V_{C_o} - V_{C_c} \tag{11}$$

$$V_{L_B(OFF)} = V_i - V_{Cc} \tag{12}$$

From equation (7), (8), (9)

$$V_1 = V_i \left(\frac{1+D}{1-D}\right) \tag{13}$$

Therefore V_2 & V_3 is written by

$$V_2 = V_3 = V_i \left(\frac{1}{1-D}\right) \tag{14}$$

$$V_o = V_1 + V_2 \tag{15}$$

From equation (15)

$$\frac{V_o}{V_i} = \left(\frac{2+D}{1-D}\right) \tag{16}$$

The converter gain is achieved by equation (12). This proposed work reduces ripple current and increases voltage gain, less voltage stress compared to other topology and it depends on inverse form.

$$\frac{V_0}{V_i} = \left(\frac{n+D}{1-D}\right) \tag{17}$$

The inductor L is selected depending up on the peak level of current source. Let the highest ripple current of inductor to be thirty percentage the inductor value L is chosen by the succeeding equation.

$$L = \left(\frac{V_i D}{2\Delta i_{L_1} f_{sw}}\right) \tag{18}$$

The capacitor's value depend on the load current I_o. Letting voltage ripple to 0.01% and assume that the capacitors C_C, C_O have same capacitance C, and calculated by equations (14) and (16)

$$C_f = \left(\frac{C_1 C_2}{C_1 + C_2}\right) \tag{19}$$

$$\Delta V = \frac{I_0}{f_{swc}} \tag{20}$$

$$C_f = \frac{P_o}{2\Pi f_{ac} V_0 \Delta V_o} \tag{21}$$

For optimal regulation of converter controller is essential which is discussed as follows:

3.2.2 PI Controller

PI controller is a closed loop feedback control system. The necessity of these controller is tuning parameters to progress chosen result. The proportional part of controller increases error along with proportional gain (K_P) and integral gain (K_i) which are to be optimized by the optimization technique.

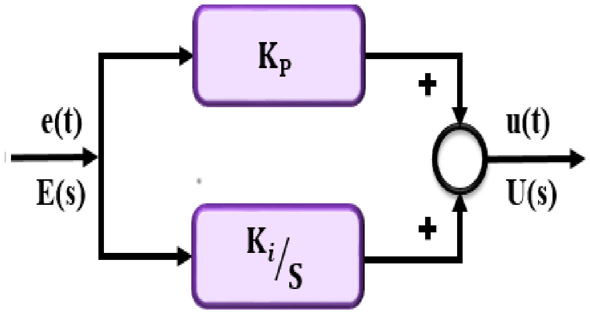


Figure 5: *Block diagram of PI controller*

$$U(t) = K_p \left[e(t) + \frac{1}{T_1} \int_0^t e(\tau)\, d(\tau) \right] \quad (22)$$

From the above stated equation $U(t)$ and $e(t)$ represents the error signal K_p and T_i are tuned constrains for proportional action. The corresponding equation is defined by

$$K(s) = K_p \left[1 + \frac{1}{T_i(s)} \right] \quad (23)$$

To attain better performance, the parameters of PI controller are fine-tuned utilizing GWO algorithm.

3.2.3 GWO- PI Controller

GWO is a nature inspired metaheuristic algorithm built on killing behavior of wolves. The method of hunting food by grey wolves is: looking for food, surrounding the food, hunting and attacking the food and they remain within a pack or group. The wolves are ranked in the group as alpha (α), beta (β), delta δ and omega ω respectively.

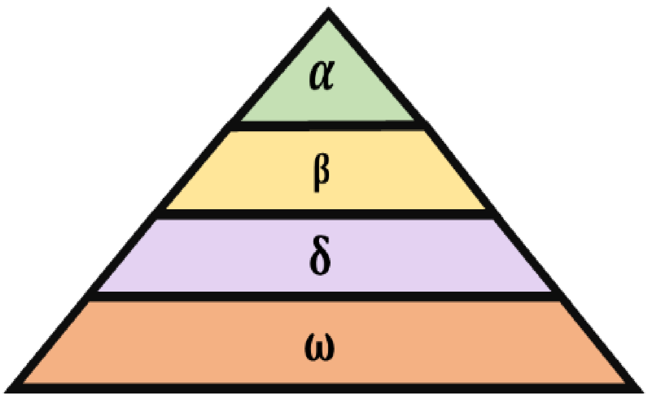


Figure 6: *Grey Wolf Hierarchy*

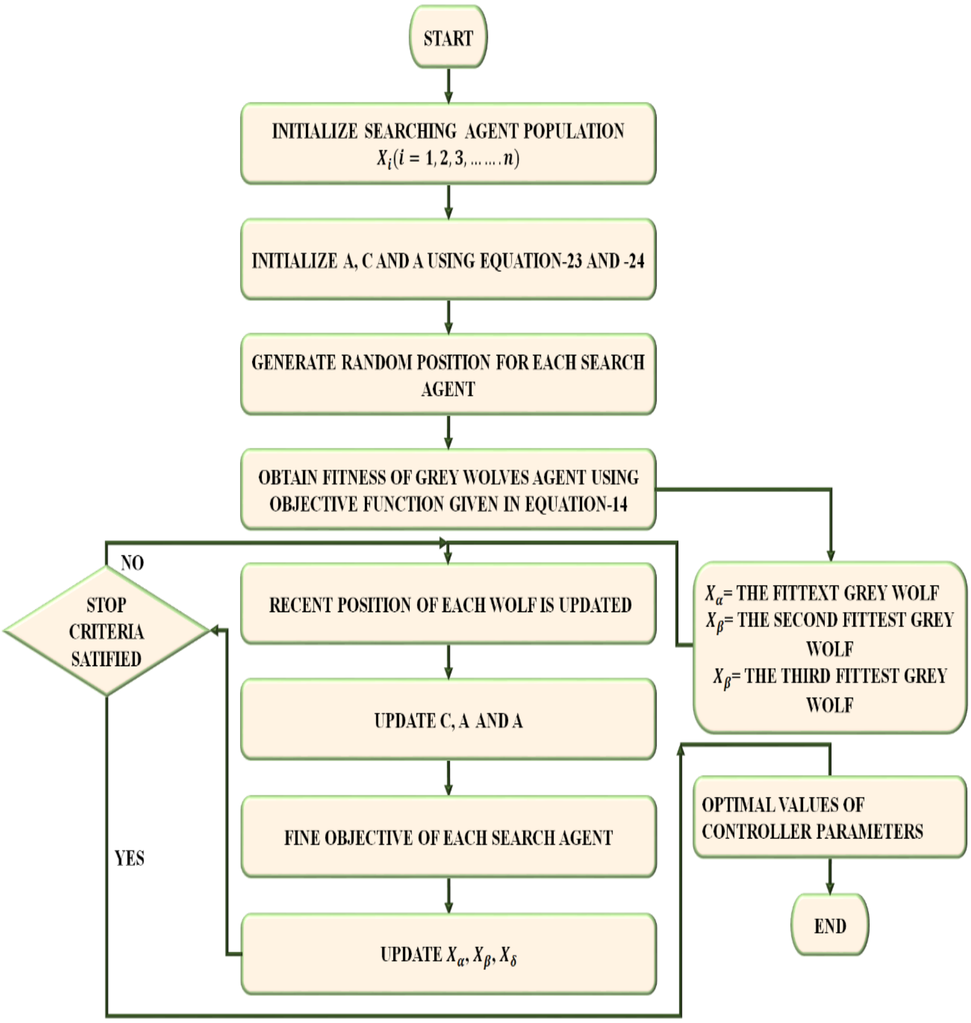


Figure 7: *Flowchart for GWO algorithm*

When the hunting process begins they encircle the prey which is expressed in mathematical expression. The following equations enlighten the surrounding of prey as:

$$\vec{D} = \left|\vec{C} \cdot \vec{X}_{p(t)} - \vec{X}_{(t)}\right| \tag{24}$$

$$\vec{X}_{(t+1)} = \left|\vec{X}_{p(t)} - \vec{A} \cdot \vec{D}\right| \tag{25}$$

The grey wolf position is denoted by $\vec{X}$ and $\vec{X}_p$ is the vector position of prey

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r}_1 - \vec{a} \tag{26}$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{27}$$

The initial hunting process is known and the exact place of prey and current location of wolves is determined by the following equations.

$$\vec{D}_{\propto} = \left|\vec{C}_1 \cdot \vec{X}_{\alpha} - \vec{X}\right| \tag{28}$$

$$\vec{D}_{\beta} = \left|\vec{C}_2 \cdot \vec{X}_{\beta} - \vec{X}\right| \tag{29}$$

$$\vec{D}_{\delta} = \left|\vec{C}_3 \cdot \vec{X}_{\delta} - \vec{X}\right| \tag{30}$$

$$\vec{X}_1 = \vec{X}_{\propto} - \vec{A}_1 \cdot \left(\vec{D}_{\alpha}\right) \tag{31}$$

Similarly for $\vec{X}_2$, $\vec{X}_3$ follows equation and the best location of prey and current location of wolves is taken as:

$$\vec{X}_{(t+1)} = \frac{\vec{X}_1+\vec{X}_2+\vec{X}_3}{3} \tag{32}$$

The flowchart in Figure.7 explains the hunting process of GWO. Therefore the parameters are fine-tuned and a good performance is achieved and it is established by the following discussion.

4. Results and discussion

This section discusses an overall results achieved from MATLAB/Simulink of proposed system. Moreover, the analysis is made over with the traditional methods to expose the significance of proposed work. Following Table 2 illuminates parameter specification for the proposed topology using MATLAB platform.

Table 2: *Parameter specification*

Parameter	Rating
PV System	
Rated Power	$7kW$
Open Circuit Voltage	$37.25V$
Short Circuit Current	$8.95A$
No. of panels connected in series	5
No. of panels connected in parallel	2
Switching frequency	$10kHz$
SEPIC converter	
Switching frequency	$10kHz$
Inductor L_A, L_B	$4.7mH$
Capacitor C_C	$22\mu F$
Capacitor C_O	$2200\mu F$

Case 1: Constant Condition

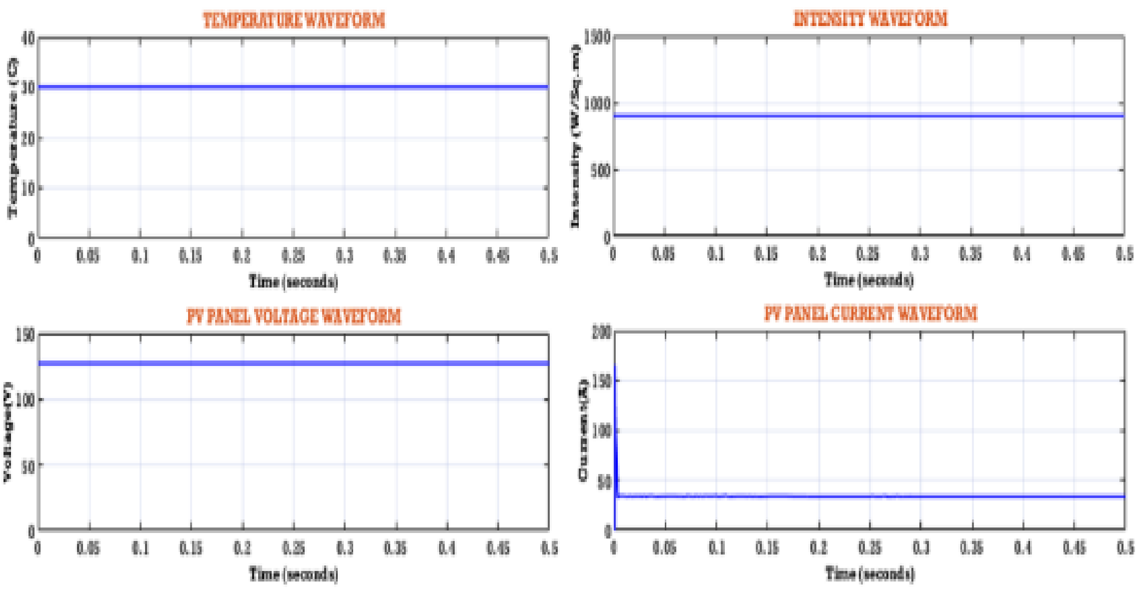


Figure 8: *PV panel waveform under case 1*

Figure 8 shows PV panel waveform under Case 1, showing the temperature and solar intensity of $30°C$ and $900(W/sq.m)$. The obtained voltage and current waveform showing $140\,V$ and $40A$, where the temperature and intensity is maintained constantly.

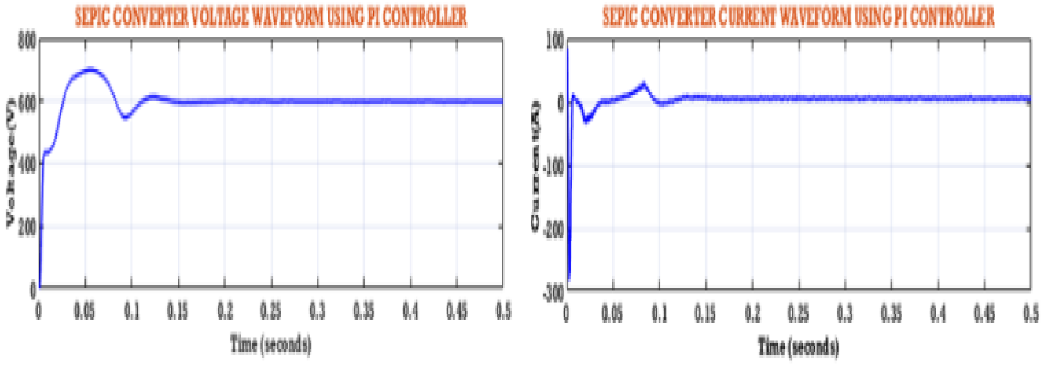


Figure 9: *SEPIC output waveform using PI*

Figure 9 illustrates the output voltage and current waveforms of the converter using a PI controller under Case 1. The output reaches $600\,V$ *and* $8.8\,A$, with a settling time of $0.17\,s$ and a rise time of $0.05\,s$.

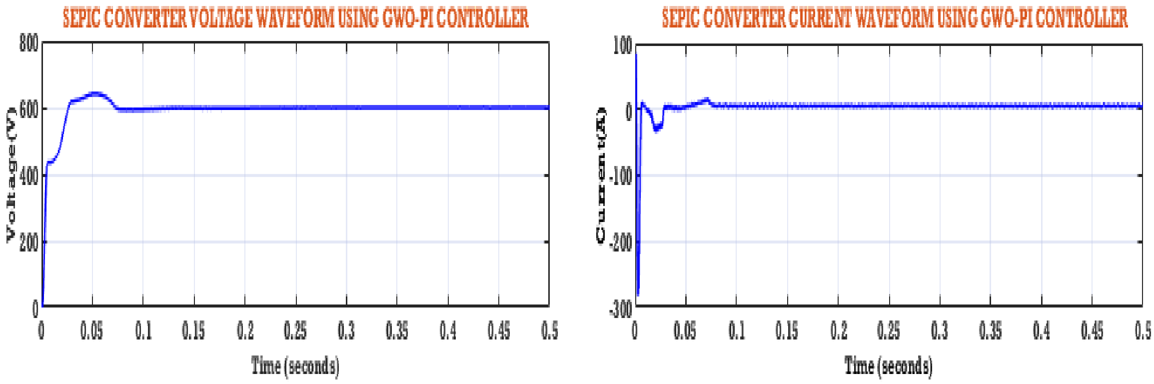


Figure 10: *Output waveform of SEPIC using GWO-PI*

Figure 10 shows the output voltage and current waveforms of converter using GWO-PI under Case 1.The output in the waveform attains $600V$ and $8.8A$, with $0.04s$ of rise time and $0.1\,s$ of settling time.

CASE 2: Varying Condition

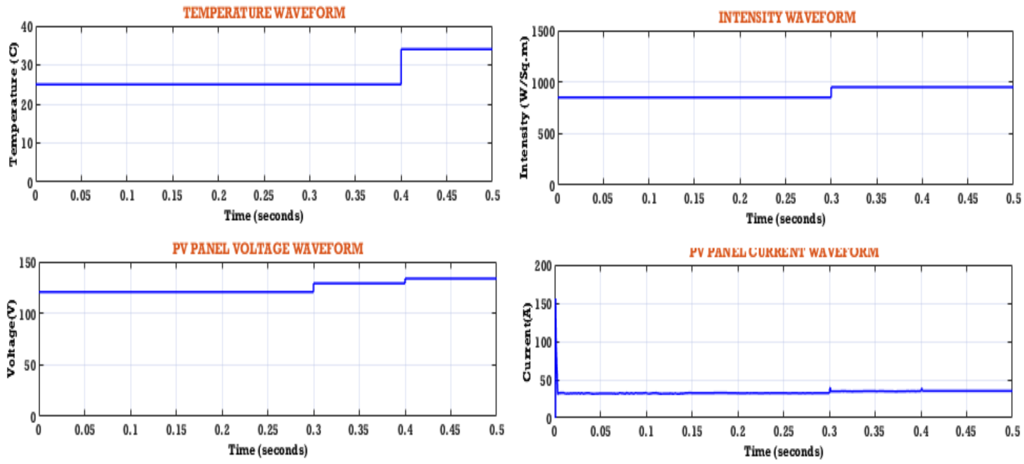


Figure 11: *PV panel voltage and current waveform*

Figure 11 represents PV panel waveform under Case 2: The temperature and intensity varies from $25°C$ and $900(W/sq.m)$ to $35°C$ and $1000(W/sq.m)$. The voltage and current waveform showing $125V$ and $40A$, after $0.4s$ the input voltage and current varies to $140V$ and $45A$ respectively.

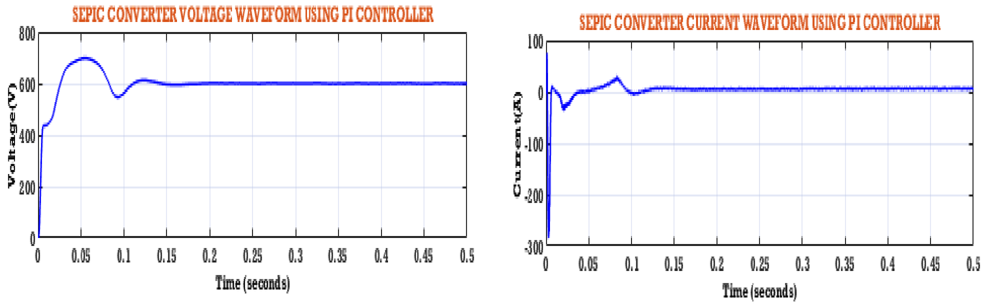


Figure 12: *SEPIC voltage and current waveform using PI*

Figure 12 shows the waveform of output voltage and current from converter using PI under Case 2: The achieved voltage and current is $600V$ and $8.8A$ with rise time of $0.05s$ and settling time of $0.17s$ correspondingly.

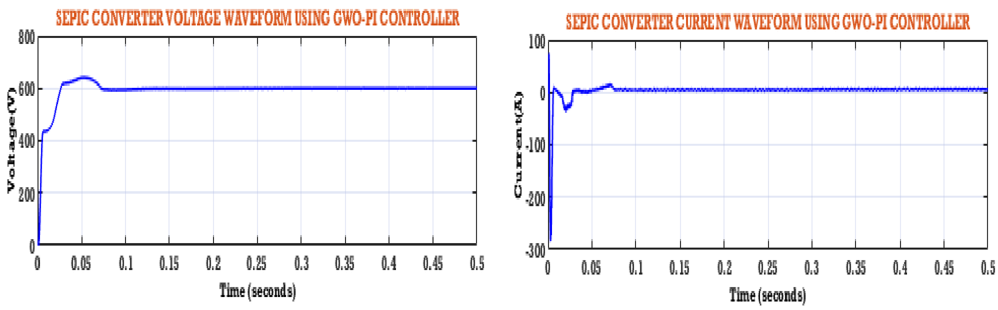


Figure 13: *SEPIC voltage and current waveform using GWO-PI*

Figure 13 illustrates the output voltage and current waveform from the converter using GWO-PI under Case 2. In this waveform the output reaches $600V$ and $8.8A$ with a rise time of $0.1s$ and settling time of $0.04s$.

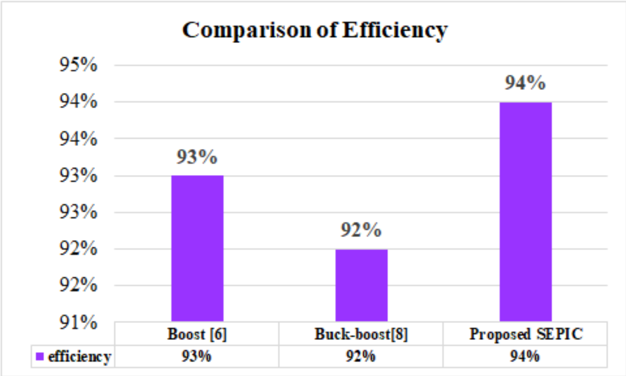


Figure 14: *Efficiency comparison*

Figure 14 shows the efficiency comparison between converters.The proposed SEPIC converter achieved enhanced efficiency of 94% compared to other converters namely boost, buck-boost, perhaps 92% *and* 93% respectively.

Table 3: *Comparative analysis of control approaches*

Control Approach	Rise Time (t_r)	Settling Time (t_s)
PI	0.05	0.17
GWO-PI	0.04	0.1

Table 3. shows the control approach of rising and settling time of PI controllers and GWO-PI. The PI controller regulates the output with steady state error. The rise time of PI is $0.05s$ and settling time is $0.17s$.Compared to GWO, PI is not suitable for complex systems which has high overshoot and high sensitivity to control gains. For achieving better performance PI needs to optimize its parameters. GWO optimizes the PI parameters that enhance overall efficiency with reduced rise time of $0.04s$ and settling time $0.1s$ .GWO-PI is more robust and results in greater performance compared with PI controller.

5. Conclusion

The proposed research presents a metaheuristic-tuned PI for PV powered by SEPIC converter. The proposed converter steps-up and step-down the input voltage with same polarity, and provides a stable output, also achieved greater efficiency. The proposed converter is operated in both constant and varying conditions which gives a higher voltage gain. The proposed GWO-PI solves various optimization problems by tuning the PI parameters. Furthermore, the proposed work is simulated using MATLAB and results obtained shows that the proposed converter has enhanced efficiency of 94%. In comparison with PI controller GWO-PI results with improved settling time of 0.1s offering stabilized DC link voltage. Thus the performance of GWO-PI is excellent when compared with PI. Henceforth the overall research subsidizes to the advancement of enhancing efficiency of proposed converter and utilization of RES, meanwhile the performance of converter is superior compared to existing. The outstanding performance of the proposed converter has the capability to boost input voltage, highly effective and a hopeful choice of various applications.

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