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COMPARATIVE ANALYSIS OF INTERLEAVED BOOST CONVERTER AND CUK CONVERTER FOR SOLAR POWERED BLDC MOTOR

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ABSTRACT

The global electrical energy consumption is ascending rate, in order to meet the growing demand, there is a need to increase the power generation capacity. Nowadays, solar energy plays an important role due to limited availability of fossil fuels. The efficiency of PV is very low and power output mainly depends on solar insulation level. DC-DC converters play a vital role in many applications such as Solar Electric Vehicle, Solar Water Pumping, which mainly required boosting the lower input voltage. In order to boost the input voltage to BLDC motor and its efficient operation, various DC-DC converter topologies are used. This paper deals with two such topologies such as interleaved boost converters and CUK converter. The comparison has been made between these two topologies based on the performance of converters with resistive load, with BLDC motor and the effect of irradiance. The performance of the system has been validated using MATLAB/Simulink

KEYWORDS: BLDC Motor, CUK Converter, Interleaved Boost Converter, PV Array

I. INTRODUCTION

Today, due to the ascending rate of global energy demand and limited availability of fossil fuel, renewable energy receives more attention. Despite low efficiency and dependence of atmospheric condition, it has several advantages such as pollution free generation, no running costs. So, it produces more attraction for researchers towards PV array installation. The permanent magnet brushless motor (BLDC) provides high efficiency, long life, high reliability, wide range of speed control, low noise and maintenance free operation. The above feature of BLDC motor attracts the researcher for various applications such as Solar Electric Vehicle and Solar pumping system [1].

A photovoltaic (PV) generation systems have quite low voltage output and require series connection to meet high output voltage to drive a BLDC motor. DC-DC converter plays a vital role in order to boost up low voltage input to required level. The various DC-DC converter topologies are available to achieve above requirement.

CUK converters are usually used in PV applications for smooth operation of DC output. CUK converter has an advantage over other converters, since it reduces the ripples on both the input and output side of the converter [2-4]. The circuit has low switching losses and has high efficiency. It has disadvantages such as high peak current flows through switch S_1, because switch S_1 has to carry the currents of inductor L1and L2. The ripple current of the capacitor C1 is also higher as the capacitor provides the energy transfer. The circuit of CUK converter also requires an additional capacitor and inductor [5].

Boost converter is popular for converting low voltage inputs into high voltage outputs [6]. As the power demand from supply increases, a single stage boost converter may be insufficient. In the high power application, the current and voltage stress can go beyond the handling capacity of power devices. This can be overcome by connecting the converters in parallel. Interleaving technique is nothing but connecting the boost converters in parallel with common capacitor and load. Interleaved technique on boost converter increases system efficiency and power density. In interleaved operation, inductor current is reduced by half, as a result the total loss of inductors significantly get reduced, effective ripple frequency increases by twice and peak to peak value of input current ripple is reduced. Thus the input filter size will be decreased with interleaved operation [7]. Compared to the conventional boost converter, the interleaved boost converter has following advantages [8-11].

- Higher boosting capacity
- Reduced inductor peak current
- Reduced output voltage ripple
- Increase efficiency

This paper is organized as follows; Section II deals with the overall system configuration and function of each block. Section III and IV deal with the selection of PV array and BLDC motor. These specifications are listed in the table. Section V explains the circuits of CUK converter and IBC. In section VI, CUK converter and IBC are simulated using MATLAB/Simulink with resistive and BLDC motor load. In section VII, simulation results of converters are discussed. The best out of two DC-DC converters are concluded in section VIII.

II. SYSTEM MODEL CONFIGURATION

Figure 1 shows the block diagram for the solar PV array based DC-DC converter fed BLDC motor drive. A DC-DC converter is used between a PV array and Inverter. The output voltage of the PV is boosted using the DC-DC converter. The pulse generator generates switching signals from DC-DC converter. The duty cycle of the DC-DC converter is adjusted such that the output voltage can drive the BLDC motor. The boosted voltage is given to the DC link. The DC link voltage is converted into AC by inverter circuit [12-13].

The rating of the components required for this work is completely based on the motor, which is to be used for the applications.

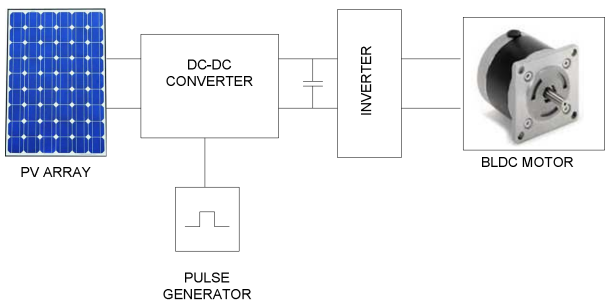

Figure 1: Configuration of Solar PV Array Fed DC-DC Converter Based BLDC Motor Drive

III. SOLAR PV ARRAY

To supply the BLDC motor a solar PV array of power capacity 1.62 kW is selected. The power capacity of the PV array is somewhat more than required by the motor, so that the performance of the system is not affected by the losses associated with the converters and the motor. The voltage of the SPV array at MPP is selected such that the DC link voltage is same as a DC voltage rating of BLDC motor. The PV modules are connected in series and parallel so as to give the required voltage. Table I shows the specifications of PV module.

Table I: Pv Module Specifications

For PV Module	
No. of cells in a module	36
O.C voltage	21V
S.C current	6.4 A
Vm	17 V
Im	5.4 A
For PV array	
Vmpp=Vpv	153 V
Pmpp=Ppv	1620 W
Impp= Ipv	Pmpp/ Vmpp= 10.6
No. of modules in series	Vmpp/Vm= 9
No. of modules in parallel	Impp/ Im= 2

IV. BLDC MOTOR

At present, various types of motors are widely used in electric vehicle and pumping application. Due to frequent maintenance required by brushes and commutators, DC motors are not preferred. An induction motor is more reliable and maintenance free as compared to DC motor for pumping applications, but it has a limitation of complex control. Among them, the BLDC motor used as the drive motor has many advantages such as good features of speed regulation, high efficiency, high power density, maintenance-free operation and high-speed operation. It overcomes the shortcomings of the mechanical commutation. This feature attracts to use BLDC motor in the SPV array pumping system and in electric vehicle application. Table II shows the specifications of BLDC motor.

Table II: BLDC Motor Specifications

Parameters	Ratings
Power	1.32 kW
Speed	3000 rpm
DC voltage	310 V
No. of poles	4
Moment of inertia	2.9 kg- cm^2
Current	4.3 A
Voltage constant	78 V/krpm
Torque constant	0.74 Nm/A
Resistance /phase	3.58 ohm
Inductance/phase	9.13 mH

V. DC-DC CONVERTERS

1. Cuk Converter

The circuit arrangement of CUK converter is as shown in Figure 2 Similar to the buck-boost converter, the CUK converter provides an output voltage that is less than or greater than the input voltage based on the duty cycle ratio, but the output voltage polarity is opposite to that of the input voltage. CUK converter combines the best features of buck and boost converter in terms of filtering on input and output.

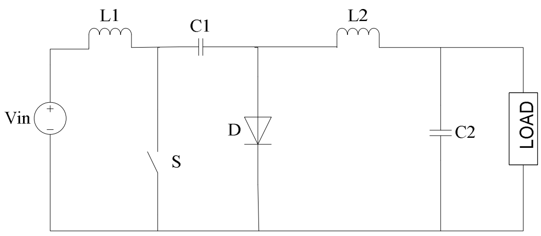

Figure 2: DC-DC CUK Converter

It has two inductors L_1 and L_2 at input and output sides respectively. CUK converter is based on the capacitor energy transfer. The capacitor C_1 is used to transfer energy from source to load. As the capacitor provides for energy transfer, the ripple current of capacitor C_1 is high.

Design of CUK Converter Parameters

A. Duty Cycle

The required DC link voltage V_{dc} = 310V and the input voltage from the solar panel is V_{pv} = 153 V, therefore the duty cycle D for CUK converter can be calculated as follows

$$D = \frac{V_{dc}}{(V_{dc} + V_{pv})} = \frac{310}{(310+153)} = 0.6695 \quad (1)$$

B. Inductor L_1

The switching frequency is selected as 20 kHz, so as to reduce the inductor current ripple and inductor size. Inductor L_1 is calculated as follows, where I_{L1} is equal to $I_{mpp.}$

$$I_{L1} = I_{mpp} = \frac{P_{pv}}{V_{pv}} = \frac{1620}{153} = 10.58\text{ A} \quad (2)$$

$$L_1 = \frac{(V_{pv} \times D)}{(F_{sw} \times \Delta I_{L1})}$$

$$= \frac{(153 \times 0.6695)}{(20K \times 0.06 \times 10.58)} = 8.068\text{mH} \approx 8\text{mH} \quad (3)$$

Where f_{sw} is the switching frequency and ΔI_{L1} is the inductor current ripple.

C. Inductor L_2

Inductor L_2 is calculated as, where the inductor current I_{L2} is

$$I_{L2} = \frac{P_{pv}}{V_{dc}} = \frac{1620}{310} = 5.22\text{A} \quad (4)$$

$$L_2 = \frac{(V_{pv} \times D)}{(F_{sw} \times \Delta I_{L2})}$$

$$= \frac{(153 \times 0.6695)}{(20K \times 0.06 \times 5.22)} = 16.3527mH \approx 17mH \quad (5)$$

ΔI_{L2} is an inductor L_2 ripple current.

D. Transfer Capacitor C_1

The intermediate energy transfer capacitor C_1 is calculated follows, where the V_{C1} is

$$V_{C1} = \frac{V_{pv}}{(1 - D)} = \frac{153}{1 - 0.6695} = 462.93\,V \quad (6)$$

$$C_1 = \frac{I_{pv} \times (1 - D)}{(F_{sw} \times \Delta V_{C1})}$$

$$= \frac{10.58 \times (1 - 0.6695)}{(20K \times 0.04 \times 462.93)} = 9.4595\mu F \approx 10\mu F \quad (7)$$

ΔV_{C1} - ripple voltage across capacitor C_1.

E. DC Link Capacitor C_2

The DC link capacitor is calculated as follows,

$$\omega = 2\pi f = \frac{2\pi \times N_r \times P}{120} = 628.3185 \quad \text{rad/sec} \quad (8)$$

$$C_2 = \frac{Idc}{6 \times \omega \times \Delta Vdc}$$

$$= \frac{5.22}{6 \times 628.3185 \times 3.1} = 446.66\mu F \approx 500\mu F \quad (9)$$

2. TWO PHASE INTRLEAVED BOOST CONVERTER (IBC)

Interleaving is the technique of paralleling converters, so that the input current can be shared among the inductors. The two inductors operate with 180º phase shift in order to reduce the current ripple of the converter.

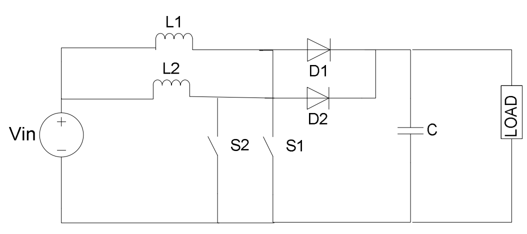

Figure 3: Two Phase Interleaved Boost Converter

Figure 3 shows the circuit of the interleaved boost converter. It consists of inductor L_1 and L_2, Diode D_1 and D_2, Switch S_1 and S_2, capacitor C_1 and load. In interleaved boost converter operation, inductors are used to transform the energy from the input voltage to the inductor current and convert it back from the inductor current to the output voltage. The inductors used in a circuit are of similar rating. Using two similar inductors will help in sharing the input current equally and the inductor peak current rating is also reduced, thereby reducing the inductor rating and cost of the inductor. As the output current is divided by the number of phases, the current stress on each switch is reduced.

The ripple content reduces with increase in number of phases. If the number of phases increase further without much decrease in the ripple content, the complexity of the circuit increases very much, thereby increasing the cost of implementation. Hence, by considering the ripple content and cost, complexity, the numbers of phases are chosen as two.

The switch which is chosen for the interleaved boost converter is MOSFET, because of its high commutation speed and high efficiency at low voltage. Each MOSFET is switching at the same frequency, but a phase difference of 180^o. The phase shift is given by $360^o/n$. Therefore, for two phases interleaved converter phase shift is 180^o, where "n" is the number of phases.

DESIGN OF INTERLEAVED BOOST CONVERTER

A. Duty Cycle

The PV array voltage V_{pv} is 153V and the DC link voltage of the inverter is 310V therefore the duty cycle of the interleaved boost converter is given as

$$D = \frac{V_{dc} - V_{pv}}{V_{dc}} = \frac{310-153}{310} = 0.506 \tag{10}$$

B. Inductor L_1 and L_2

The switching frequency of IBC is taken as 20 kHz in order to minimize the ripple current. The value of inductance of two inductor L_1 and L_2 is calculated as,

$$I_L = N_p \times I_m = 2 \times 5.4 = 10.8\text{ A} \tag{11}$$

$$L_1 = L_2 = \frac{(V_{pv} \times D)}{(F_{sw} \times \Delta I_L)}$$

$$= \frac{(153 \times 0.506)}{(20K \times 0.06 \times 10..8)} = 5.97\text{mH} \approx 6\text{mH} \tag{12}$$

Where ΔI_L is ripple current of value 6% of I_L

C. DC Link Capacitor C

The DC link capacitor is calculated as follows,

$$\omega = 2\pi f = \frac{2\pi \times N_r \times P}{120} = 628.3185 \quad \text{rad/sec} \tag{13}$$

$$C = \frac{I_{dc}}{6 \times \omega \times \Delta V_{dc}}$$

$$= \frac{5.22}{6 \times 628.3185 \times 3.1} = 446.66\mu F \approx 500\mu F \tag{14}$$

VI. SIMULATION RESULTS

A. Simulation of Converters with Resistive Load

1) CUK Converter with Resistive Load

Figure 4 shows a Simulink model of CUK converter with the resistive load. The input voltage is V_{in} = 153 V, switching frequency is 20 kHz and duty cycle D= 0.6695. The load resistance R_L= 59.50 ohm.

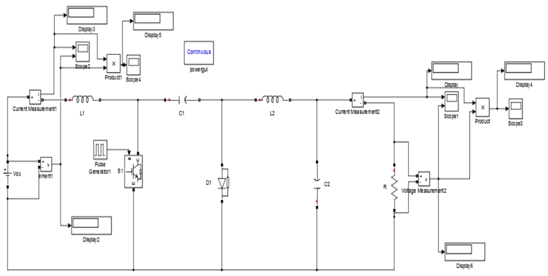

Figure 4: Simulink Model of CUK Converter with R Load

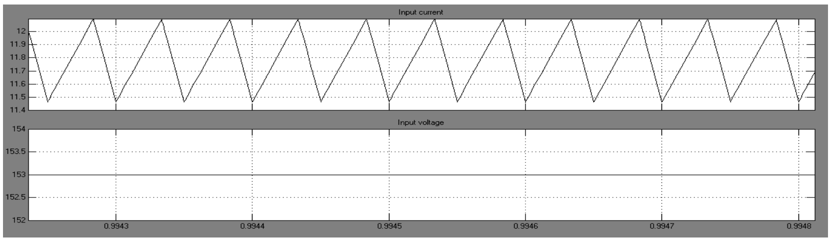

Figure 5: Input Current and Input Voltage of CUK Converter

2) IBC with Resistive Load

Figure 6 shows a Simulink model of IBC with the resistive load. The input voltage is V_{in}= 153 V, switching frequency is 20 kHz and duty cycle D= 0.506. The load resistance R_L= 59.50 ohm.

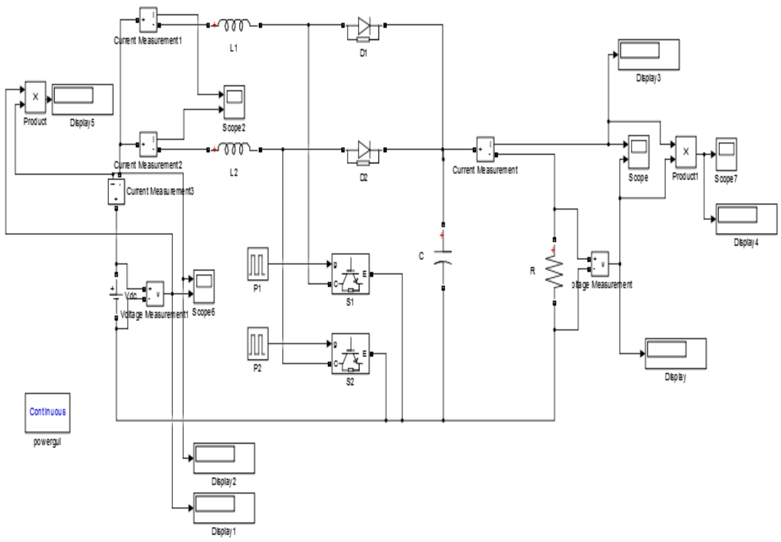

Figure 6: Simulink Model of IBC Converter with R Load

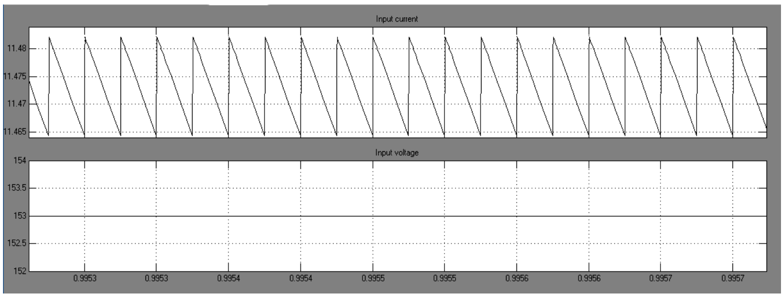

Figure 7: Input Current and Input Voltage of IBC

Simulation result shows that IBC has the ability to share the input current and reducing the ripples in the input current.

B. Simulation of Converters with BLDC Motor

1). Vcuk Converter with BLDC Motor

The CUK converter is simulated with BLDC motor in Figure 8. The input voltage V_{pv} = 153 V, the rated input voltage of BLDC motor is 310 V and rated speed of 3000 RPM at full load. The waveform of output voltage and rotor speed is as shown in Figure 9 and Figure 10 respectively.

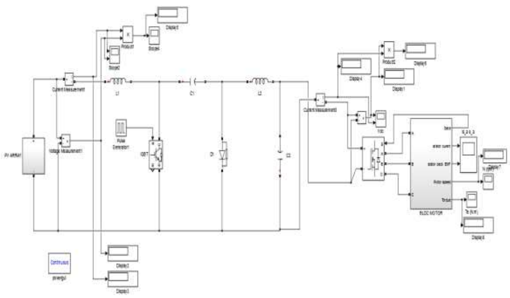

Figure 8: Simulink Model of CUK Converter with BLDC Motor

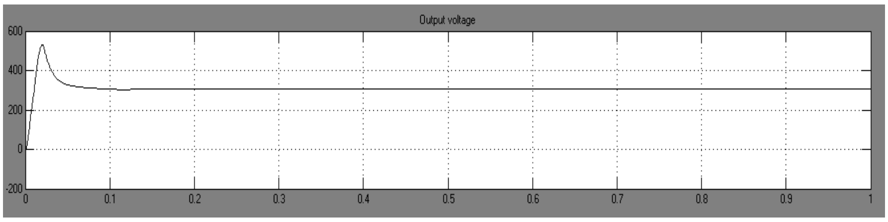

Figure 9: Transient and Steady State Response of CUK Converter

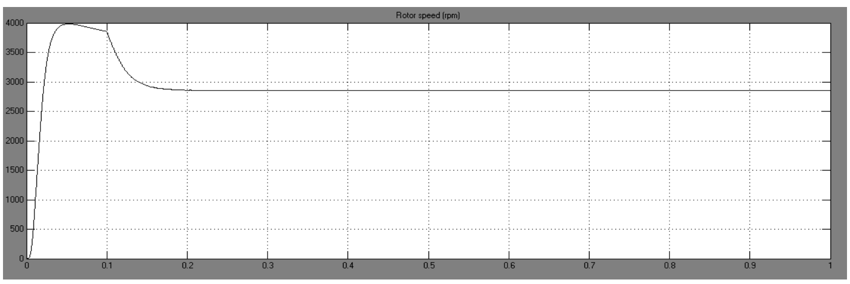

Figure 10: Rotor Speed of BLDC Motor is using CUK Converter

2). IBC with BLDC Motor

The IBC converter is simulated with BLDC motor in Figure 11. The input voltage V_{pv} = 153 V, the rated input voltage of BLDC motor is 310 V and rated speed of 3000 RPM at full load. The waveform of output voltage and rotor speed is as shown in Figure 12 and Figure 13 respectively.

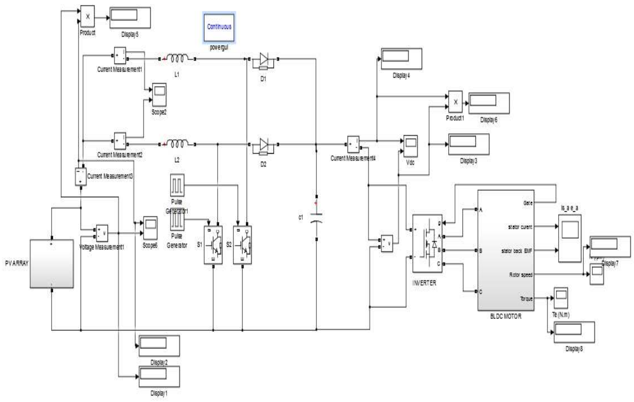

Figure 11: Simulink Model of IBC Converter with BLDC Motor

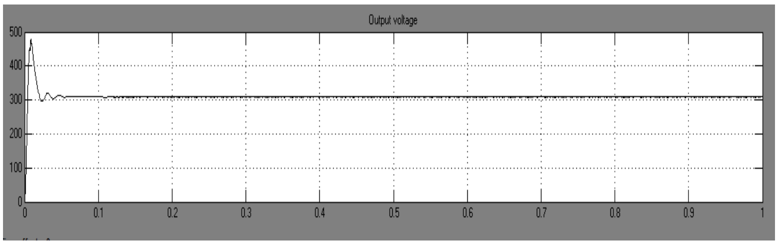

Figure 12: Transient and Steady State Response of IBC

From Figure 9 and Figure 12, Peak overshoot of IBC is less than the CUK converter and also IBC has less settling time.

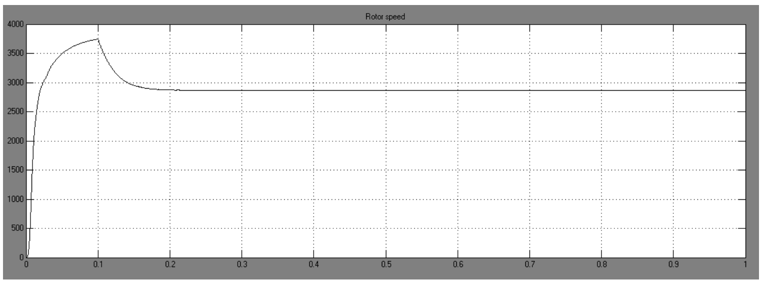

Figure 13: Rotor Speed of BLDC Motor Using IBC

Figure 10 and Figure 13 shows the speed response of BLDC motor using IBC and CUK converter respectively. From the figure it is seen that the rise time by using IBC is less than that of CUK converter.Also the full load rotor speed motor is more in case of IBC.

VII. RESULTS AND DISCUSSIONS

Table III: Performance Parameters of Converters with R-Load

Parameters	IBC	CUK
V_i	153	153
I_i	11.46	11.46
P_i	1754	1754
Duty cycle	0.506	0.6695
V_o	308.5	307.5
I_o	5.194	5.177
P_o	1603	1592
ΔV_o	0.0035	.0094
ΔI_i	0.0178	0.636
Efficiency (%)	91.39%	90.76%

To get the required output voltage, the IBC operated at D=0.506 and CUK converter operated at D=0.6695. From table III the simulated results show that the output voltage and output power of IBC is more than that of the CUK converter. The IBC has a higher frequency and reduced input ripple current by 97% and ripple output voltage by 63%.

Table IV: Performance Parameters of Converters with BLDC Motor

Converter	V_{in}	Duty cycle D	Vo	P_{out} Watt	Speed RPM	Torque N-m
IBC	153	0.506	308.8	1549	2866	3.662
CUK	153	0.6695	308	1315	2854	3.116

The performance of the converters is simulated with the BLDC motor load listed in Table IV. From simulation results it is seen that BLDC motor gives better performance with IBC in terms of efficiency, speed and torque of the motor.

Table V: Effect of Irradiation

Irradiation W/m^2	IBC				CUK			
	V_i	W_i	V_o	W_o	V_i	W_i	V_o	W_o
200	36.94	100.3	73.1	89.97	36.94	99.28	72.1	87.51
400	73.45	401.7	147.2	364.7	73.45	400.2	146.2	359.7
600	107.8	868.1	216.8	791.3	107.8	866.8	215.8	783.9
800	135.2	1368	272.3	1249	135.2	1367	271.3	1239
1000	153	1754	308.5	1603	153	1754	307.5	1592

Performance of DC-DC converter with variation in Irradiance S, from 200 W/m2 to 1000W/m2 is listed in the Table V. From the simulation results it is seen that IBC gives better performance in terms of output voltage and efficiency at different irradiance level.

VIII. CONCLUSIONS

The selection of converter plays a considerable role in efficient utilization of the renewable energy. This paper discussed the principle of operation and various design parameters of IBC and CUK converter. Performance of IBC and CUK converter is analyzed in MATLAB with resistive and BLDC motor load. The simulation results obtained under various conditions illustrate that the IBC is more efficient than the CUK converter. The interleaved technique reduces the input ripple current by 97% and output voltage ripple by 63%. The transient and steady state response of BLDC motor is better with the IBC. The performance of converters with different irradiation level shows that Interleaved DC-DC Boost converter is a suitable choice for solar power.

IBC topology has been found suitable for the applications involving solar powered BLDC motor driven Electric vehicle also this topology can be used for solar powered water pumping system.

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