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Paper Authors **Jagadeesh.K 1,* Ch.Chengaiah2**

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Performance Analysis of PV-based DC-DC Converters for EV Charging Applications

Jagadeesh.K [1,*] Ch.Chengaiah[2]

Department of EEE, Sri Venkateswara University College of Engineering, Sri Venkateswara University, Tirupati, Email-ID: Svujagadeeshk@gmail.com

Abstract:

Energy conversion requires efficient converter systems, which can convert AC to DC or DC to AC. Power electronic converters play a key role in photovoltaic systems integrated with energy storage systems like batteries. They enable efficient charging and discharging, voltage regulation, and synchronization with the grid. The switching of power electronics devices plays a significant role in DC to DC-conversion. The grey wolf optimization (GWO) metaheuristic algorithm generates duty ratios, and a PWM pulse generator generates triggering pulses. This work analyzes the ZETA converter with PV as input and EV as the application. In a MATLAB environment, a 5-by-5 PV system with Buck-Boost, SEPIC converter, and Zeta converter are simulated. The minimal output ripples support the smooth and efficient charging of EV batteries, promoting the use of clean energy.

Keywords: Solar PV system, DC-DC converters, grey wolf optimisation (GWO), Electrical Vehicles, optimisation.

Introduction:

Power electronic converters play a vital in photovoltaic (PV) applications by aiding efficient conversion, control, and management of the electrical energy produced by solar panels [1,2]. Solar modules generate different voltage and current levels depending on environmental conditions such as sunlight and temperature. Solar module power is typically in the form of direct current (DC) at low voltage levels [3]. Grid-connected inverters, or power electronic converters, convert the direct current generated by the solar modules into grid-compatible alternating current (AC)[4]. These inverters also provide synchronization, voltage regulation, and control functions to ensure safe and reliable integration of photovoltaic systems into the grid. Power electronic converters in grid-connected PV systems can also provide reactive power control. By controlling the inverter power, you can regulate the flow of reactive power into and out of the grid [5]. Power electronic converters play a key role in photovoltaic systems that are integrated with energy storage systems such as batteries. These converters allow efficient charging and discharging of batteries, voltage regulation, and synchronization with the grid [9]. Overall, power electronic converters play a critical role in PV applications by optimizing power generation, enabling grid integration, facilitating energy storage, and ensuring system protection and security.

A brief review of various converters used for EV charging applications is discussed and the theoretical aspects of different DC-DC converters are discussed. The design and simulations of the interleaved boost converter for extraction of maximum power from the PV system show that the power output has improved by 16% when compared with the conventional boost converter [12]. The use of a boost converter with a resonant circuit has smooth switching and less switching losses when compared to a conventional boost converter [13]. The use of a modified P&O technique to enhance the power output from a solar PV system using a SEPIC Converter enhances the power output when compared to the conventional P&O method [14]. Different types of PV configurations can be applied for the PV system in order to get the desired output [15]. A new variable-step size P&O algorithm has been adopted to improve solar power generation efficiency. The algorithm uses a fixed step size when the distance between the working point and maximum power point is far. When the working point crosses the peak point, the step size is reduced by half until the final step is smaller than the set threshold, and the operating point stabilizes at the maximum power point. The proposed method has been tested through simulations, which show that it reduces the tracking time by 0.08 seconds and eliminates power oscillation near the maximum power point. This is a significant improvement compared to the fixed-step P&O algorithm [16].

DC – DC converters are mainly used in the conversion of DC voltage from one level to another level. They are broadly classified as Buck, Boost, Buck-Boost, Cuk, SEPIC, and ZETA converters. Buck converters steps the input voltage from a higher level to a lower level and is mainly used in charging applications. The voltage ripple and noise factors are high in this type of converter. Boost converter is used to boost the voltage from one level to a higher level this can be achieved by adjusting the duty ratio. In spite of the disadvantages like higher voltage ripple these converters find applications in lightning and charging applications. Buck-Boost converter has the advantages of both buck and boost converter which can increase or decrease the output voltage and also invert the output voltage. This converter is used in solar chargers, and USB applications. It has low voltage gain. Cuk converter is used for inverting output and is used in inverting applications. SEPIC is a single-ended primary inductance converter can step up or step down the voltage and can be realized by inserting a high pass filter in the middle of the boost converter and is used for constant current applications.

Operation of Buck-Boost Converter:

Buck – Boost converter is a combination of both buck and boost converters. The advantages of both buck and boost converters are embedded in the buck-boost converter. The advantage of using a buck/boost converter is that it can step up or down the input voltage, making it suitable for a wide range of applications. The buck-boost converter provides lower duty cycles and higher efficiency over a wide range of input and output voltages. Buck-boost converters are widely used in a variety of applications including battery-powered devices to extend battery life. These are also suitable for solar power systems to regulate voltage levels and maximize power output. Buck-boost converters are used in LED lighting systems to regulate voltage levels and maintain constant current. This converter can be used in applications where constant voltage is required.

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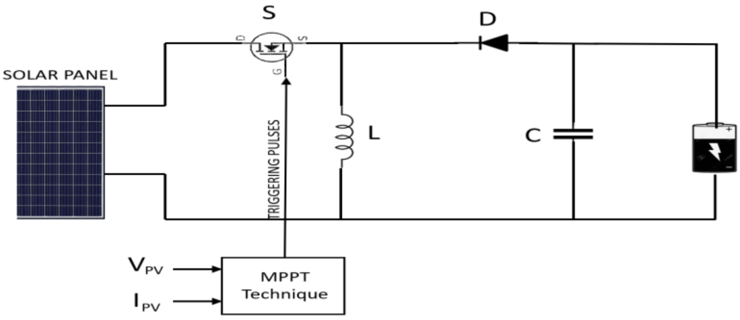

Fig. 1 Basic circuit diagram of Buck-Boost converter

When the switch (MOSFET) is turned on, the power supply current begins to flow through the switch, through the inductor, and back to the power supply, as shown in Fig.1.

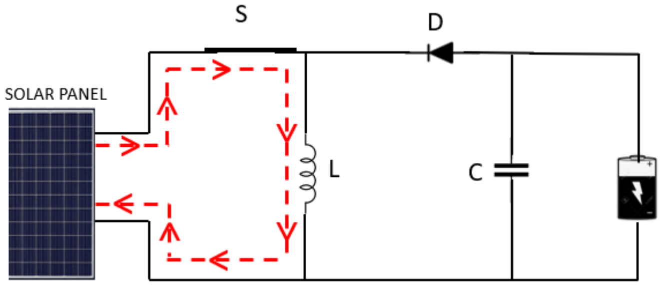

Fig. 2 Mode 1 operation of Buck-Boost converter

The diode (D) is reverse-biased and acts as an open switch, isolating the load from the supply current. When the power supply energizes the inductor, the inductor starts charging with the polarity shown in Fig.2.

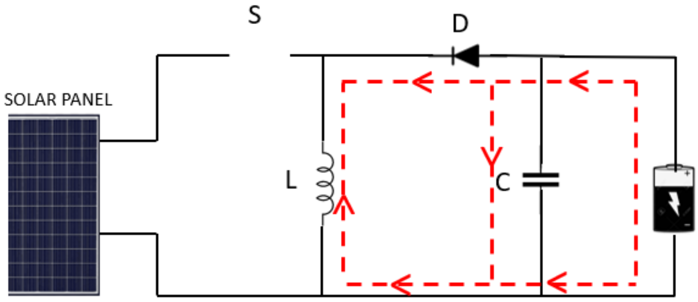

Fig. 3 Mode 2 operation of Buck-Boost converter

When the switch is off, the reduction in inductor current creates a negative voltage across the inductor. The current that flowed through the switch and inductor in the previous interval flows through the inductor, capacitor, load, diode, and back to the inductor as shown in Fig.3. The inductor continues to discharge and the inductor current decreases until the MOSFET turns on again in the next cycle.

$$V_o = \frac{D}{1-D} V_i \qquad [1]$$

Therefore, from the above equation (1), the output voltage depends on the duty cycle. If the duty cycle (D) is greater than 0. 5, the circuit operates as a boost converter or boost DC converter.

Operation of SEPIC Converter:

SEPIC is abbreviated as a single-ended primary inductance converter. It is a type of DC-DC converter that enables a DC voltage range on the input side and provides a stable voltage on the output side. This type of converter is very similar to buck-boost converters and Cuk converters which provide an output voltage greater than, less than, or equal to the input voltage.

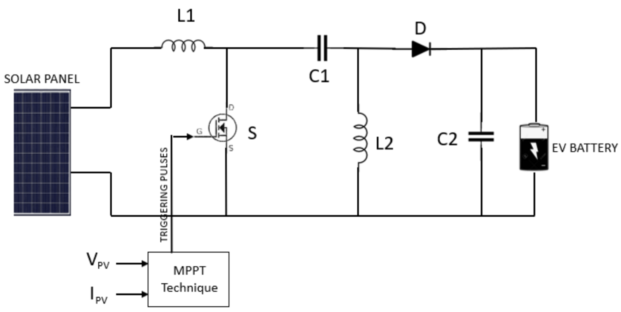

Fig. 4 Basic circuit diagram of SEPIC converter

The basic circuit diagram consists of a Switch “S”, two inductors (L_1, L_2), two capacitors (C_1, C_2), and one Diode. A switch is a semiconductor device, in the SEPIC converter generally a transistor (MOSFET, IGBT, or BJT) is used as shown in Fig.4. MOSFETs are preferred over IGBTs and BJTs in most DC/DC converters because of their high input impedance and low voltage drop.

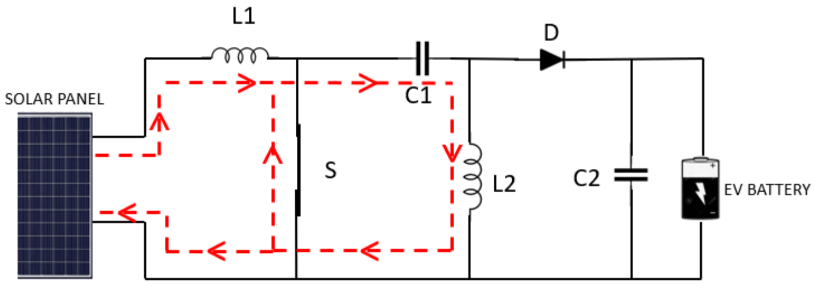

Fig. 5 Mode 1 operation of SEPIC Converter

Initially the switch “S” is closed and the current from the source will pass through the switch, inductor L_1, and back to the source as shown in Fig.5. This will cause an increase in the inductor's current, I_{L1}, which will start charging from the input source. During this charging process, the inductor's instantaneous voltage, V, will be approximately equal to the source voltage, V. Moreover, when the Switch “S” is on, the energy released by capacitor C1 will charge the inductor L_2. Through the Switch “S”, the capacitor C_1 will release its energy to the inductor L_2.

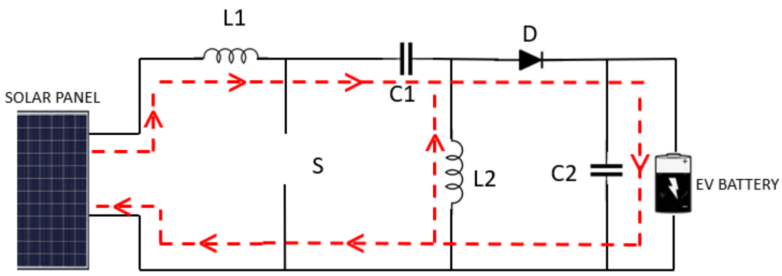

Fig. 6 Mode 2 operation of SEPIC Converter

After the Switch “S” is turned off, the inductor L_1 reverses polarity and discharges to capacitor C_1. The charged inductor L_2 then discharges, forward-biasing the diode and transferring energy to the load as shown in Fig. 6. When the Switch “S” is turned on again, the cycle repeats.

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Operation of ZETA Converter:

In general, the ZETA converter belongs to DC to DC converter family which converts unregulated DC to regulated DC. The purpose of the switch used in this converter is to regulate the amount of power flow through the load. This can be achieved by effectively utilizing the duty cycle. The circuit diagram of the ZETA converter is shown in Fig. 7.

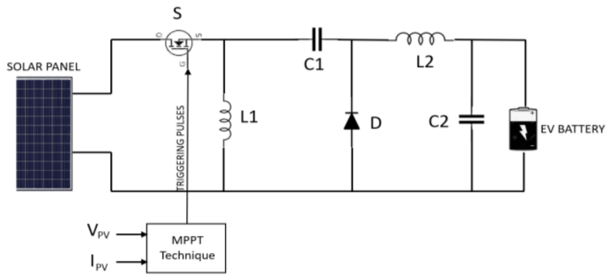

Fig. 7 Basic circuit diagram of Zeta converter

The circuit diagram consists of 2 inductor L_1 and L_2 respectively and two capacitor C_1 and C_2 respectively with a diode for freewheeling action. The capacitor acts as isolation between the source and the load. When the switch "S" is closed then the source current begins to flow through the switch, inductor L_1, and returns to the source. Therefore, inductor L_1 stores energy supplied by the supply with the polarity shown in Fig. 8.

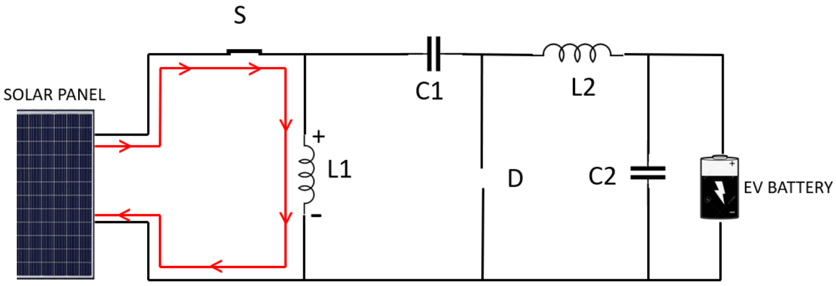

Fig. 8 Mode 1 operation of Zeta converter

When the triggering signal for the switch "S" is removed, the source current no longer flows through inductor L_1. Now the inductor L_1 starts discharging the stored energy with opposite polarity. Therefore, energy flows from inductor L_1 through the diode to capacitor C_1. Series capacitor C_1 starts charging with the energy provided by inductor L_1 Fig.9.

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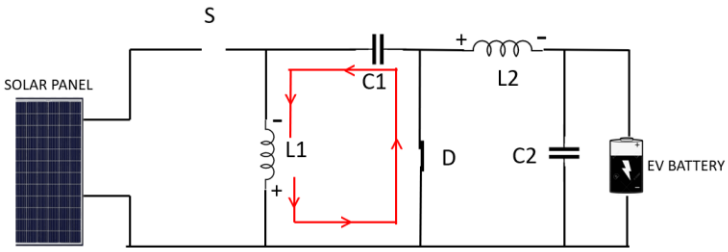

Fig. 9 Mode 2 operation of Zeta converter

When the switch is turned on again, the discharged inductor L_1 is charged from the source, as seen in mode 1. Also, in this state, capacitor C_1, which was charged in the previous mode, starts discharging through inductor L_2, the load, the source and back to capacitor C_1, as shown in Fig.10.

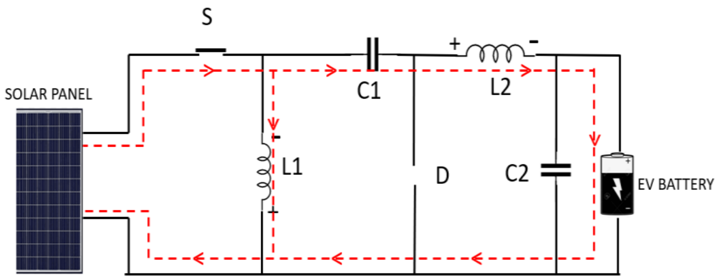

Fig. 10 Mode 3 operation of Zeta converter

Capacitor C_1 supplies its energy to inductor L_2 to charge it. Therefore, in this mode the load receives power and inductor L_2 is charged. H. Inductor L_1 reverses polarity and charges the discharged capacitor C_1 through the diode. At the same time, due to the sudden change in current, inductor L_2 also reverses polarity and starts delivering power to the load through the same diode as shown in Fig.11.

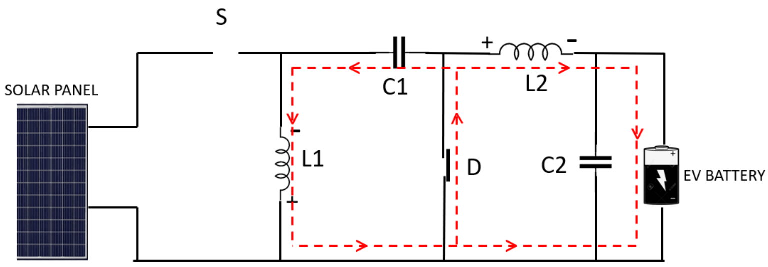

Fig. 11 Mode 4 operation of Zeta converter

From the above four modes of operation of the zeta converter, the following points can be drawn i.e. When the switch is on, inductors L_1 and L_2 are charged by the source and capacitor

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C_1, respectively. When the switch is in the off state, capacitor C_1 is charged by inductor L_1 and inductor L_2 supplies power to the load.

Grey Wolf Optimization Technique:

The switching or triggering pulses for the switches are given through the Grey Wolf optimisation algorithm.

GWO is a new novel-inspired heuristic algorithm based on the mimics' leadership hierarchy and hunting mechanism of grey wolves in nature developed by Mirjalili [18]. Four types of grey wolves such as alpha (α), beta (β), delta (δ), and omega (ω) are employed for simulating the leadership hierarchy. Further, the three key steps of hunting pointed for prey encircling prey, and attacking the prey are implemented.

Mathematical Modelling/formulation of GWO

The following are the major steps in mathematical formulation

Social Hierarchy of GWO

Considering the wolves α, β, δ in the algorithm α is considered to be the solution of best fit; followed by β and δ the second and third best solutions fit respectively. The 'ω' wolves follow α, β, and δ and the hunting in the GWO algorithm is guided by these three wolves as shown in fig 12.

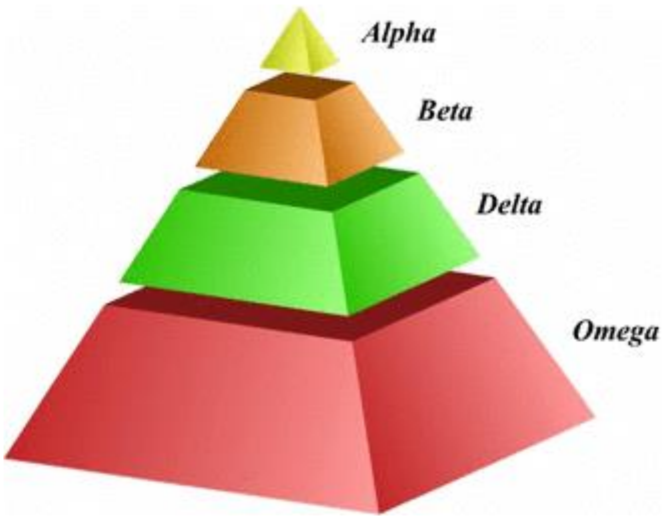

Fig. 12 social hierarchy of GWO

Grey wolves encircling prey

While hunting grey wolves' foremost encircling prey the encircling position [12] and represented as follows.

$$\vec{K} = |\vec{C} \cdot \vec{V_k}(it) - \vec{V}(it)| \quad (2)$$

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$$\vec{V}(it+1)=\vec{V_k}(it)-\vec{D}\cdot\vec{H} \quad (3)$$

where it is the current iteration, $\vec{V}$ and $\vec{V_k}$ denote the position vector of a grey wolf and its prey respectively. $\vec{C}$ and , $\vec{D}$ be the sign co efficients vectors ad are intended by the following equations.

$$\vec{D}=2.\vec{a}\,r_1-\vec{a} \quad (4)$$

$$\vec{C}=2.r_2 \quad (5)$$

$$\vec{a}=2(1-\frac{it}{\max-w}) \quad (6)$$

here r_1 and r_2 are the random numbers between 0 and 1. a component is decreased linearly from 2 to 0 over the course of iterations.

Hunting Prey

Mathematically to simulate the hunting behaviour of grey wolves, assume that α, β, and δ have netter information concerning the potential position of the prey. So the first three best solutions set so far are saved for compelled to update their positions according to their best positions. in the formulas were developed in this view.

$$\vec{H_\alpha}=|\vec{C_1}.\vec{V_\alpha}-\vec{V}| \quad (7)$$

$$\vec{H_\beta}=|\vec{C_2}.\vec{V_\beta}-\vec{V}| \quad (8)$$

$$\vec{H_\delta}=|\vec{C_3}.\vec{V_\delta}-\vec{V}| \quad (9)$$

$$\vec{V_1}=\vec{V_\alpha}-\vec{D_1}.\overrightarrow{(H_\alpha)} \quad (10)$$

$$\vec{V_2}=\vec{V_\beta}-\vec{D_2}.\overrightarrow{(H_\beta)} \quad (11)$$

$$\vec{V_3}=\vec{V_\delta}-\vec{D_3}.\overrightarrow{(H_\delta)} \quad (12)$$

$$\vec{V}(it+1)=\frac{\vec{V_1}+\vec{V_2}+\vec{V_3}}{3} \quad (13)$$

The exploration and exploitation abilities of the GWO's are represented by searching and attacking of grey wolves for prey respectively [19]. The hierarchy of the GWO top to bottom u, B, is shown in the fig 12 [20].

GWO algorithm:

STEP - 1 : Read peak voltage and peak current of the given system.

STEP - 2 : Initialize the parameters of number of wolfs size, max-iterations, rated parameters.

STEP - 3 : Generate wolf hierarchy according to the rating of panel.

STEP - 4 : Simulate the objective functions of the optimization techniques (GWO) till the error will be minimal.

STEP - 5 : Check for minimal error of Gbest solution, if satisfied go for optimization technique result.

STEP - 6 : Else initialize new random wolfs by using eq. (14) to (25), go to step 4.

Flowchart of GWO has shown in fig 13.

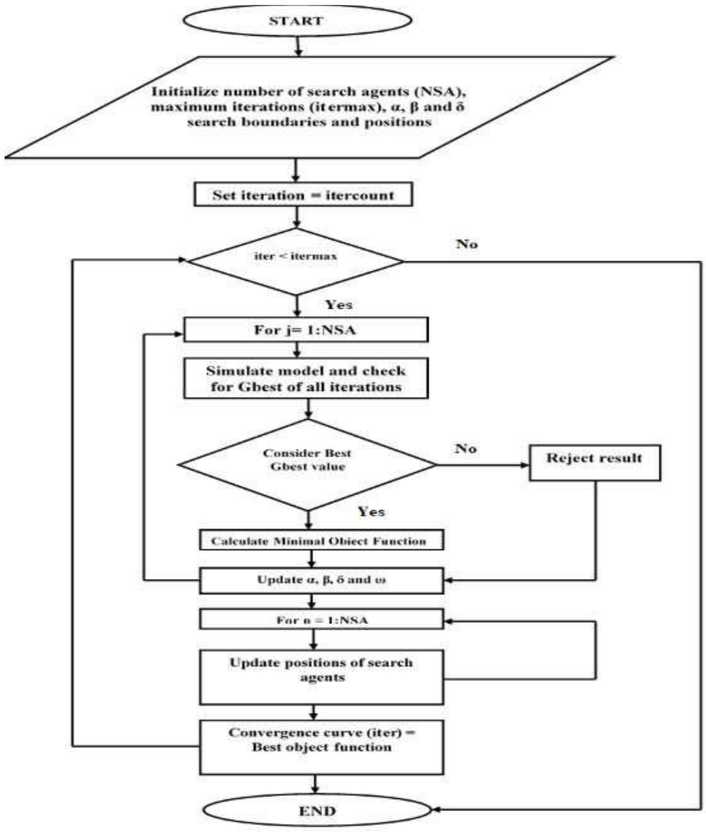

Fig. 13 Flowchart of GWO method

Design of DC – DC Converters:

The operation of Buck-Boost and SEPIC are discussed in the previous section and the circuit diagram is simulated in MATLAB/Simulink environment with renewable energy as input in this case solar power as input. The triggering pulses are given to the switch by using the Grey wolf optimization technique . Here a 5 by 5 PV system and the output of the PV system are connected to both the converter and the simulation diagrams are shown in Fig. 14 and 15.

The output of the converters are connected to the EV battery. The Zeta converter explained above is simulated in a MATLAB environment with renewable energy as input in this case we have used solar power as input. The triggering pulses are given to the switch by using the Grey wolf optimization technique . Here we have considered a 5 by 5 PV system and the output of the PV system is connected to ZETA converter and the output of the converter is given to the EV battery. The simulation parameters considered and the characteristics of the PV system are shown in Fig.16.

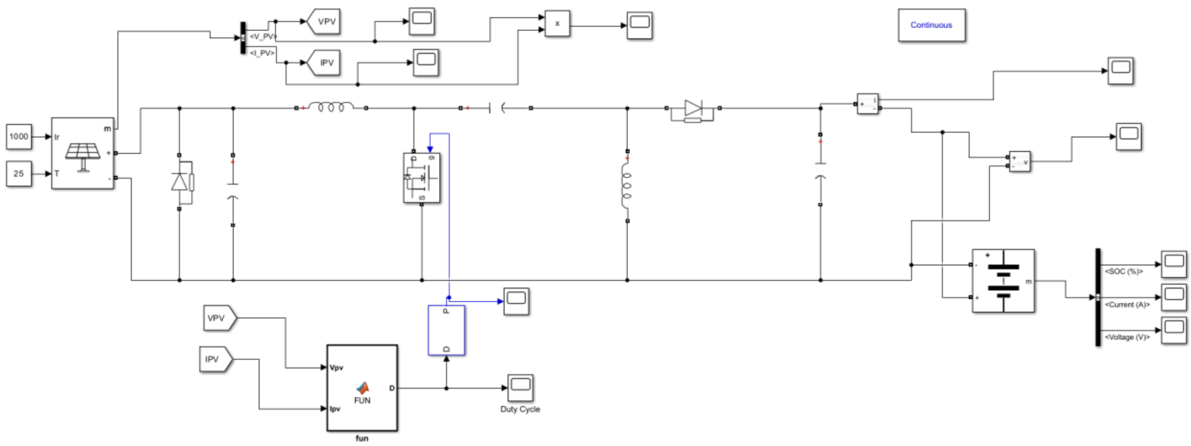

Fig. 14 Simulink model of PV based Buck Boost converter

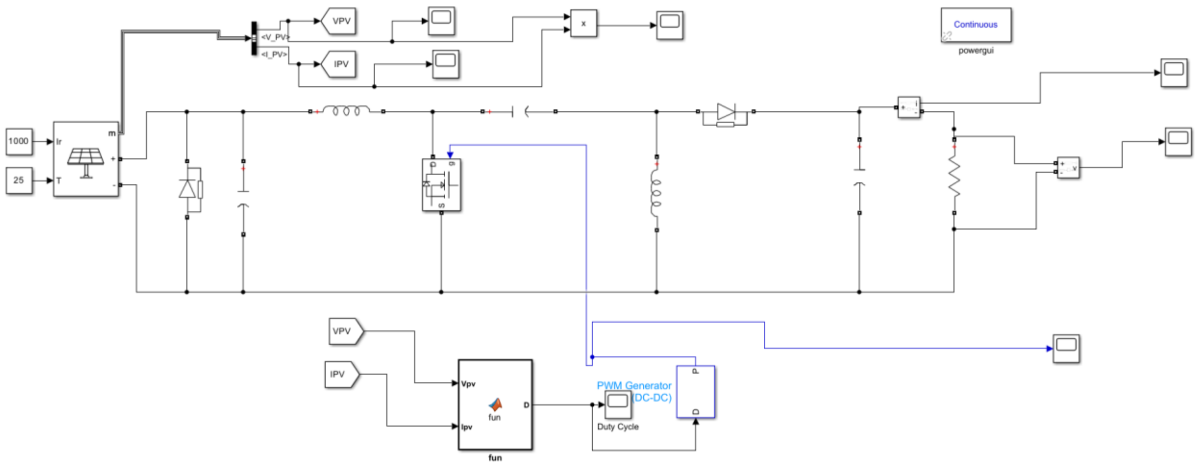

Fig. 15 Simulink model of PV based SEPIC converter

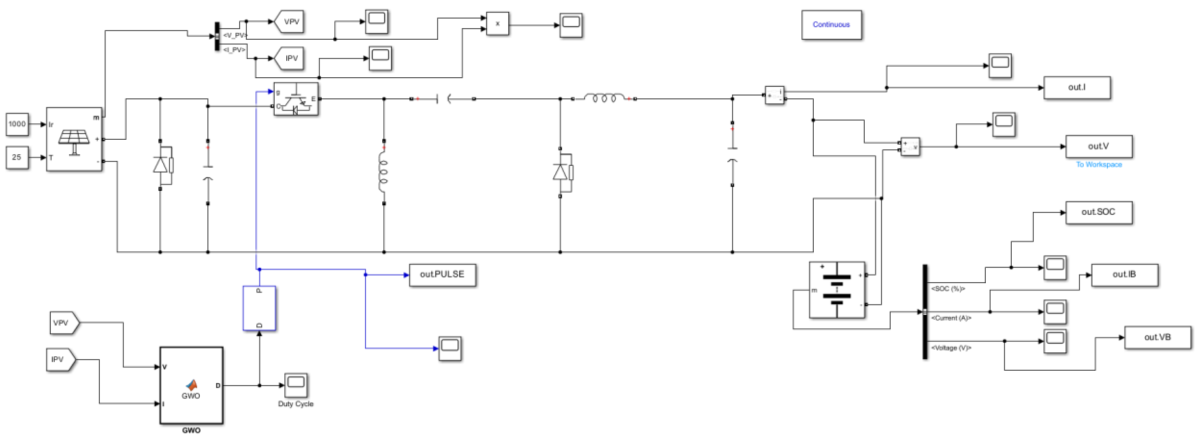

Fig. 16 Simulink model of PV based ZETA converter

The simulation parameters considered and the characteristics of the PV system are shown in Fig.17.

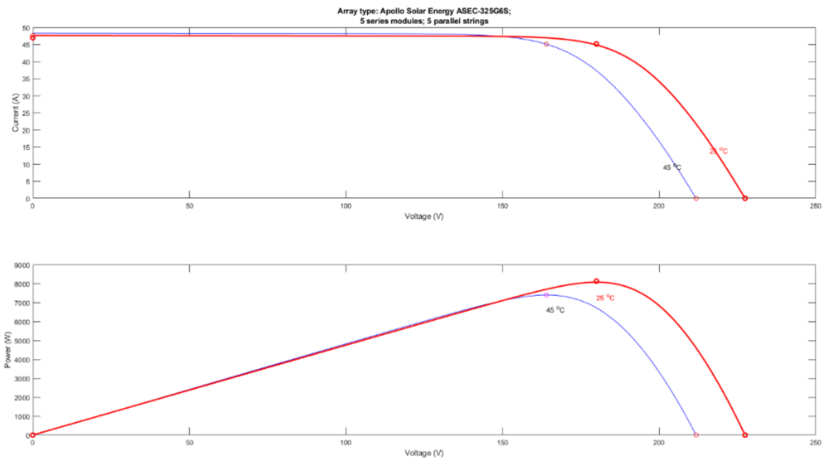

Fig. 17 PV and IV characteristics of solar PV panel

and Buck-boost and SEPIC converter parameters are shown in Table 1.

Table 1. Parameter Specifications

Parameter	BUCK – BOOST Values	SEPIC Values	ZETA Values
L1	0.1514mH	3.57µH	1.04µH
L2	-	1.04µH	1.04µH

C1	35.045µF	5.55µF	8.045µF
C2	-	44.453mF	45.453mF
Battery voltage	48 V	48 V	48 V
Battery SOC	50%	50%	50%

The triggering pulses for buck boost, SEPIC and ZETA converters are shown from Fig. 14 to 16 which are generated by using the Grey wolf optimization technique.

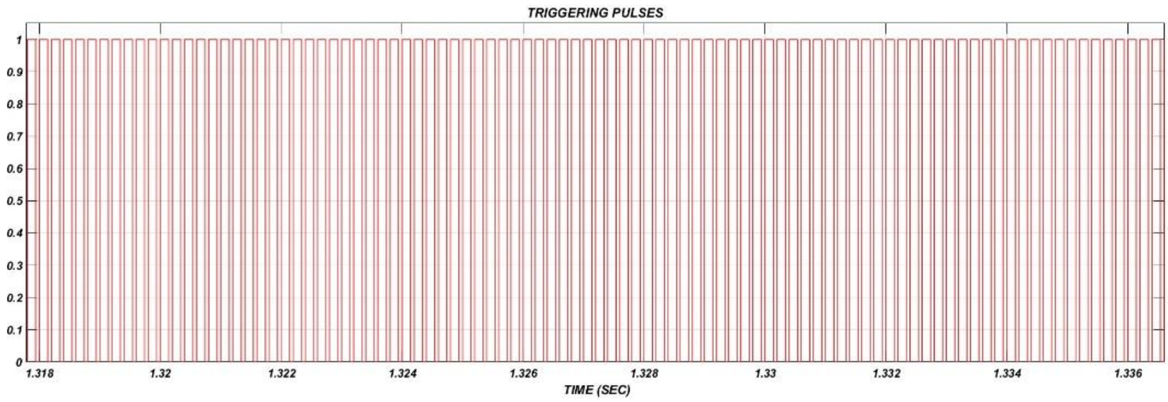

Fig.18 Triggering pulses to the Buck Boost converter

Fig.19 Triggering pulses to the SEPIC Converter

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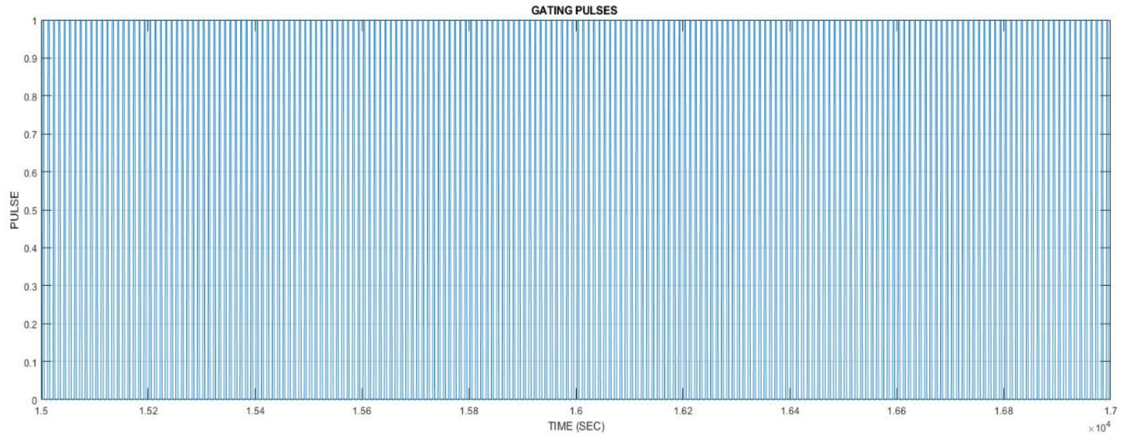

Fig.20 Triggering pulses to the converter

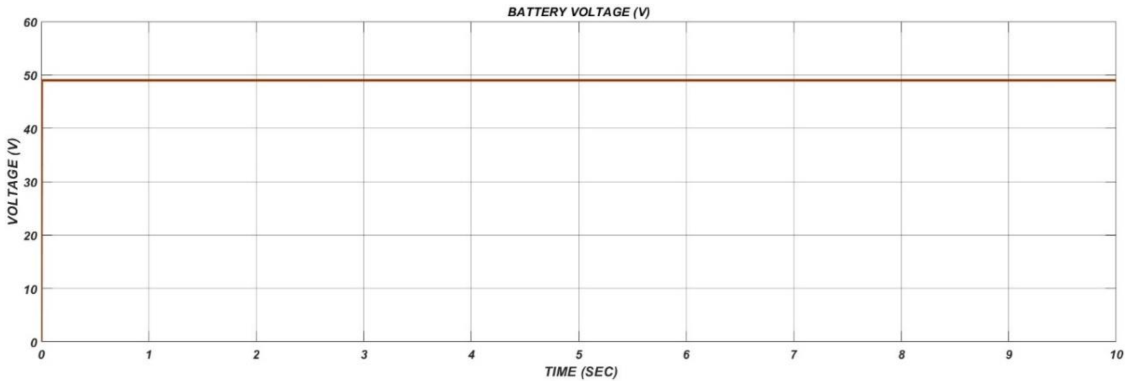

Fig.21 Battery Voltage of Buck Boost Converter

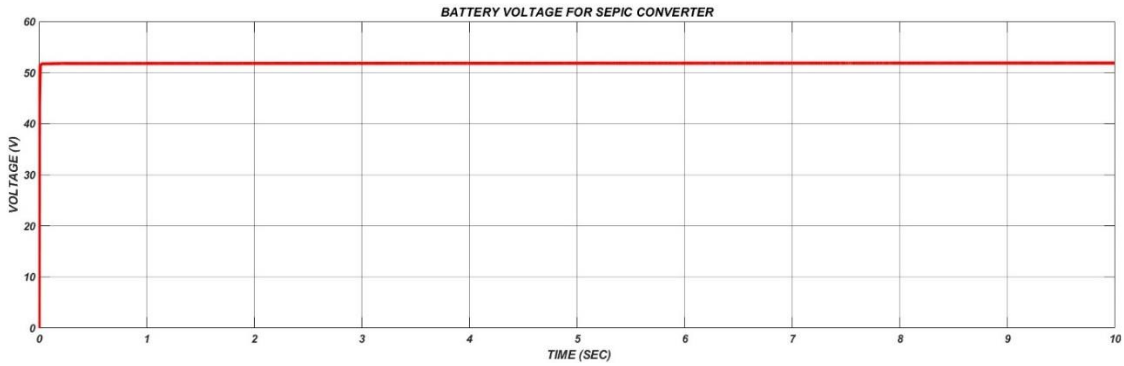

Fig.22 Battery Voltage of SEPIC Converter

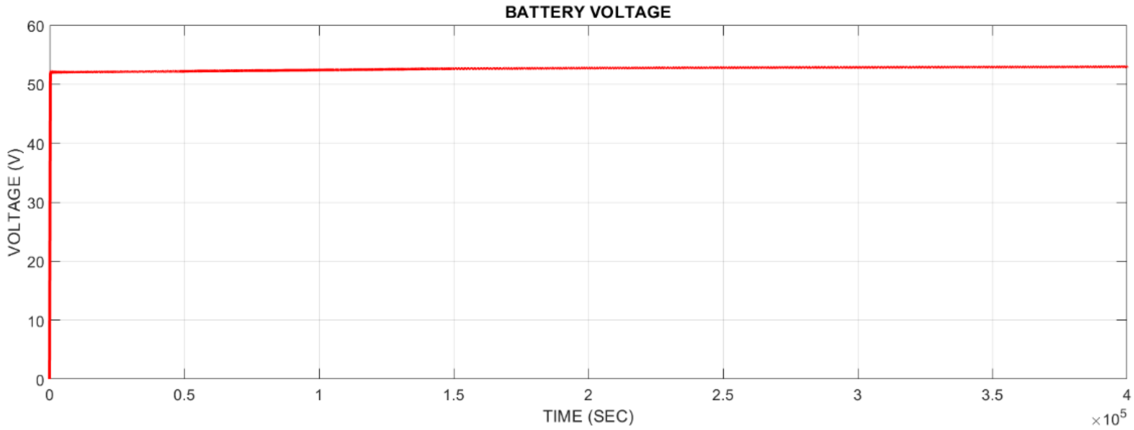

Fig.23 Battery voltage of ZETA Converter

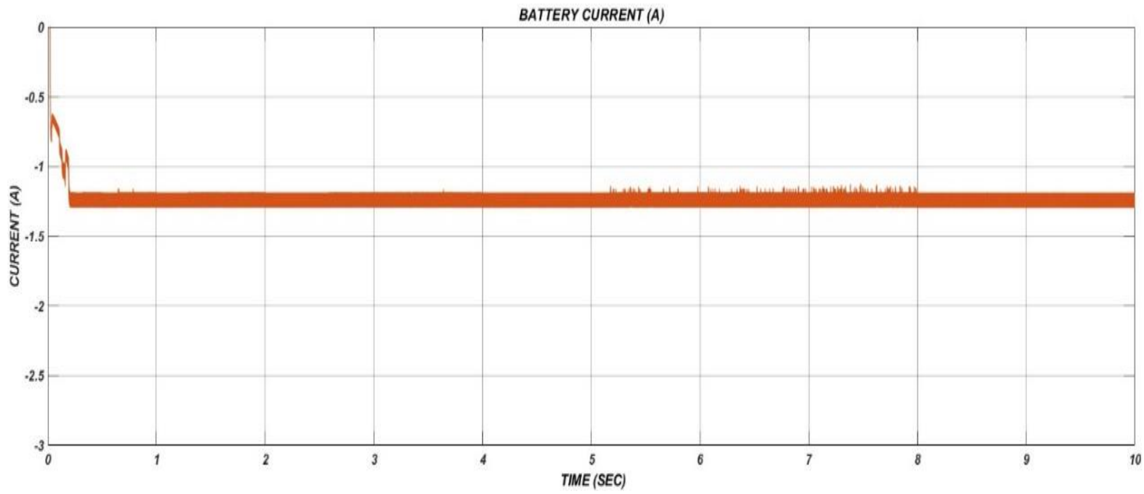

Fig.24 Battery Current in Buck Boost Converter

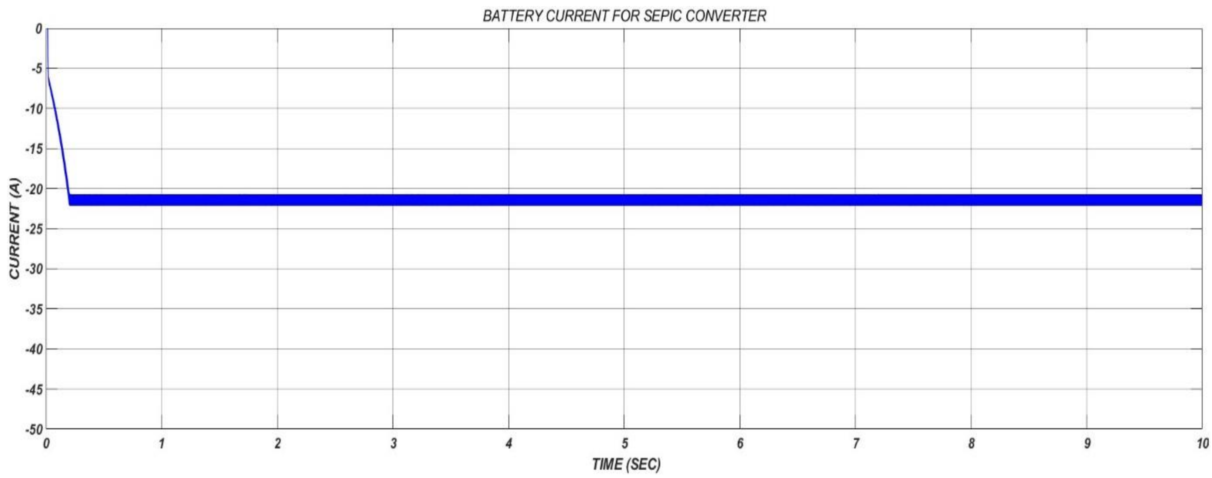

Fig.25 Battery Current in SEPIC Converter

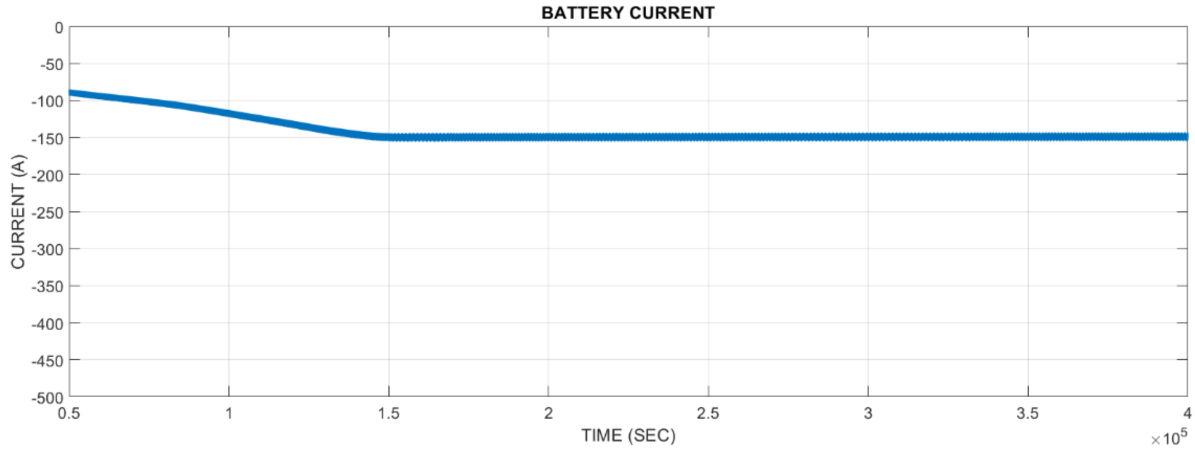

Fig.26 Battery Current in ZETA Converter

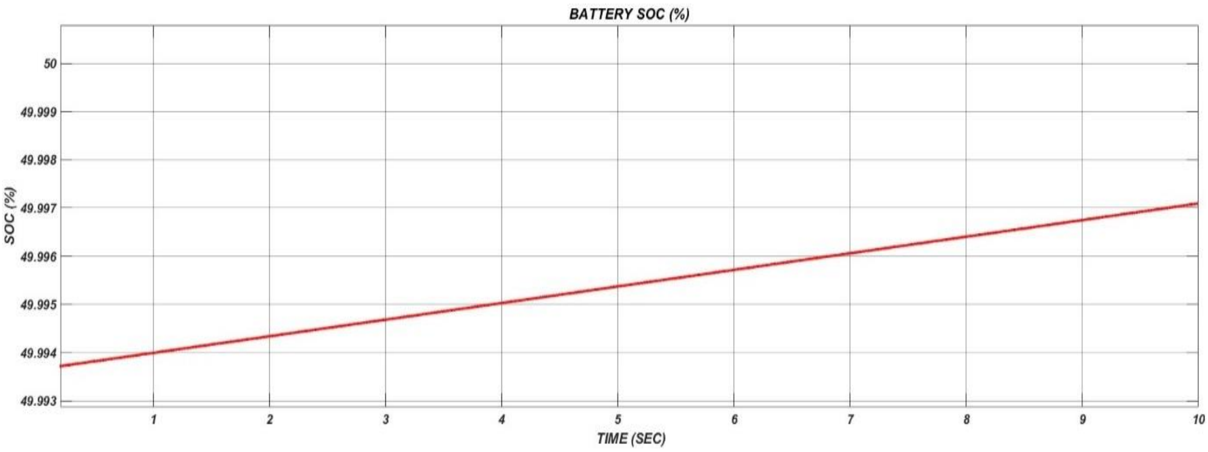

Fig.27 Battery state of charge (SOC) in Buck Boost Converter

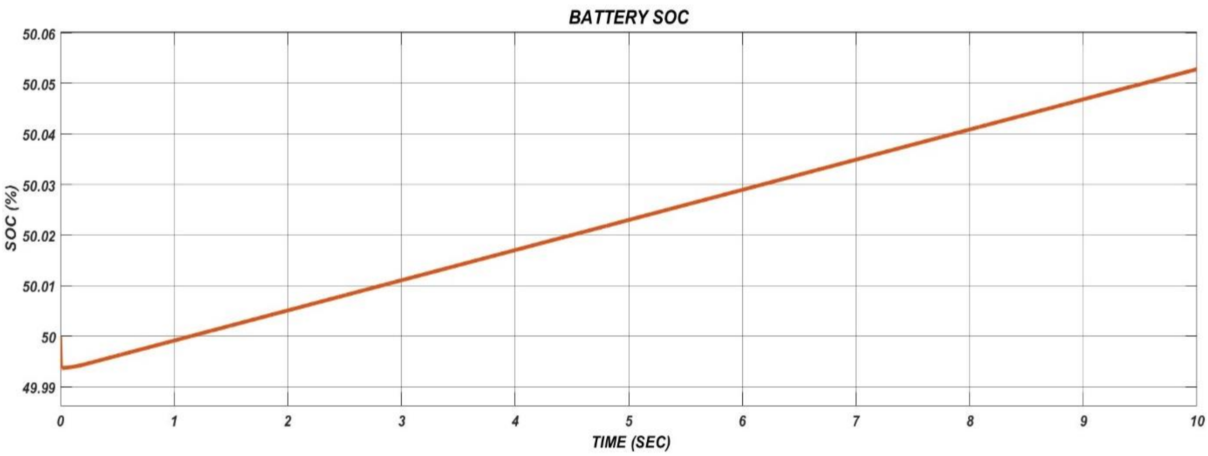

Fig.28 Battery state of charge (SOC) in SEPIC Converter

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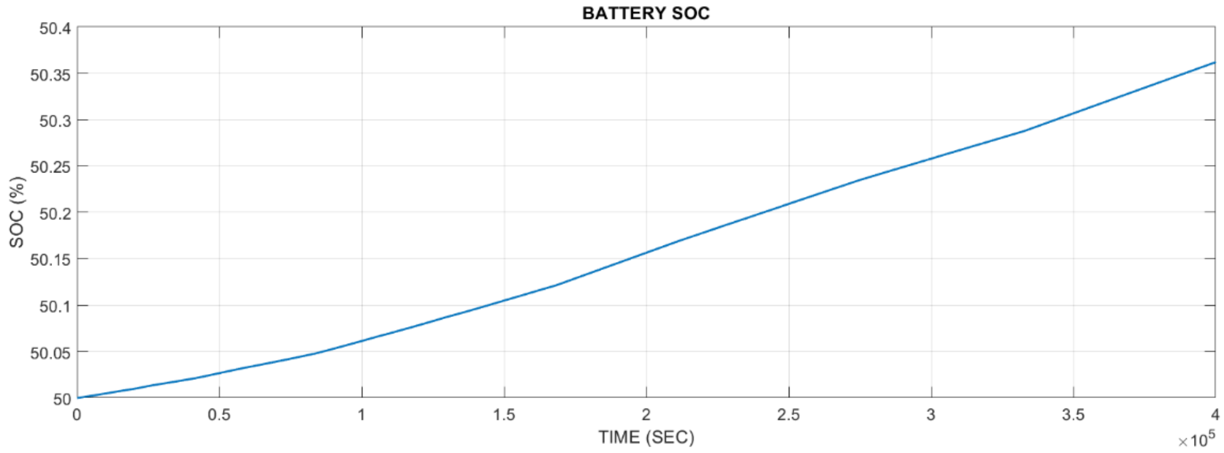

Fig.29 Battery state of charge (SOC) in ZETA Converter

The Fig. 21, 22, 23 show the battery voltage, Fig. 24, 25, and 26 depicts the current, and state of charge (SOC) is shown in Fig. 27, 28 and 29 for all the converters. Although the battery voltage is almost the same for converters, the current delivered by them is different. The SEPIC converter delivers 20 amps of current for charging the battery, while the buck boost converter delivers only 1.35 amps whereas the ZETA converter delivers 150 amps of current for charging. The SOC of the battery gradually increases in all the cases, but the charging is faster in the ZETA converter compared to the other two converters. During charging, the battery draws current from the source, so the battery current is negative. Based on the simulation results, the ZETA converter with solar power as input is more efficient in charging the EV battery, producing more charging current and less output ripples.

Conclusion:

A PV-based Charging mechanism for an EV using a Buck Boost, SEPIC and ZETA converters with grey wolf optimization MPPT is simulated in MATLAB/ Simulink Environment and the results are studied. From the simulation results the ZETA converter with solar power as input is more efficient in charging the EV battery, producing more charging current and less output ripples.

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