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J. Electrical Systems 18-4 (2022): 533-555

Regular paper

Journal of Electrical Systems

Performance Evaluation of isolated and non-isolated panel integrated DC-DC converter based on switching characteristics

DC-DC converters are used in many power electronics applications including PV integrated system to boost the voltage to the required level. Many isolated and non-isolated DC-DC converter topologies are used to improve the performance of the PV system. Based on the voltage level and conversion efficiency suitable topology is selected for an application. Performance of the DC-DC converter is evaluated based on inrush current, settling time, switching time, switching losses, switching stress, power output, filter requirement and conversion efficiency. It is very much important to select an appropriate topology for a desired application considering the above parameters. In this work, design and analysis of non-isolated and isolated converters namely conventional boost converter, boost converter with interleaved operation, flyback converter and flyback converter with interleaved operation is evaluated for 200W PV integrated DC-DC converter system. Switching characteristics and its effect on efficiency of power converters is evaluated.

Keywords: Photo Voltaic (PV), Switching losses, Switching time, Inrush current, Dc-Dc converter, power converter.

1. Introduction

Selection of proper power converter is very essential to meet the requirement of load in an application to obtain optimum performance. Many isolated and non-isolated DC-DC converter topologies are used to meet load requirements from low voltage, nonlinear power sources. Practically power converters are designed and build to incorporate isolation between input circuit and output load circuit for safety reasons and also to obtain multiple outputs with different voltages. Isolated converters are generally buck based or buck boost based isolated converters. Many applications use non-isolated DC-DC converters with high output voltage gain either with extreme duty ratio or a large circulating energy. From low voltage, large input current is obtained in PV system. Due to this low voltage, devices with less $R_{DS\text{-}on}$ are selected for the converter to reduce conduction losses [1].

Various DC-DC converter topologies are used for PV panel integration to convert full panel power or a fraction of it. In PV system with implementation of DC-DC converters on panel level, maximum power can be extracted regardless of any mismatch [2]. DC-DC converters with coupled inductors provide high voltage gain but with degradation of efficiency due to associated losses with leakage inductors. Applied converter technology is one of the main drivers in a PV system to cut down the cost by boosting overall efficiency of the PV system [3]. By simulating and analyzing various DC-DC converters for typical irradiance and user scenarios best DC-DC converter topology can be selected that maximize overall PV system

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efficiency. Main factors that affect the efficiency of a DC-DC converter is mainly due to low input voltage, high inrush current and static gain. Conventional boost converter has static gain and high switching stress. Also, conventional boost converter has high current ripples with more conduction losses. High step-up converters are affected with high input current, and to overcome this problem converter should be operated at high switching frequencies. Various topologies are proposed in literature to reduce input inrush current with faster settling time. Interleaving is one of the topologies to improve efficiency of the DC-DC converter. For applications requiring high voltage gain, non-isolated DC-DC converters are generally preferred which operates at high efficiency, taking high currents from low voltage dc sources [4].

Interleaving provides parallel path for input current where converters are connected in parallel. It is equivalent to a parallel combination of two sets of switches, diodes and inductors connected to a common filter capacitor and load. This technique reduces stress on switches and thus reduce the size of filter components. By parallel operation current gets divided and hence i2R loss minimizes thereby decreasing current stress and reduce ripple. Utilizing magnetic coupling voltage gain can be improved by adjusting turns ratio [4-5]. Fig.1 shows conventional non-isolated boost and interleaved boost circuit configuration.

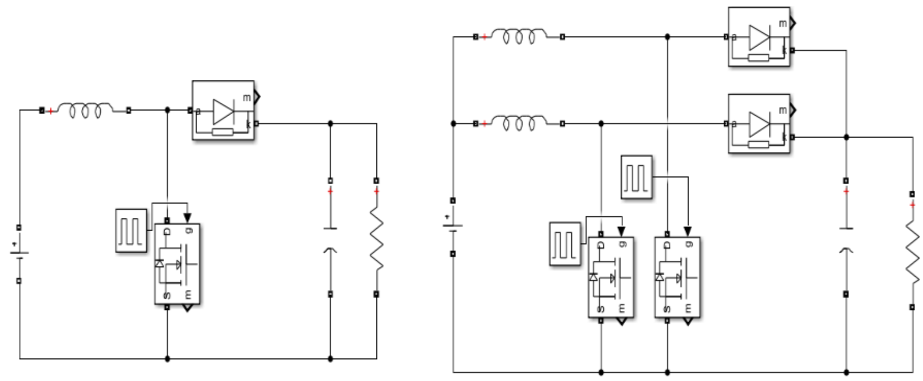


Fig.1 Non isolated conventional boost and interleaved boost converter

Among various converter topologies for PV applications to perform MPPT the topologies such as, high voltage gain, shaped output current with galvonic isolation, flyback converter are most commonly used due its simple structure and control and provides high efficiency [6-7]. A flyback isolated converter as shown in Fig. 2 has splitted inductor to form a transformer. Design of transformer and selection of duty cycle decides the output voltage in such converters. Generally in the available literature, the design of flyback converter is discussed for boundary and discontinuous mode of operation due to its inherant constant current source characterisicts. Control algorithms in Continuous Conduction Mode (CCM) are more complicated than in Discontinuous Conduction Mode (DCM) and Boundary Conduction Mode (BCM) [7].To reduce input current ripple interleaved operation of flyback converter is preferred. Flyback converter are suitabled for high frequency with low power applications. Transformer in flyback converter is a two winding inductor which acts as storage and also provides electrical isolation[6-12]

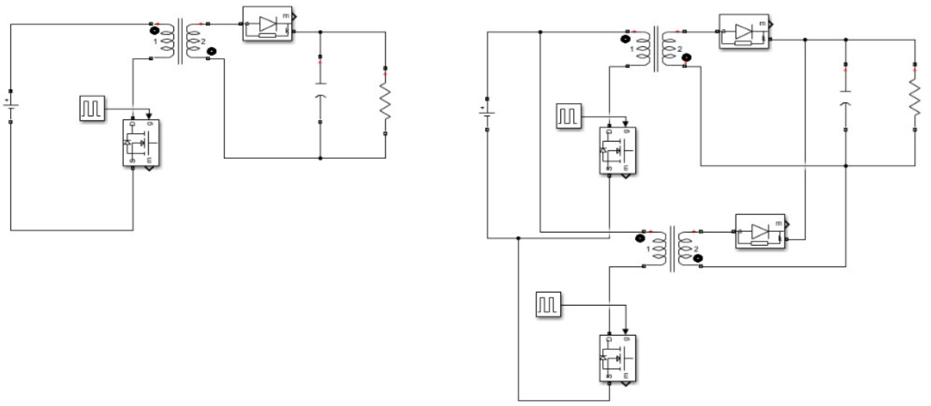


Fig.2 Flyback and interleaved Flyback converter

DC-DC converter can be designed to operate either in continuous conduction mode(CCM)or discontinious conduction mode (DCM).Voltage gain of boost converter operating in DCM is higher than that in CCM mode.For low current and high voltage applications DC-DC converters are operated in discontinuous conduction mode whereas for high current ,low voltage applications DC-DC coverters are operated in continuous conduction mode.DCM mode of operation is preffered for fast response to load current and input voltage variation compared to CCM.Boost converters are used in most of the step up applications due to its simple circuit architecture and easy control.

Converter efficiency is affected by various losses that occurs in DC-DC converter .Various losses that effects efficiency of a power converter are

Losses in switches due to drain -source resistance.

Losses in diode due to diode series resistance

Losses in inductor due to internal series resistance

Losses in capacitor due to internal resistance

Total power loss is calculated using equation 1 and converter efficiency is calculated using equation 2[8-9].

$$P_{loss} = P_{switch} + P_{diode} + P_{inductor} + P_{capacitor} \qquad (1)$$

$$\eta = \frac{P_{output}}{P_{output} + P_{loss}} \qquad (2)$$

In the literature survey carried out, the design and analysis of isolated and non-isolated converters for a specific load, along with interleaved operation is not adequately discussed. Also in addition, the switching transient’s analysis is not discussed in detail. In this paper comparative performance evaluation of conventional non-isolated boost and isolated flyback DC-DC converter along with interleaved operation is carried out for a PV system with load capacity of 200W.The system comprises of a PV panel, DC-DC converter connected to a constant load. Performance comparison of the DC-DC converter is carried out with respect to switching, associated switching loss and efficiency. The work carried out is presented in the following sections. Section 2 discusses the design and analysis of non-isolated boost converter, non-isolated interleaved boost converter, flyback converter, interleaved flyback converter. Section 3 discusses results obtained in detail.

2.Design specifications of isolated and non-isolated dc-dc converter

In this work analysis of PV integrated DC-DC converters are carried out for 200W design and the specifications are as shown in Table 1. The converter is designed for 10% ripple current and 2% ripple voltage. The associated equations and the calculated values are tabulated as shown in Table 2. PV module specifications used for simulation is shown in Table 3. P-V and I-V curve of the selected PV module as per specification is shown in Fig 3. Transformer for flyback operation has turns ratio V1:V2 as 29:120 with nominal power of 200W and frequency of 30KHz.Transformer magnetization resistance and inductance for simulation selected are 500Ω and 500mH respectively.

Table 1. Design specification of DC-DC converter

Power output Pout	Switching frequency fs	Output voltage V0	Input voltage Vin	Load resistance R
200W	30KHz	120V	29V	72Ω

Table 2. Designed values of L and C

Converter	Formula	2% Vripple& 10 % Iripple
Boost	$L = \frac{V_{in} D}{f_s \Delta I}$ $C = \frac{I_0 D}{f_s \Delta V_0}$	L=4.398mH C=17.539μF
Flyback	$L_m = \frac{(V_{dcmin} D_{max})^2}{2P_{in} f_s \text{ Ripplefactor}}$ $C = \frac{I_0 D}{f_s \Delta V_0}$	Lm=18.2μH C=11.56μF

Table 3. PV module specification

Short circuit current ISC	Open circuit Voltage Voc	Current at maximum power Imp	Voltage at maximum power Vmp
7.85A	34.92V	6.87A	29.1V

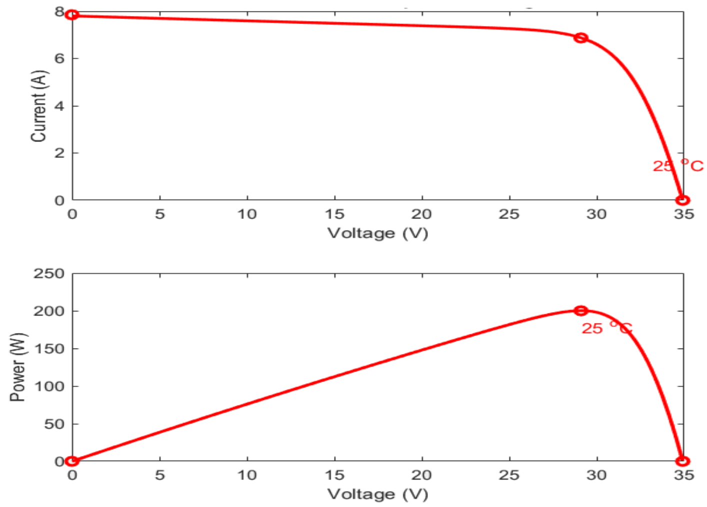


Fig 3. I-V and P-V curves of the PV module

2.1 non-isolated conventional boost converter

PV array connected to a non-isolated boost converter is as shown in Fig 4, whose voltage gain can be obtained using equation 3 [9]. Input and output voltage, input and output current waveforms for 200W load capacity in non-isolated boost converter are shown in Fig 5. The switching waveforms are shown in Fig 6.

$$\frac{V_O}{V_{IN}} = \frac{1}{1-D} \qquad (3)$$

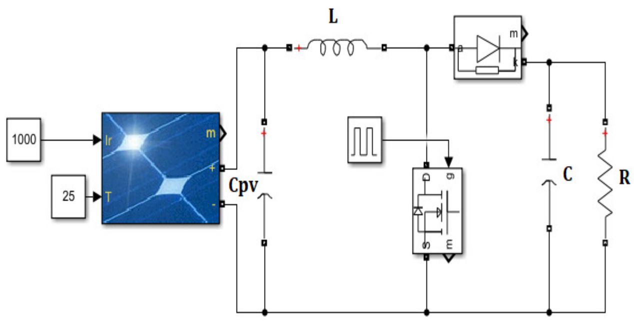


Fig 4.Non isolated Boost converter

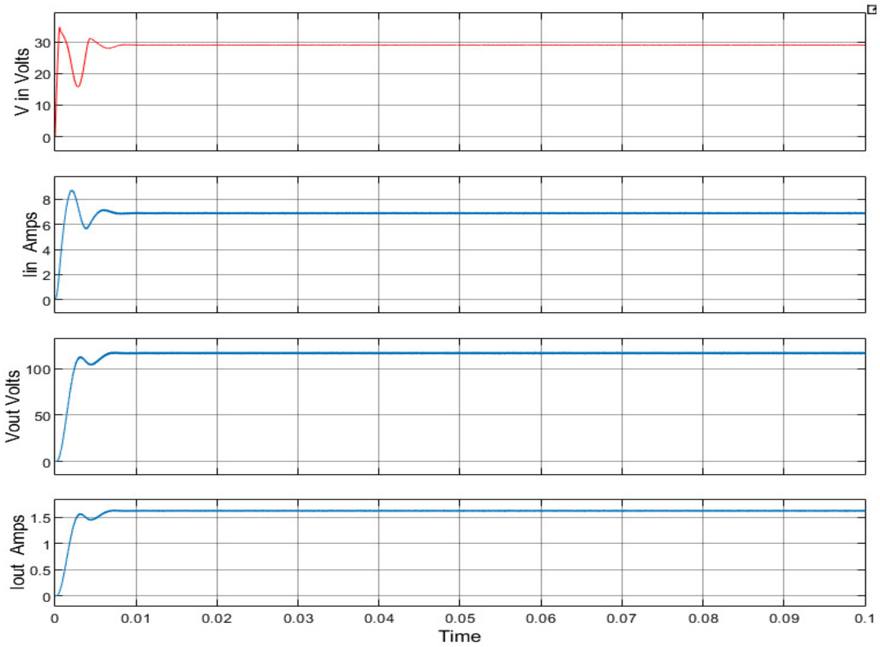
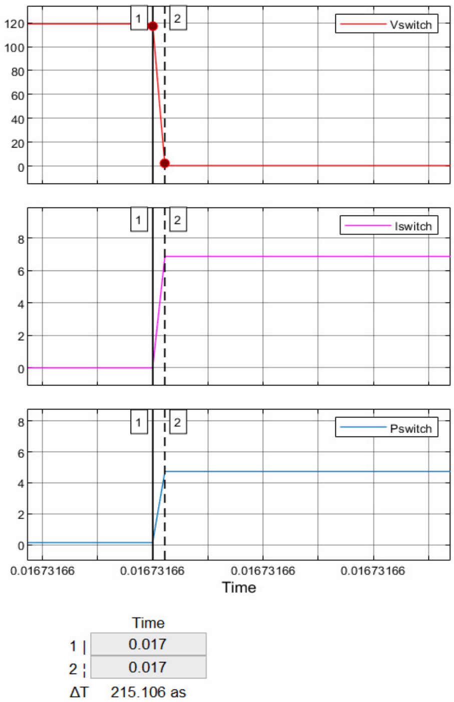


Fig 5. Input and output voltage, current waveforms

From voltage and current waveforms, it is observed that for an input voltage (V_{in}) of 29V with 0.758 duty ratio (D) 117.3V is obtained as output (V_{out}). Power delivered (P_{out}) to load of 72Ω is 191W which draws a current (I_{out}) of 1.62A. Transient inrush inductor peak current is 8.8 A as shown in I_{in} waveform with a settling time of 9.17ms.



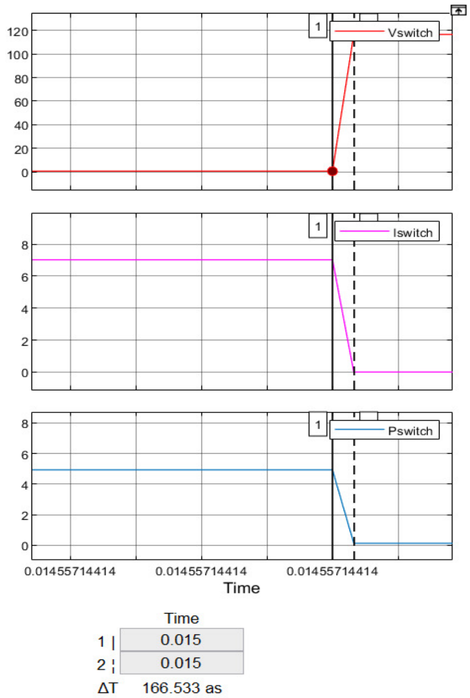


Fig 6a.Turn on switchingFig 6b.Turn off switching

From switching charecteristics as shown in Fig 6a and in Fig 6b, it is found that turn on time is 215.106 atto sec and turn off time is 166.533 atto sec and converter will be operating in continuous conduction mode .During turn on dv/dt is found to be 0.532V/as as observed from graph and similarly di/dt is found to be 0.031A/as.During turn off ,as observed from graph dv/dt is 0.71V/as and di/dt is 0.04A/as.

2.2 Interleaved non isolated Boost converter

Fig 7 shows interleaved non isolated boost converter circuit configuration. The interleaved boost structure has advantages of low input current ripple and current sharing performance [10].The waveforms for current through the inductor L1(IL1),L2(IL2)and total input current(IL) are shown in Fig 8. Input and output voltage, current waveforms in non-isolated boost converter are shown in Fig 9. The switching waveforms are shown in Fig 10.

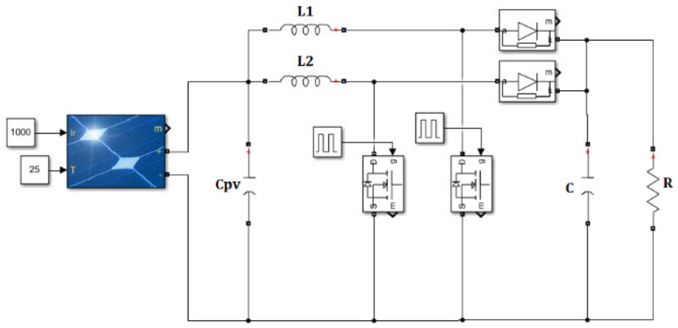


Fig 7. Interleaved boost converter

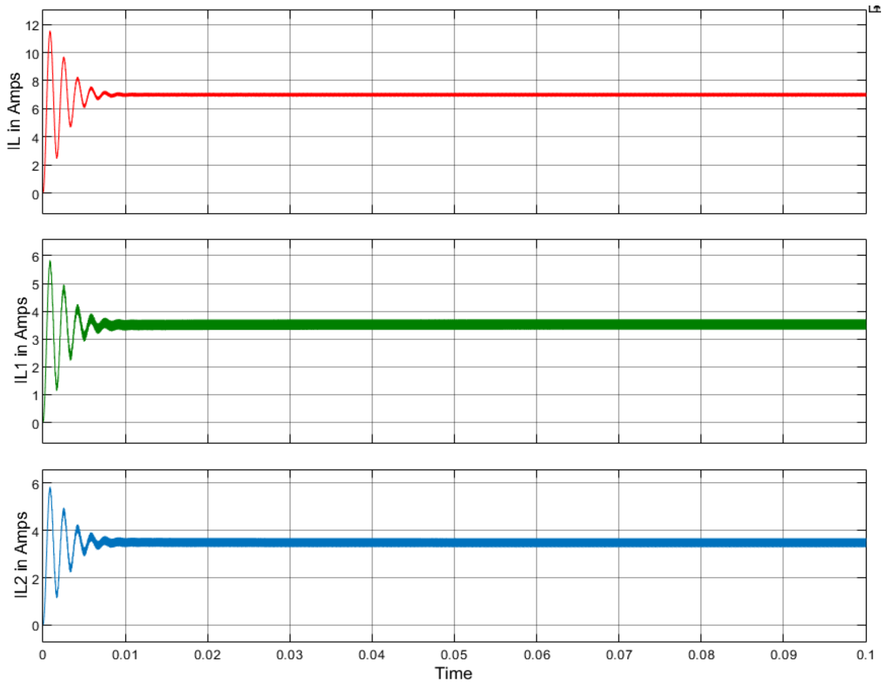


Fig 8.Inductor current waveforms

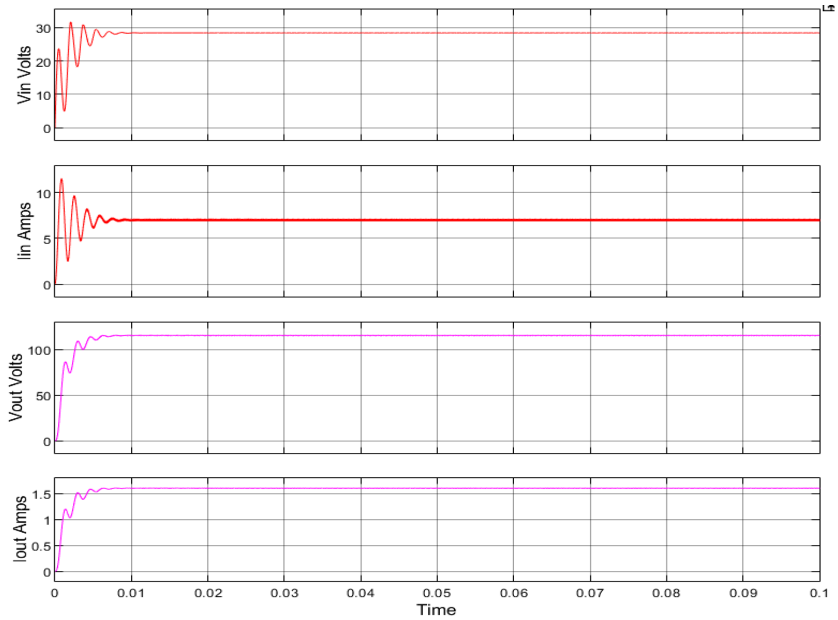


Fig 9. Input and output voltage, current waveforms

From voltage and current waveforms, it is observed that for an input voltage (V_{in}) of 29V, with 0.758 duty ratio (D),115.7V output (V_{out}) is obtained maintaining maximum power output from the PV panel. Power delivered to load (P_{out})of 72Ω is 185.91W which draws a current (I_{out}) of 1.604A. Input inrush peak inductor current is 5.82A with settling time of 15msec.

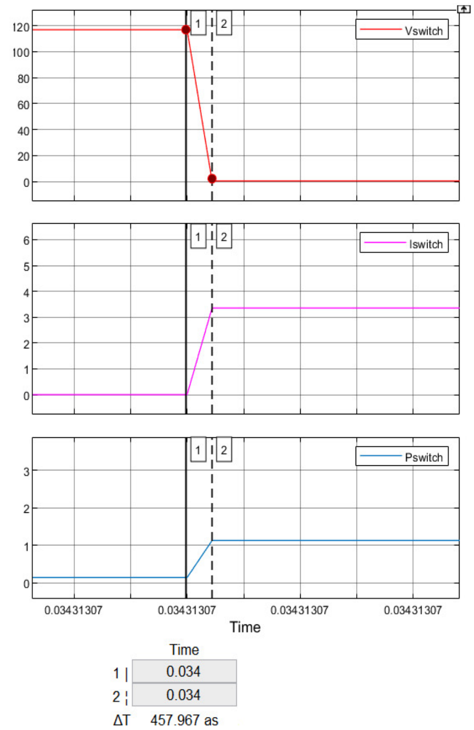


Fig 10a. Turn on switching

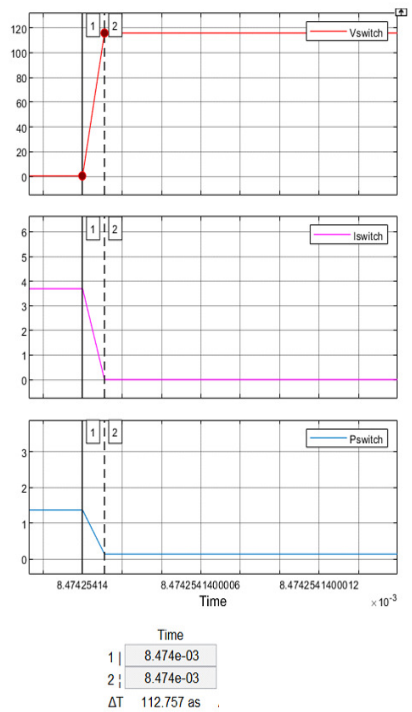


Fig 10b. Turn off switching

From switching charecteristics as shown in Fig 10a and in Fig 10b ,it is found that turn on time is 457.967as and turn off time is 112.757as and converter will be operating in continuous conduction mode. During turn on dv/dt is 0.253V/as and di/dt is 0.008A/as.During turn off dv/dt is 1.02V/as and di/dt is 0.03A/as.

2.3 Fly back Converter

Fig 11 shows flyback dc-dc converter with isolation. Voltage gain in flyback converter is obtained as in equation 4 [11]. Isolation separates input and output side. Input and output voltage, current waveforms in flyback converter are shown in Fig 12. The switching waveforms and time during circuit operation is shown in Fig 13.

$$\frac{V_0}{V_{IN}} = \frac{N_2}{N_1}\frac{D}{1-D} \qquad (4)$$

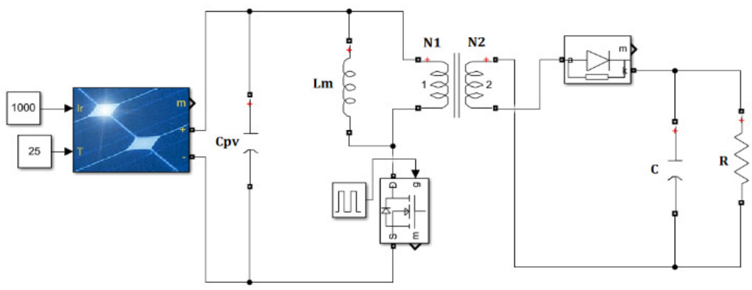


Fig 11. Flyback converter

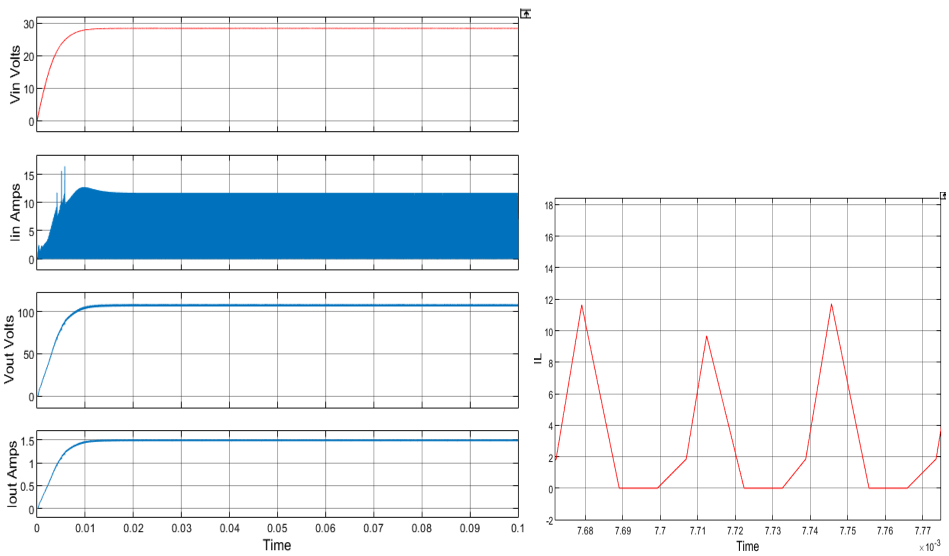


Fig 12. Input and output voltage, current waveforms

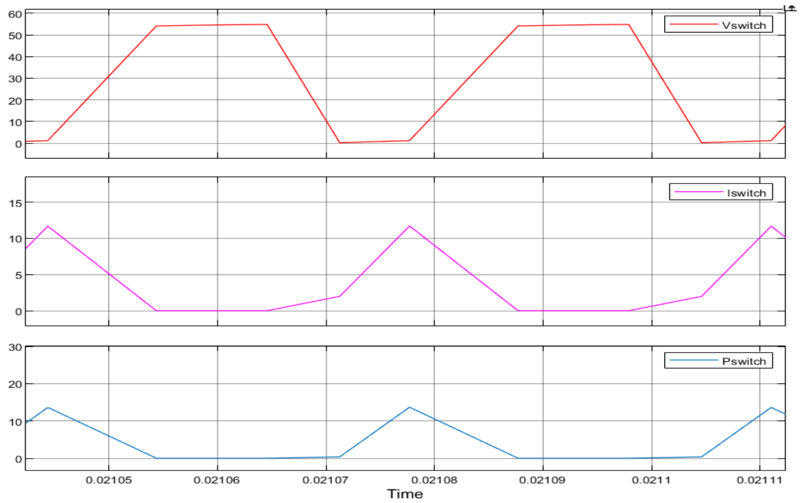


Fig 13. voltage and current stress waveforms across the switch

From switching charecteristics it is found that turn on time is 6.767µs and turn off time is 10.339µs. During turn on dv/dt is 7.785V/µs and di/dt is 1.35A/µs.During turn off dv/dt is 5.14V/µs and di/dt is 1.19A/µs.

2.4 Flyback Interleaved Operation

Interleaved flyback topology is shown in Fig 14. A proper design of snubber can limit drain -source overshoot of the flyback's main switch during turn -off process [12]. Input and output voltage, input and output current waveforms in interleaved flyback converter is shown in Fig15. The switching waveforms during circuit operation is shown in Fig 16.

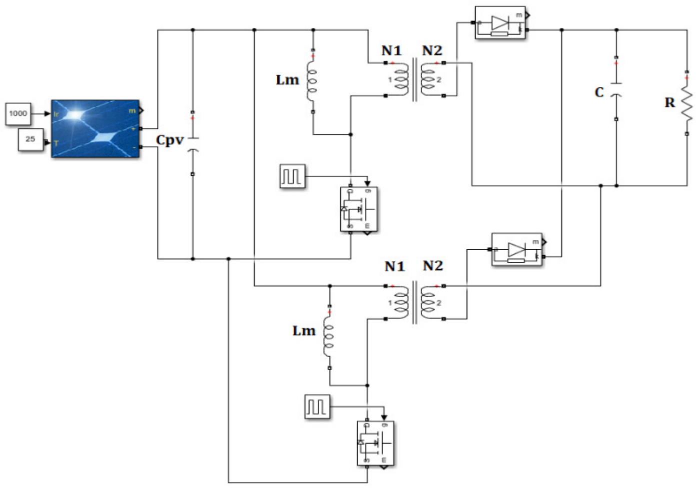


Fig 14.Interleaved Flyback converter

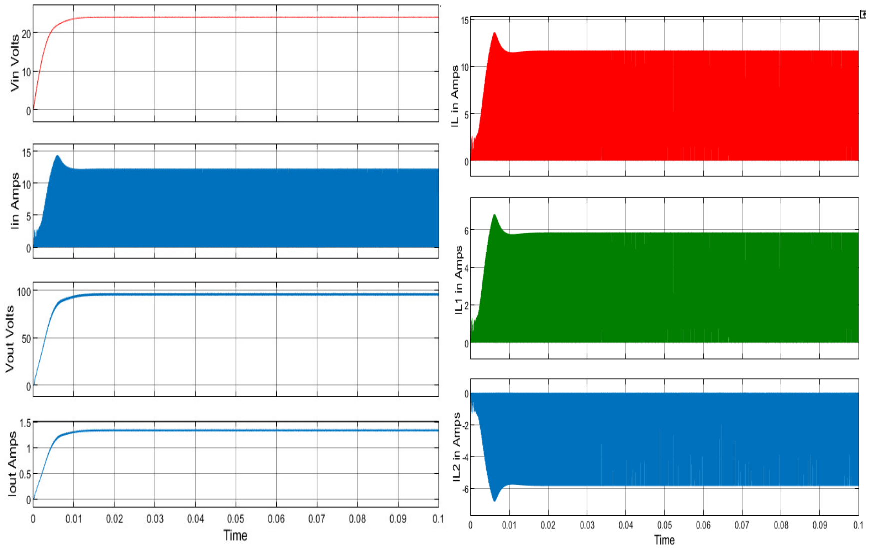


Fig 15. Input and output voltage, current waveforms

From voltage and current waveforms, it is observed that for an input voltage (Vin) of 29V with 0.394 duty ratio (D) 96.57V is obtained as output (V_o). Power delivered (P_{out}) to load of 72Ω is 129.5W which draws a current (I_{out}) of 1.52A. With the designed values converter operates in discontinuous mode. Inrush input peak current in each inductor is 6.825A with settling time 12.78ms.

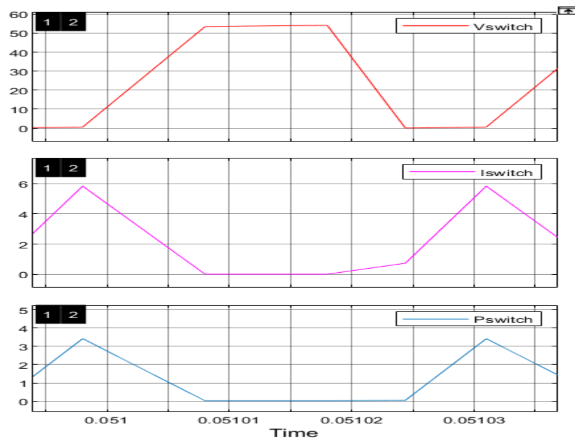


Fig 16. voltage and current stress waveforms across the switch

From switching charecteristics it is found that turn on time is 6.349µs and turn off time is 10.091µs. During turn on dv/dt is 8.5V/µs and di/dt is 0.92A/µs.During turn off dv/dt is 5.35V/µs and di/dt is 0.57A/µs.

3 Results and Discussions

In this work, performance of non-isolated and isolated boost and flyback Dc-Dc converter is evaluated based on output power, ripple content, efficiency and voltage stress on MOSFET switch. The results obtained for a fixed load of 72Ω, switching frequency of 30KHz and irradiation of 1000W/m^2 are discussed. Analysis of interleaved operation of converter is carried out considering series snubber capacitor value of 250nF, diode series snubber resistance of 500Ω as well as with 1500Ω.To arrive at an optimal switching frequency and to analyze the switching power loss, simulation is carried out for two different switching frequencies of 30KHz and 50kHz.The results obtained are shown in Fig 17,18 and 19.

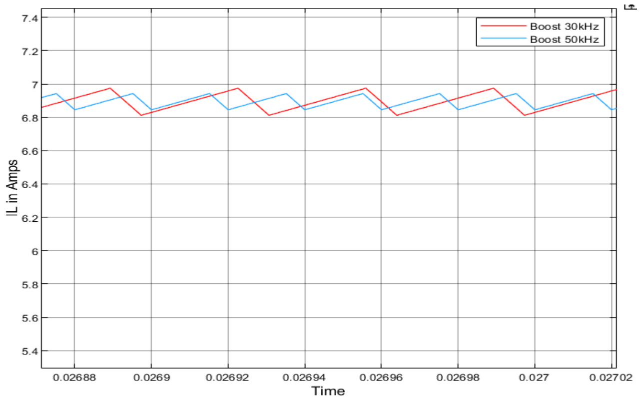


Fig 17.Current ripple in input inductor current at 30KHz and 50KHz

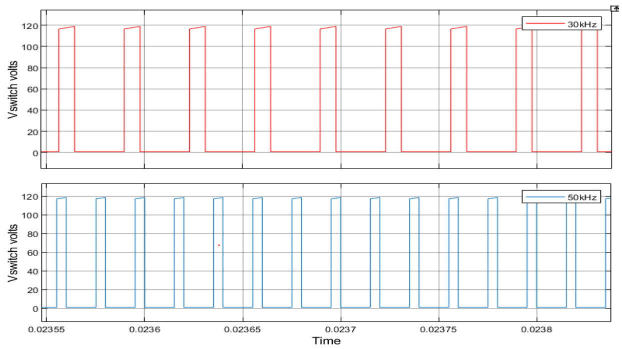


Fig 18.Switching voltage across switch at 30KHz and 50KHz

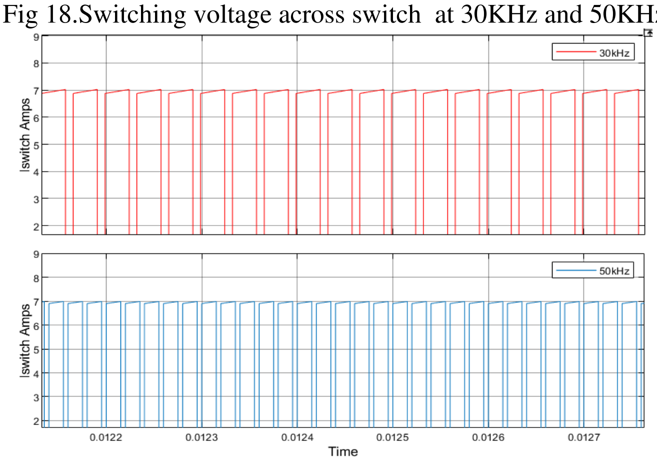


Fig 19.Current through switch at 30KHz and 50KHz

From switching charecteristics it is observed that at switching frequency of 30KHz inductor current ripple is 0.162A with switching voltage of 118.42V where as at 50KHz it is 0.1A with switching voltage of 118.3V.From the results it is observed that compared to 30KHz for the same load conditions, current ripple and voltage stress at 50KHz switching reduces.However ,it is observed that the switching power loss increases at 50KHz.Hence in this work the simulation is carried out for switching frequency of 30KHz to obtain better efficiency of converter .

3.1. Performance of Boost and Interleaved boost converter

For the same switching frequency and load, conventional boost and interleaved boost converter operations are compared with respect to switching loss and converter efficiency. The results obtained are tabulated in Table 4. The parameters P_{panel}, P_{out}, ΔV, ΔI, V_0, Psw, %η indicates power output from panel, power delivered to load, ripple in output voltage, ripple in input current, output voltage, power loss in switch and percentage converter efficiency respectively. The transients in inductor current during converter operation is shown in Fig 20. Efficiency of converter at various load conditions are shown in Fig 21 and Fig 22.

Table 4:Switching loss and efficiency in conventional boost and interleaved boost converter with duty ratio 75.8%

Converter	$R_{sb}\Omega$	L mH	C µF	P_{panel} W	P_{out} W	ΔV V	ΔI A	V_0 V	P_{sw}W	%η
Boost	500	4.398	17.539	199.6	191	2.36	0.57	117.3	5.065	95.69
Interleaved Boost	500	1.9	17.539	199.7	185.9	0.78	0.4	115.7	2.675	93.08
	1500	1.9	17.539	199.9	193.9	0.87	0.3	118.2	2.551	96.99

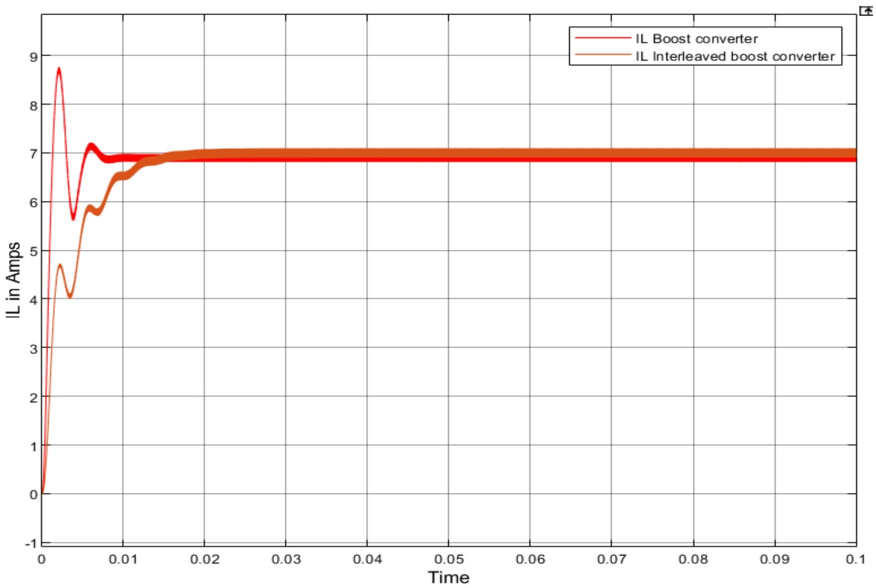
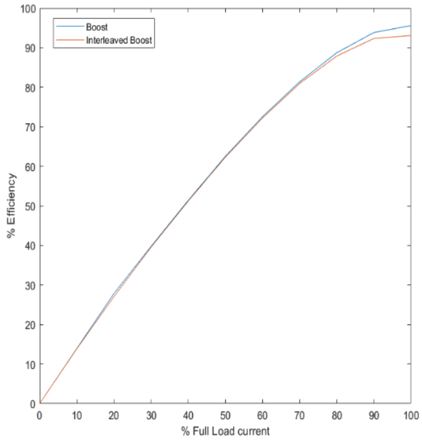


Fig 20. Inductor current in boost and interleaved operation

From results it is observed that inductor current transients are more in conventional boost converter compared with interleaved boost converter operation. Interleaved operation gives better performance in terms of current stress and switching losses there by increasing converter efficiency.



21. Efficiency with snubber 500Ω

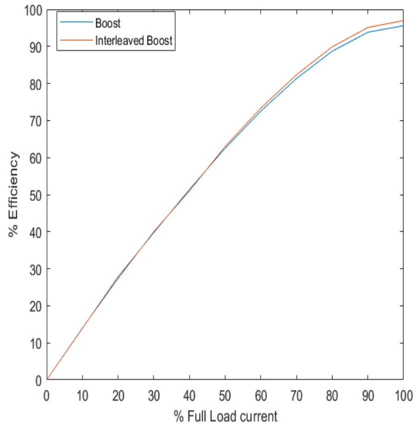


Fig 22.Efficiency with snubber 1500Ω

3.2. Performance of Boost and Flyback converter

For the same switching frequency and load, conventional boost and flyback converter operations are compared with respect to switching loss and converter efficiency. The results obtained are tabulated in Table 5. Efficiency of converter at various load conditions are shown in Fig 23.

Table 5: Switching loss and efficiency in conventional boost and flyback converter

Converter	% D	L H	C F	P_{panel} W	P_{out} W	ΔV	ΔI	V_0 V	P_{sw} W	%η
Boost	75.8	4.398m	17.539μ	199.6	191	2.36	0.57	117.3	5.065	95.69
Flyback	39.4	18.2μ	11.56μ	199.3	161.5	2.5	0.03	107.8	4.896	80.78

From results it is observed that efficiency of flyback converter is low compared to conventional boost converter.Current ripple is high due to presence of transformer .For same switching frequency and load conditions flyback efficiency is less

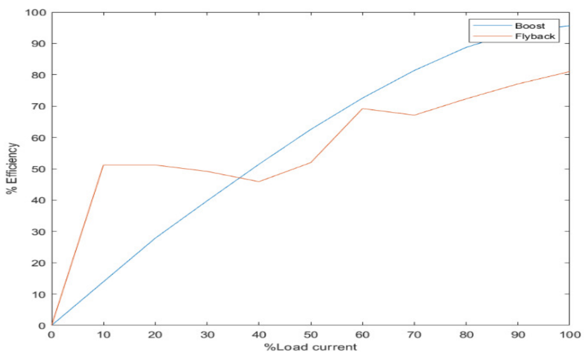


Fig 23. Efficiency of boost and flyback converter

3.3. Performance of Flyback and Interleaved flyback converter

For same switching frequency and load requirement results obtained for flyback and interleaved fly back converter operation is tabulated in Table 6.

Table 6: Switching loss and efficiency in flyback and in interleaved flyback converter with dyty ratio 39.4%

Converter	$R_{snubber}$ Ω	L μH	C μF	P_{panel}W	P_{out} W	ΔV V	ΔI A	V_0 V	P_{sw} W	%η
Flyback	500	18.2	11.56	199.3	161.5	2.5	0.03	107.8	4.896	80.78
Interleaved	500	34.6	11.56	199.3	129.5	2.34	0.03	96.57	3.427	64.72
Flyback	1500	34.6	11.56	192.3	168.6	2.2	0.03	110.2	2.504	87.67

From results it is observed that efficiency of interleaved flyback converter is high compared to normal flyback operation. With 500Ω snubber resistance it is observed that converter efficiency is 64.72% but with 1500Ω snubber value it is 87.67% and this is due to reduction in switching losses due to snubber.

3.4. Performance evaluation of isolated and non-isolated converters for the designed values

Performance evaluation parameters of conventional boost, interleaved boost, flyback and interleaved flyback DC-DC converter for a specific load of 200W are tabulated in Table 7. The converter efficiency obtained at various load conditions with diode series snubber resistance of 500Ω as well as with 1500Ω with series snubber capacitor value of 250nF is tabulated in Table 8 and Table 9.

Table 7: Performance evaluation of isolated and non-isolated converters

Converter	**Conventional Boost**	**Interleaved Boost**	**Flyback**	**Interleaved Flyback**
Designed Wattage W	200	200	200	200
Load Resistance Ω	72	72	72	72
P_{panel} W	199.6	199.9	199.3	192.3
P_{out} W	191	193.9	161.5	168.6
P_{switch} W	5.065	2.675	4.896	2.5
Input inrush current A	8.76	5.8	12.71	6.83
Settling time ms	8.32	12	9.486	12.78
Voltage stress V	118	118	54	54
% Efficiency	95.69	96.99	80.78	87.67
Mode of operation	CCM	CCM	DCM	DCM
Voltage ripple V	2.36	0.8	2.5	2
Current ripple A	0.57	0.3	0.03	0.03
Filter inductor H	4.398m	1.9m	18.2μ	34.6μ
Filter capacitor μF	17.539	17.539	11.56	11.56

Table 8: Efficiency at varying load with snubber 500Ω

% Full Load current	R_{Load}	η_{Boost}	$\eta_{InterleavedBoost}$	$\eta_{Flyback}$	$\eta_{FlyInterleaved}$
10	720	13.92	13.84	51.18	55.29
20	360	27.82	27.04	51.17	44.24
30	240	39.74	39.55	49.14	37.99
40	180.72	51.4	51.17	45.86	34.2
50	144	62.52	62.29	51.93	53.93
60	120	72.54	72.2	69.19	50.82

70	102.89	81.36	80.92	67.08	48.95
80	90	88.72	87.88	72.3	54.13
90	80	93.83	92.33	77.06	59.13
100	72	95.6	93.08	81	64.97

Table 9: Efficiency at varying load with snubber 1500Ω

% Full Load current	R_{Load}	η_{Boost}	$\eta_{InterleavedBoost}$	$\eta_{Flyback}$	$\eta_{FlyInterleaved}$
10	720	13.92	14	51.18	79.8
20	360	27.82	27.36	51.17	70.5
30	240	39.74	40	49.14	53.3
40	180.72	51.4	51	45.86	49.58
50	144	62.52	63	51.93	65.8
60	120	72.54	73.36	69.19	66.56
70	102.89	81.36	82.36	67.08	72.1
80	90	88.72	89.89	72.3	75.76
90	80	93.83	95.12	77.06	80.72
100	72	95.6	96.98	81	87.67

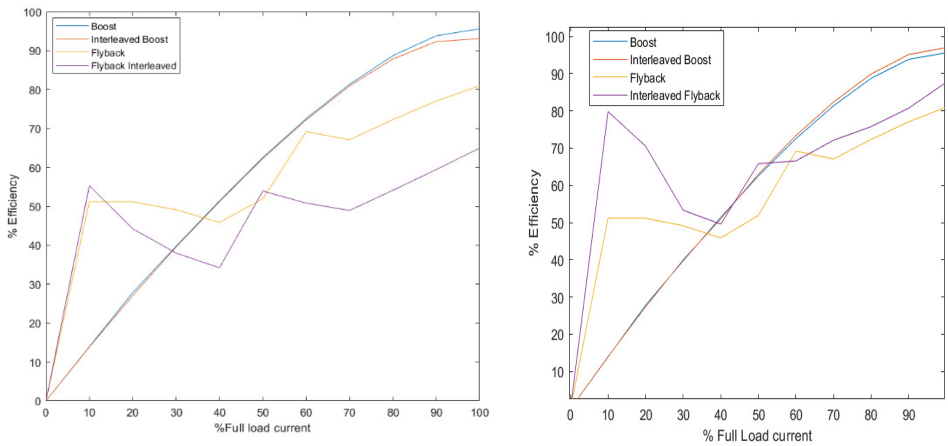


Fig 24. Efficiency curves with snubber 500Ω and 1500Ω

Conclusions

In this work, design and analysis of conventional boost, flyback converter with interleaved boost and interleaved flyback converter ae carried out. From simulation results it is analyzed and observed that efficiency of isolated converter is relatively less when compared to non-isolated topology due to use of coupled inductors or transformers. However, in both types of the converters, the overall efficiency of the system increases due to interleaved operation. In addition, for the same switching frequency of 30KHz, there is reduction in ripple in output voltage and ripple in inductor current in interleaved converters. Efficiency of flyback converter is comparatively low compared with conventional boost converter. It is evident from the results that, in isolated DC-DC converters switching stress and input inrush current for inductor is reduced. Conventional converters without interleaving have fast settling time. Hence with proper design of magnetics, selection of switches and power diodes with proper snubber circuit, efficiency of the PV panel integrated DC-DC converter can be improved.

Acknowledgment

Authors gratefully acknowledge the support of PES University for their valuable suggestions and support.

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