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Design, Analysis and Comparison of Suitable Converters for Photovoltaic System

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Abstract: This paper deals with the design, analysis and comparison of power electronic converter that suits the best for photovoltaic system. Renewable energy has become the center of rising interest now-a-days. They are the sustainable energy sources that come from the natural environment. It is a clean alternative to fossil fuels. Therefore, power electronics application to field such as photovoltaic generation, wind power generation etc. has become vital. Converters and inverters are used so that the generation using these renewable resources is carried out easily and efficiently. This project deals with the comparison of design, modeling, simulation and implementation of DC to DC converters used for photovoltaic. The performance of the system in terms of Total harmonic distortions and efficiency of the output produced by the converter are compared by using various converter topologies namely, buck-boost converter, Cuk converter and Sepic converter. By choosing the best efficient and ripple-free converter, the need of filter circuits can be reduced or eliminated significantly. Based on the total harmonic distortion and efficiency, the best suitable converter for the photovoltaic is concluded. A photovoltaic panel rated 24v delivers 250W Power, with a switching frequency of 20 KHz for the converters.

Index Terms: Power Electronic Converters, Photovoltaic, Total Harmonic Distortion, Efficiency.

I. INTRODUCTION

Renewable energy technologies offers clean, abundant energy gathered from self-Renewing resources. They are considered as an alternative energy source to meet the load demand. At present, research in electricity generation is geared up towards the renewable energy sources (RES) due to inexhaustible in nature, pollution free and abundant presence. The main drawbacks of RES are uncontrollable and unpredictable in nature. Thus it is difficult to generate the required quantity of power to meet the load demand and also the generated power, contain a lot of variations in frequency and voltage.

These problems can be overcome, by integrating two or more renewable energy sources along with a storage system. Mostly solar and wind energy sources are integrated together because of its abundance in nature and both are complement to each other to a certain extent. Usually in sunny days no wind occurs and strong winds are often occurring on cloudy days or during night time. So that, when one of the sources is unavailable or insufficient to meet the load demand the other source will compensate the difference and meet the load demand.

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For such integration, the system requires power electronic converters to enhance the power transfer efficiency and to ensure reliability of the system. In hybrid power generation system [1, 2, 3], different types of power electronic converters (PEC) are used for integration of diverse energy sources. The possible configurations of hybrid systems [4, 5] are mainly AC shunt coupled, DC shunt coupled and hybrid coupled systems Many DC-DC converter topologies are proposed for integration of different energy sources in the recent years. The advantage of the proposed converters is to eliminate the necessity of input filters to reduce the high frequency harmonics and it will operate in both individual mode of operation. The best suitable converters for the PV systems are to be analyzed.

This paper is organized as follows. Section II presents modeling of the photovoltaic cell/ module system. The circuit structure and operation of buck-boost, Cuk and Sepic converters are presented in section III and the proposed. Section IV extends to the analysis simulated results of the converter topologies with photovoltaic source and the conclusion is given in section V.

II. MODELLING OF A PHOTOVOLTAIC CELL

A solar cell or a PV cell is used to convert light energy into electrical energy. PV cells are connected together to form photovoltaic module or photovoltaic panel. The equivalent circuit of a solar cell is shown in fig. 1.The PV panel is used as voltage source in the boost mode of operation. The characteristics of Ipv-Vpv are described in the following equation (1).

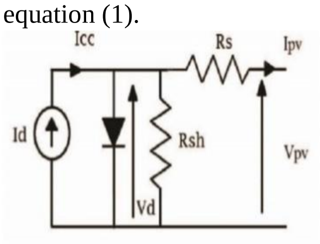

Fig 1: Equivalent circuit of a solar cell

$$Ipv = Icc - Is\left[\exp\left(Q\left(\frac{Vpv + RsIpv}{mKT}\right)\right) - 1\right] - \frac{Vpv + RsIpv}{Rsh} \quad \textbf{(1)}$$

Where
Is = Saturation current;
Icc = Light-generated current;
k = Boltzmann's constant (k=1.3xI0-23 J/K);
T = Absolute temperature in Kelvin degrees**(273.15 +°C);**
q = Electron charge (q= 1.602 x I 0-19 Coulomb);
m = Ideality factor of the junction (I < m <2);
Rs and Rsh Resistors represent the losses of metal contacts and leakage of the PN junction respectively.

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photovotaic array

The solar photo-voltaic array is chosen for a Matlab/Simulink, module, the solar photo-voltaic array consists of 40 photovoltaic cells connected in series. The photovoltaic array provides 250W maximum power.

Solar temperature and irradiation plays an important role for predicting the behavior of PV array. The solar temperature affects the output terminal voltage and the irradiation affects the open circuit current. The modularity of a photovoltaic cell to an array is shown in the fig.2.

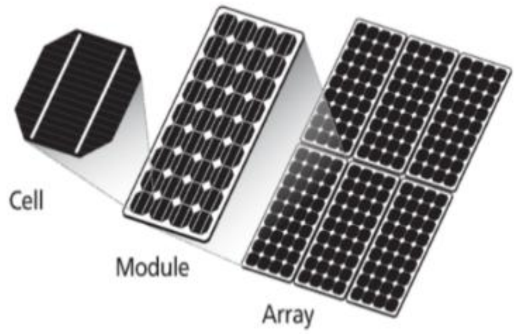

Fig.2: Modularity of photovoltaic cell to an array

The word 'photo-voltaic' is derived from two different words; the word 'photos', from the Greek, meaning light and the word 'voltaic' developed from the name of the Italian scientist, Volta, who studied electricity. This explains what a PV system does; it converts light energy from the sun into electrical energy. The basic element of a PV System is the photovoltaic (PV) Cell, also called a Solar Cell. The output of the PV Cell which depends on Temperature (T) and Irradiance can also be varied.

Table 1: Variable range for irradiance and temperature in a photovoltaic cell

Irradiance(w/m²)	600	800	1000
Temperature(°c)	25	50	75

Photovoltaic Module Simulation

Fig.3 gives the simulation circuit of a photovoltaic module which is provided with constant irradiation. However variable irradiation can also be given to the photovoltaic panel. Typically a PV cell generates a voltage around 0.5 to 0.8 volts depending on the semi-conductor and build-up technology. This voltage is low enough as if cannot be of use. Therefore to get benefits from this technology, PV cells are connected in series to form a PV module this module can be interconnected in series and/or parallel to form a PV panel. In case these modules are connected in series, these voltages are added with the same current.

The basic block diagram of the transformerless photovoltaic grid connected system is shown in the fig 3.

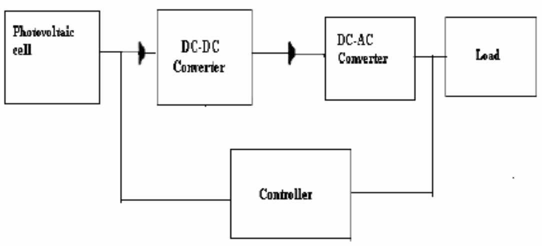

Fig. 3: Block diagram of PV fed converter

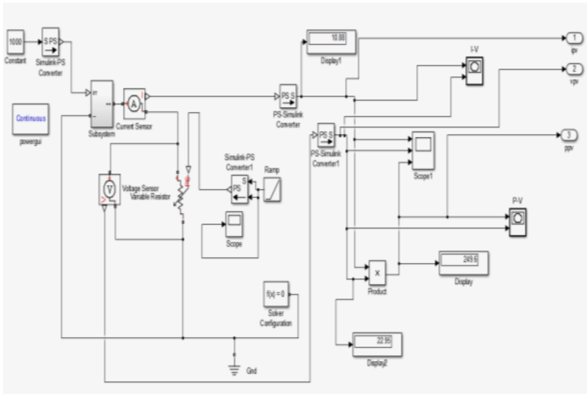

Fig. 4: Simulation circuit of a photovoltaic module

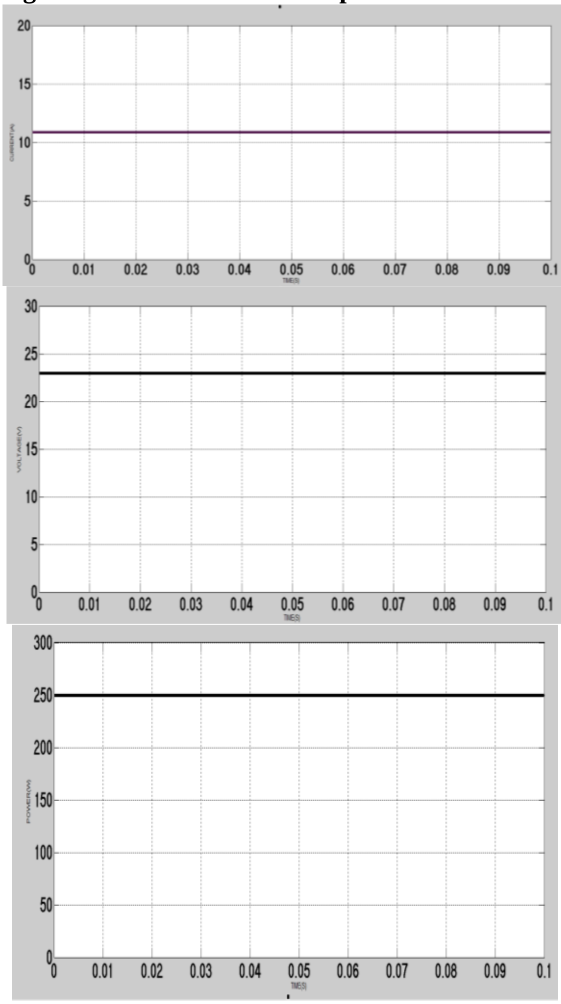

Fig. 5: PV Current, Voltage and Power waveforms

The simulation model of the photovoltaic system represents a constant current source with dc supply and without any disturbance. The voltage and current waveforms of PV panel is shown fig 5.

III. CIRCUIT STRUCTURE AND OPERATION

Buck-Boost Converter

The general configuration of Buck-Boost converter is shown Fig.6. A buck-boost converter can be obtained by cascade connection of the two basic converters namely, the step down converter and the step up converter.

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The circuit operation can be explained in two modes

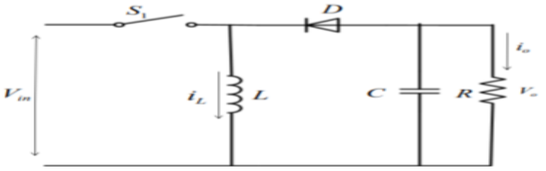

Fig. 6: Circuit diagram of buck-boost converter

MODE 1: when switch is turned on

During mode 1, the switch S_1 is turned on and the diode D is reversed biased. The input current, rises, flows through inductor L and switch S_1.

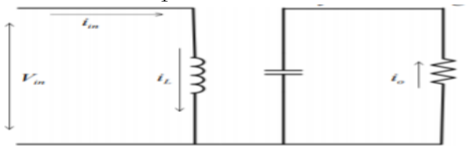

Fig. 7: When switch is closed

MODE 2: when switch is turned off

In mode 2, the switch S_1 is off and the current, which was flowing through the inductor, would flow through L, C, D and load. In this mode the energy stored in the inductor (L) is transferred to the load and the inductor current (L_i) falls until the switch S_1 is turned on again in the next cycle.

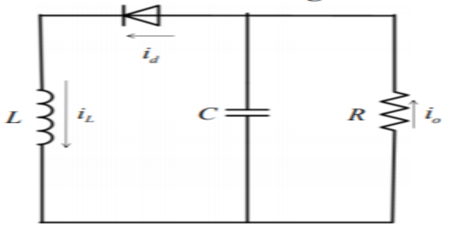

Fig. 8: When switch is open

Design calculations for Buck-boost converter are as follows:

1. Calculation of duty cycle

$$V_{out} = -\frac{V_{in*D}}{1-D} \qquad (2.1)$$

2. Inductor value can be obtained from

$$L = \frac{V_i*D}{\Delta I * f_S} \qquad (2.2)$$

3.Capacitor value can be given by

$$C = \frac{D_{MAX}*I_o}{f_s*\Delta V} \qquad (2.3)$$

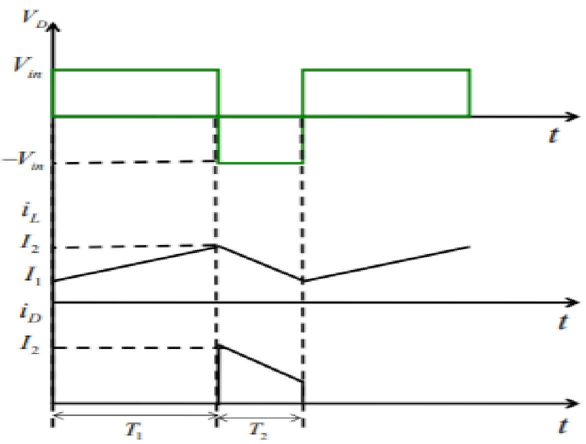

Fig. 9: Voltage and current waveforms of buck-boost converter

Cuk Converter

Cuk converter named after its inventor is obtained by using the duality principle of a buck-boost converter. The Cuk converter provides a negative-polarity regulated output voltage with respect to the common terminal of the input voltage.

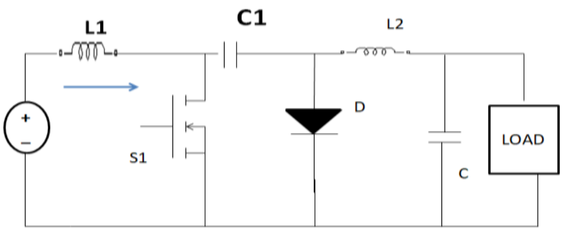

Fig. 10: Circuit diagram of Cuk converter

The capacitor c_1 acts as a primary means of storing and transferring energy from the input to the output. In steady state, the average inductor voltage v_{L1} and v_{L2} are zero. Therefore,

$$V_{c1} = V_d + V_o \qquad (2.4)$$

Therefore, V_{c1} is larger than both V_d and V_o. assuming c_1 to be sufficiently large, in steady state the variation in V_{c1} from its average value can be assumed to be negligible, even though it stores and transfers energy from the input to the output.

Mode 1: When the switch is OFF

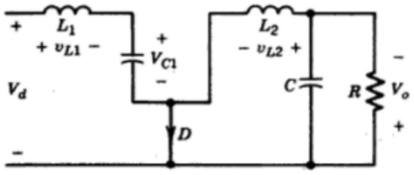

Fig. 11: Cuk converter when switch is turned off

When switch is turned off, the inductor currents i_{L1} andi_{L2} flow through the diode. Capacitor c_1 is charged through the diode by energy from both the input and L_1. Current i_{L1} decreases because V_{c1} is larger than V_d. energy stored in L_2 feeds the output. Therefore, i_{L2} also decreases.

Mode 2: when the switch is ON

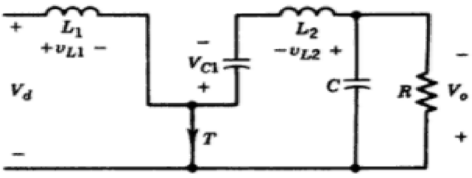

Fig. 12: Cuk converter when switch is on

When the switch is on, V_{c1} reverse biases the diode .the inductor currents i_{L1} andi_{L2} flow through the switch. Since V_{c1} is greater than V_O, C_1 discharges through the switch, transferring energy to the output and L_2. Therefore i_{L2} increases. The input feeds energy to L_1 causing i_{L1} to increase. The inductor currents i_{L1} andi_{L2} are assumed to be continuous.

Design calculations for Cuk converter are as follows

Calculation of duty cycle

$$V_{out} = \frac{V_{in*D}}{1-D} \qquad (2.5)$$

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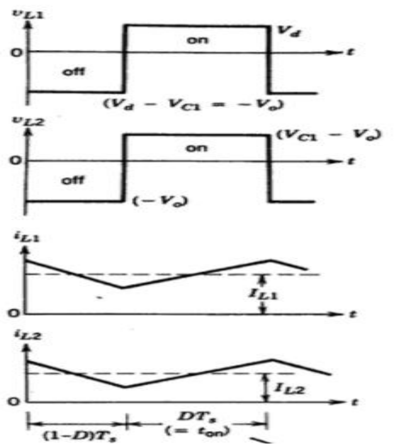

Fig. 13: Voltage and current waveforms of Cuk converter

Inductor and Capacitor value can be obtained from

$$L = \frac{V_i * D}{\Delta I * f_S} \quad (2.6)$$

$$C = \frac{D_{MAX} * I_o}{f_s * \Delta V} \quad (2.7)$$

Sepic Converter

Single –ended primary inductor converter. Sepic is a type of DC-DC converter allowing the electrical potential as its output to be greater than, less than or equal to that at its input. The output of the Sepic converter is controlled by the duty cycle of the control transistor. The Sepic converter operates in two modes namely, Continuous conduction mode and discontinuous conduction mode.

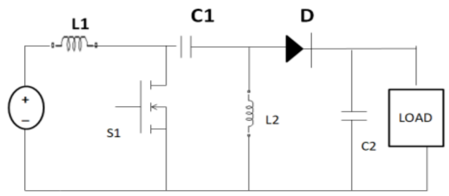

Fig. 14: Circuit diagram of Sepic converter

Continuous mode

A Sepic is said to be in continuous conduction mode. If, current through the inductor is never falls to zero. During steady operation, the average voltage across capacitor C1 is equal to the input voltage. Because capacitor C_1 blocks the direct current (DC), the average current through C1 is zero, making inductor L_2 the only source of DC load current. Average voltage

$$V_{in} = V_{l1} + V_{c1} + V_{c2} \quad (2.8)$$

The average voltage V_{c1} is equal to V_{in}

$$V_{l1} = -V_{l2} \quad (2.9)$$

Mode1: When switch S_1 is turned on Current I_{l1} increases and the current I_{l2} goes more negative. The energy to increases the current I_{l1} comes from the input source. Since S_1 is a short while closed, and the instantaneous voltage V_{c1} is approximately $-V_{in}$. Therefore, the capacitor C_1 supplies the energy to increases the magnitude of the current in I_{l2} and thus increases the energy stored in L_2.

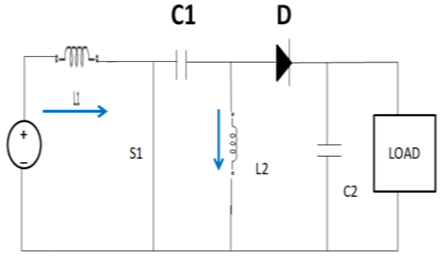

Fig. 15: Sepic converter when switch is on

Mode2: When switch S_1 is turned off

The current through I_{c1} becomes same as the current I_{l1} since inductor don't allow instantaneous changes in current. The current I_{l2} will continue in the negative direction, in fact it never reverse direction. The negative I_{l2} will add to the current I_{l1} to increases the current delivered to the load.

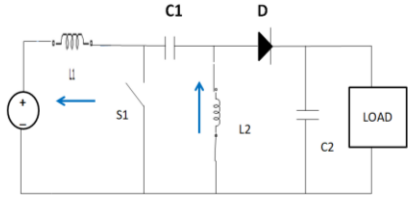

Fig. 16: Sepic converter when switch is off

Using Kirchhoff current law,

$$I_{d1} = I_{c1} - I_{l2} \quad (2.10)$$

It can be concluded that while s_1 is off, power is delivered to the load, from both L_1 and L_2. C_1 however is being charged by L_1 during this off cycle and will in turn recharge l_2 during the on cycle.

Discontinuous mode

A Sepic is said to be discontinuous conduction mode or discontinuous mode, if the current through the inductor L_1 is allowed to fall to zero.

Design specifications of sepic converter:

1. Duty cycle can be calculated as

$$D = \frac{V_{out} + V_d}{V_{in} + V_{out} + V_d} \quad (2.11)$$

2. Inductor and output Capacitor value can be obtained from

$$L_1 = L_2 = \frac{V_{in} * D}{\Delta I * f_s} \quad (2.12)$$

$$C_2 = \frac{I_o * D_{max}}{V_{ripple} * V_d * F_s} \quad (2.13)$$

IV. SIMULATION OF POWER ELECTRONIC CONVERTERS WITH PHOTOVOLTAIC SOURCE

The Simulink model of power electronic converters like Buck-boost converter, Cuk converter and Sepic converter with Photovoltaic input are shown below.

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V. SIMULATION OF BUCK-BOOST CONVERTER

The Simulink model of buck-boost converter with the corresponding output waveforms with THD waveforms are shown below.

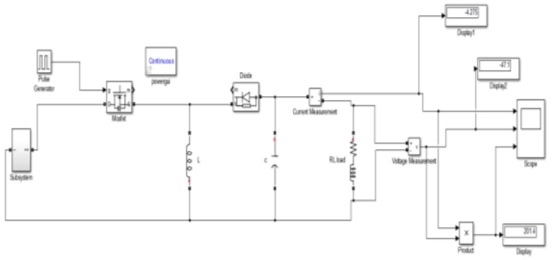

Fig. 17: Simulink model of buck-boost converter with PV source

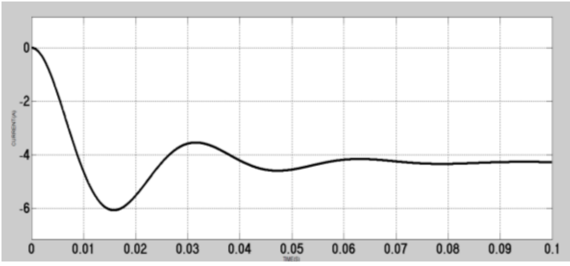

Fig. 18: Output current waveform of buck-boost converter

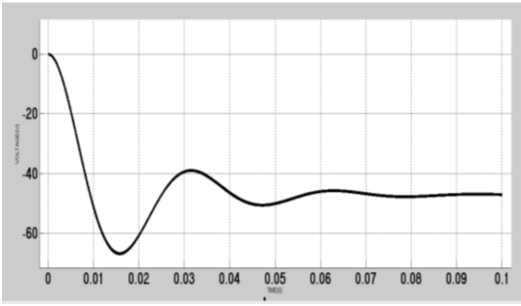

Fig. 19: Output voltage waveform of buck-boost converter

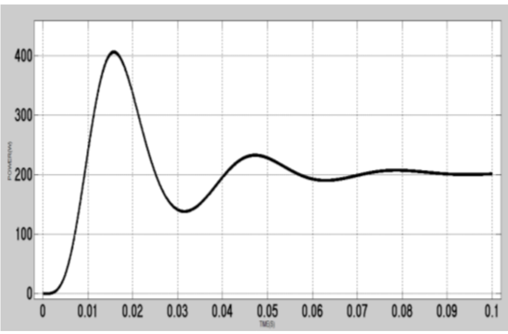

Fig. 20: Output Power waveform of buck-boost converter

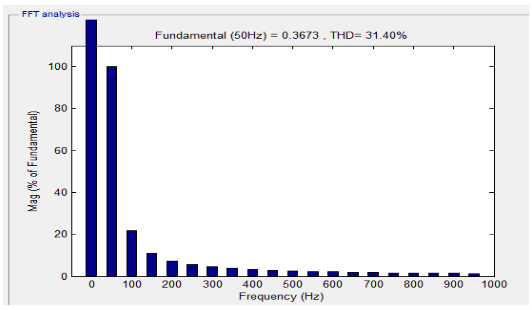

Fig. 21: THD analysis of output voltage of Buck-boost converter

The results obtained from simulation are tabulated in the table as shown below.

Table 2: Observations of PV Source with buck boost converter

	Voltage(V)		Current(A)		Power(W)		THD (%)	EFFICIENCY(%)
	DESIGN VALUE	OBSERVED VALUE	DESIGN VALUE	OBSERVED VALUE	DESIGN VALUE	OBSERVED VALUE		
INPUT	24	23	10.42	10.88	250	249.6	31.40	80.68
OUTPUT	48	47.1	5.2	4.275	250	201.4		

VI. SIMULATION OF CUK CONVERTER

The Simulink model of Cuk converter with the corresponding output waveforms with THD waveforms are shown below.

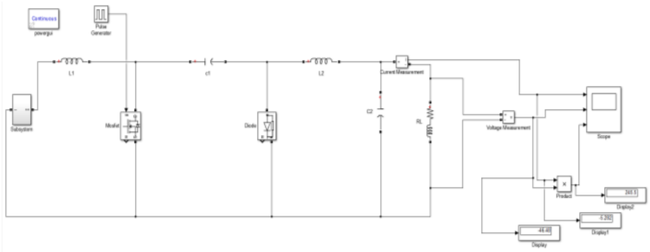

Fig. 22: Simulink model of Cuk converter with PV source

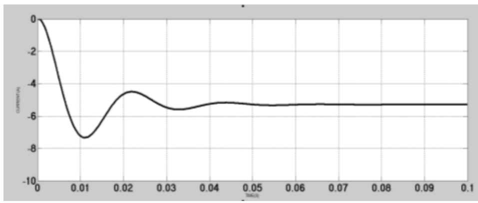

Fig.23: Output current waveform of Cuk converter

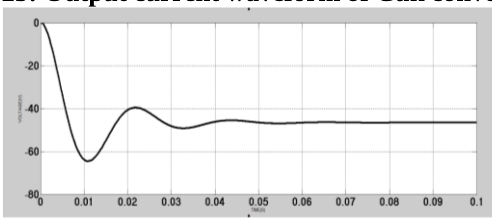

Fig.24: Output voltage waveform of Cuk converter

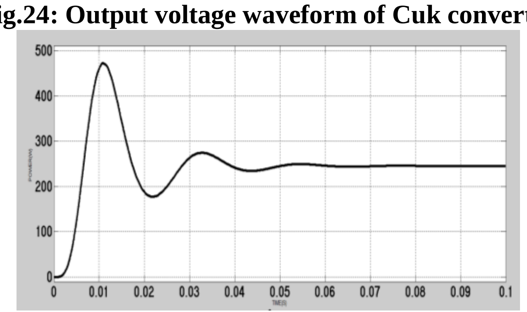

Fig.25: Output power waveform of Cuk converter

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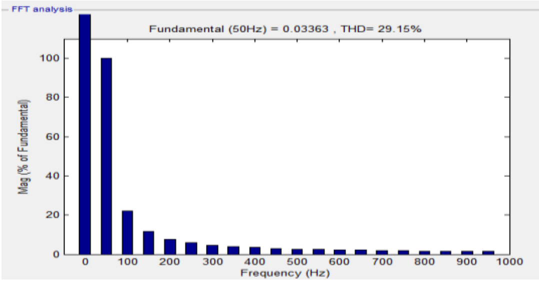

Fig.26: THD analysis of output voltage of Cuk converter

The results obtained from simulation are tabulated in the table as shown below

Table 3: Observations of PV Source with Cuk converter

	Voltage(V)		Current(A)		Power(W)		THD (%)	EFFICIENCY(%)
	DESIGN VALUE	OBSERVED VALUE	DESIGN VALUE	OBSERVED VALUE	DESIGN VALUE	OBSERVED VALUE		
INPUT	24	23	10.42	10.88	250	249.6	29.15	98.35
OUTPUT	48	46.48	5.2	5.28	250	245.5		

VII. SIMULATION OF SEPIC CONVERTER

The Simulink model of Sepic converter with the corresponding output waveforms with THD waveforms are shown below.

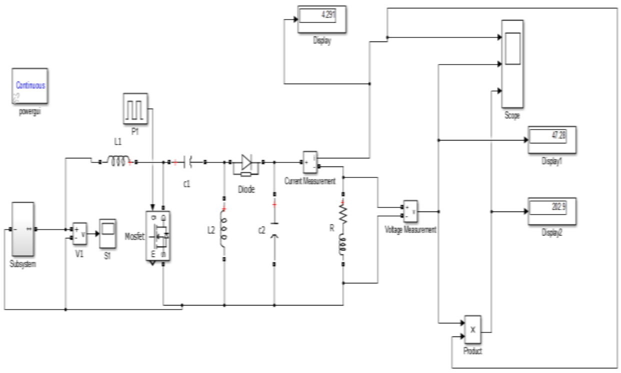

Fig.27: Simulink model of Sepic converter with PV source

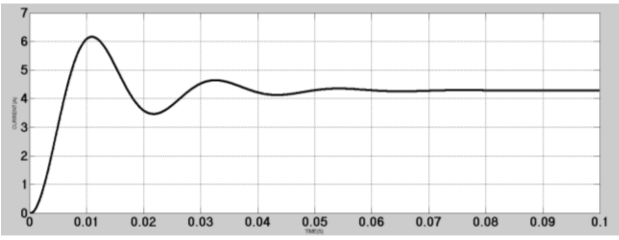

Fig.28: Output current waveform of Sepic converter

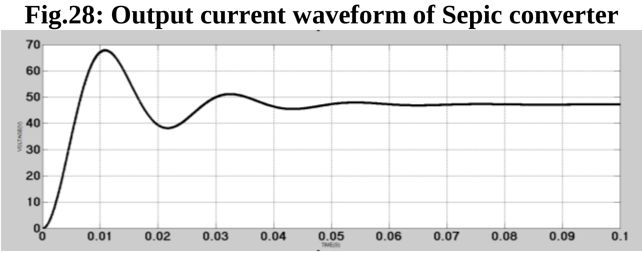

Fig.29: Output voltage waveform of Sepic converter

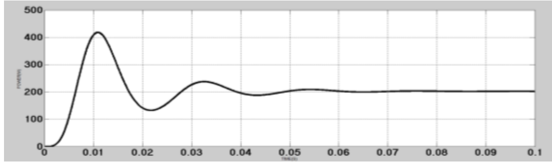

Fig.30 Output Power waveform of Sepic converter

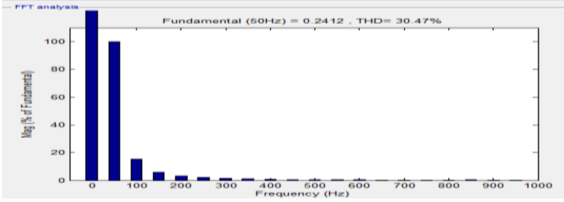

Fig.31: THD analysis of output voltage of Sepic converter

The results obtained from simulation are tabulated in the table as shown below

Table 4: Observations of PV Source with Sepic converter

	Voltage(V)		Current(A)		Power(W)		THD (%)	EFFICIENCY(%)
	DESIGN VALUE	OBSERVED VALUE	DESIGN VALUE	OBSERVED VALUE	DESIGN VALUE	OBSERVED VALUE		
INPUT	24	23	10.42	10.88	250	249.6	30.47	81.29
OUTPUT	48	47.28	5.2	4.291	250	202.9		

VIII. CONCLUSION

The design, analysis and comparison of power electronic converters like buck-boost, Cuk and Sepic converters for photovoltaic energy generation

Systems were analyzed. This chapter concludes the simulation of power electronic converters with photovoltaic energy system under open loop without varying irradiance disturbance. The simulation for open loop has been simulated and the desired output voltage and current waveform are presented using MATLAB simulator.

Table 5: Final observations from the simulated results

NAME OF THE CONVERTER	OUTPUT POWER (W)	THD (%)	EFFICIENCY (%)	BEST CONVVERTER FOR PV SYSTEM
BUCK BOOST CONVERTER	201.4	31.4	80.68	×
CUK CONVERTER	245.5	29.15	98.35	√
SEPIC CONVERTER	202.5	30.47	81.29	×

On analysing the performance of the converter topologies namely buck-boost converter, Cuk converter and Sepic converter for photovoltaic systems, it has been proven that compared to the buck-boost converter and Sepic converter, Cuk converter has better performance in terms of total harmonic distortion and efficiency for photovoltaic systems. Efficiency of this converter can be improved by using an addition of a Snubber circuit. Cuk converters are efficient converters in exchanging power between two voltage levels, from the PV input voltage to the load. This obviously reduces the number of switches, switching losses thereby improving efficiency and reduced harmonics.

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