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# Analysis and Experimentation of Soft Switched Interleaved Boost Converter for Photovoltaic Applications

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Conventional energy sources are fast depleting due to poor conservation practises and excessive usage while the world's energy demands are growing by minute. Additionally, the cost of producing conventional energy is rising also leading to an increase in harmful environmental pollution. Hence, there is a need to look at alternative energy sources such as sun, water and wind. Photovoltaic (PV) is a very promising option as it uses energy from naturally available sunlight distributed throughout the Earth which is not only pollution free but also abundant and recyclable in nature.Among the different DC-DC converters proposed in literature, interleaved boost converter is best suited for PV and other high power density applications.Conventional interleaved boost converters experience switching losses and switching stresses during turn-on and turn-off periods due to hard switching. In order to eliminate the power loss in the converter devices, soft switched interleaved boost converter (IBC) is proposed in this paper. Soft switching is achieved with the use of an LC resonant tank circuit. The tank circuit is responsible for zero voltage switching (ZVS) and zero current switching (ZCS), eliminating the power loss in the switches appreciably. Since photovoltaic source is used as the input to the converter, a maximum power point tracking (MPPT) algorithm is implemented to extract maximum available power from the PV panel. Furthermore, the device losses, ripple and current sharing based on input and output characteristics are recorded and examined. Simulation study of the design is carried out using MATLAB/SIMULINK software. A hardware prototype with PV module is developed to validate the simulation results.

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## 1. INTRODUCTION

Interleaving in the boost converter effectively reduces the ripple as a function of duty cycle. Interleaving of boost converters is done to minimize the input current ripple, output voltage ripple, reduce the passive component size, improve the transient response and increase the power level making them ideal for high power density applications. In boost converters, due to fast turn-on and turn-off of the switches, there is considerable power loss in the devices. This method of switching the devices is called hard switching. These losses are highly responsible for lowering the converter performance. Hence, soft switching technique is used where the voltage and current through the switches are forced to zero before turning on and turning off the devices respectively. It is known as zero voltage switching (ZVS) and zero current switching (ZCS). The ZVS and ZCS are achieved using an LC resonant tank in the interleaved boost converter. The soft switching technique [1-4] helps in eliminating the switching losses and stresses to a large extent and is found to be more efficient when compared to the hard switching technique in conventional boost converters.

Photovoltaic system design has two parameters for consideration: solar irradiation and temperature. It is required to supply a constant output voltage to the load irrespective of the variation in the temperature and solar irradiation levels. Since the relationship between voltage and current in a PV array is non-linear, it is difficult to extract maximum power from the solar panel. As a result, it is necessary to employ a maximum

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power point tracking algorithm to extract maximum power at any given point from a low voltage PV source which can then be used in supplying power. The low voltage PV source is coupled with the soft switched interleaved boost converter that encounters low levels of switching losses and switching stresses in the converter circuit. As a result of coupling, the ripple contents at the input current and output voltage are reduced maximising the system efficiency. This is accomplished by adopting a soft switched interleaved boost converter topology. The input current is shared equally between the switches. The circuit can drive heavy loads with high levels of efficiency due to impedance matching achieved by energy storing elements (resonant tank and variable output capacitor). Better switch timing for ZVS and ZCS is also obtained using bypass networks [5]. The clamped diode acts as a bypass path reducing the conduction losses. Coupling capacity between auxiliary unit and main switches reduces the voltage stress of the switches during switching operations.

The paper in sections begins with outlining the phases of operation of soft switched IBC circuit with explaining how each phase works [6]. The next section highlights the design considerations of IBC. The subsequent section covers interfacing of IBC with PV module, whose validation is done through the simulation results of soft switched IBC with PV module and MPPT and PV panel characteristics.

The section that follows, details the simulation waveforms of soft switched IBC highlighting the advantages of soft switching over conventional hard switching techniques. The ripple values, switching device losses and IBC efficiency are calculated to amply prove that the soft switched IBC using an auxiliary resonant tank circuit is indeed an ideal fit for PV applications. Finally, to validate the simulation results a hardware prototype is implemented.

## 2. SOFT SWITCHED IBC CIRCUIT

The circuit of soft switched IBC is shown in Figure 1. The circuit consists of two main switches ($S_{S1}$ and $S_{S2}$), an auxiliary switch $S_{ax}$, three diode rectifiers ($D_S$, $D_{r1}$, $D_{r2}$) and two clamped diodes ($D_r$ and $D_c$).The circuit has two boost inductors $B_{L1}$ and $B_{L2}$ as in the basic IBC topology and soft switching is achieved using a resonant tank comprised of a resonant capacitor $C_{rc}$ and resonant inductor $L_{rc}$ which are responsible for ZVS and ZCS function [7, 8].

**2. 1. Operation of Soft Switched IBC** The IBC is operated with a duty cycle of 40%. There are eighteen operational phases in one complete cycle.

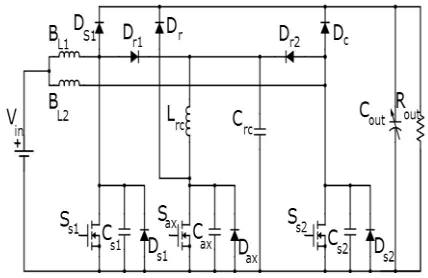


**Figure 1.** Schematic of two-phase IBC

Out of the eighteen phases, nine are related to main switch $S_{S1}$ and the others to main switch $S_{S2}$. The output is equal for both switches due to the symmetrical nature of the interleaving circuit [2].

The driving signals for the main switches and the auxiliary switch are shown in Figure 2. The various current waveforms and voltage waveforms during the different phases are also shown in Figure 3.

The modes of operation are divided into nine modes and in mode-1, the control of switches is excited by pulse which is meant to turn off the switches $S_{S1}$ and $S_{S2}$. Hence, the parasitic capacitance of the two main switches $C_{S1}$ and $C_{S2}$ gets charged. The voltage across the parasitic capacitors $C_{S1}$ and $C_{S2}$ of the main switches and resonant capacitor $C_{rc}$ are all equal to the output voltage i.e., $V_{S1}=V_{S2}=V_{rc}=V_0$ in the previous phase. The resonant inductor current $I_{Lrc}$ linearly ramps up until it reaches $I_{in}$ at $t=t_1$. During $t_1$-$t_2$, the resonant inductor keeps on charging and continues to increase to the peak value during which the main switch voltages $V_{S1}$ and $V_{S2}$ decrease to zero, because of resonance among $C_{S1}$, $C_{S2}$, $C_{rc}$, $L_{rc}$ [3]. Then, the body diodes $D_{S1}$ and $D_{S2}$ of switches $S_{S1}$ and $S_{S2}$, respectively, can be turned ON. In the interval, $t_2$-$t_3$, the main switch voltage $V_{S1}$ decreases to zero. As a result the body diode $D_{S1}$ of switch $S_{S1}$ is turned ON at $t_2$. At this time, the main switch can achieve ZVS.

During $t_3$-$t_4$**,** the auxiliary switch $S_{ax}$ is turned OFF and the clamped diode $D_r$ is turned ON. During this time interval, the energy stored in the resonant inductor $L_{rc}$ is transferred to the output load. The resonant inductor current $I_{Lrc}$ decreases to zero and the clamped diode $D_r$ is turned OFF at $t_4$. In the interval $t_4$-$t_5$, the clamped diode $D_r$ is turned OFF. The energy of the boost inductor $L_2$ is transferred to $C_{rc}$ and $C_{S2}$ and the energy stored in the parasitic capacitor $C_{ax}$ of the auxiliary switch is transferred to the resonant inductor $L_{rc}$ and the resonant capacitor $C_{rc}$ at this time.

During $t_6$-$t_7$, the clamped diode $D_r$ is turned ON. The energy stored in the resonant inductor $L_{rc}$ is transferred to the output load by the clamped diode $D_r$. At $t_7$, the clamped diode $D_r$ is turned OFF because the auxiliary switch $S_r$ is turned ON.

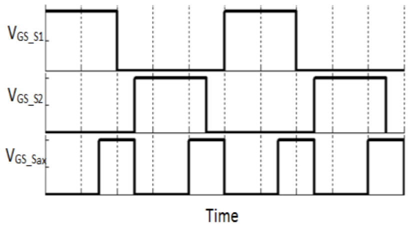


**Figure 2.** Driving signal for switches

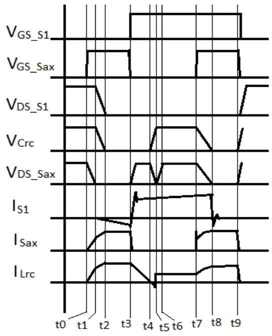


**Figure 3.** Switching phases

During the time interval $t_7$-$t_8$, the resonant inductor current continues to increase to the peak value and the main switch voltage $V_{S2}$ decreases to zero because of resonance among $C_{S2}$, $C_{rc}$ and $L_{rc}$. At $t=t_8$, the body diode $D_{S2}$ of switch $S_{S2}$ is turned ON. In this phase, the resonant inductor current $I_{Lrc}$ equals the inductor current $I_{L2}$. This state is called critical state where the rectified input to the switches is zero. So, the switch $S_{S1}$ tends to achieve ZCS. As a result the switch $S_{S1}$ is turned OFF at the end of $t_9$. The energy stored in the resonant inductor $L_{rc}$ is transferred to the output load by the clamped diode $D_r$.

**2. 2. Design of IBC** The output voltage of IBC can be obtained from the following relation:

$$V_0 = \frac{V_{in}}{1-D} \tag{1}$$

where $V_0$ is the output voltage, $V_{in}$ is the input voltage and $D$ is the duty cycle.

The boost inductors $L_1$ and $L_2$ are calculated based on parameters such as switching frequency $f_s$, input and output voltage, inductor current ripple $\Delta I_L$.

$$L_1 = L_2 = L = \frac{V_{in} * (V_o - V_{in})}{\Delta I_L * f_s * V_o} \tag{2}$$

$\Delta I_L$ is calculated as:

$$\Delta I_L = (0.2) * I_{out} * \frac{V_o}{V_{in}} \tag{3}$$

The value $I_{outmax}$ is calculated as:

$$I_{outmax} = \frac{P_o}{V_o} \tag{4}$$

where $P_0$ is the output power of IBC.
The output capacitance is calculated as:

$$C_O = \frac{I_{outmax} * D}{f_s * \Delta V_O} \tag{5}$$

where $\Delta V_0$ is the output voltage ripple and it is taken as 5% of the output voltage $V_0$. The resonant frequency $f_r$ is:

$$f_r = \frac{1}{2\pi\sqrt{L_{rc} C_{rc}}} \tag{6}$$

By fixing the value of $f_r$ and $C_{rc}$, the value of $L_{rc}$ is calculated as:

$$L_{rc} = \frac{1}{f_r^{\,2} * 4 * \pi^2 * C_{rc}} \tag{7}$$

Using the above design equations [9], the simulation parameters for IBC is calculated as shown in Table 1.

## 3. INTERFACE OF IBC WITH PV MODULE

In order to use the IBC for photovoltaic applications, a PV module is used to supply power to the IBC [10]. The relationship between current and voltage in a PV panel is shown in Figure 4.

**TABLE 1.** Simulation parameters for IBC

| Parameter | Value |
|---|---|
| Input voltage ($V_{in}$) | 21.16V |
| Duty cycle(D) | 40% |
| Switching frequency($f_s$) | 25kHz |
| Inductors ($L_1$ and $L_2$) | 376.18μH |
| Resonant frequency ($f_r$) | 50kHz |
| Resonant inductor ($L_{rc}$) | 6.67μH |
| Resonant capacitor ($C_{rc}$) | 1.5μF |
| Output capacitor ($C_0$) | 25μF |
| Output resistor ($R_0$) | 13.05Ω |

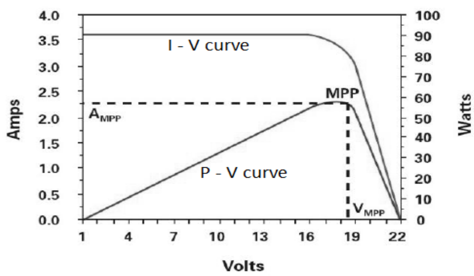


**Figure 4.** I-V and P-V curve characteristics for a sample panel

From the figure, it can be found that the relationship between current and voltage is non-linear and it is difficult to draw the maximum power from the panel. Hence, a maximum power point tracking (MPPT) algorithm is used to draw maximum power from the panel [11]. According to maximum power transfer theorem, when the load impedance matches with the source impedance, maximum power can be transferred from the source to the load. Hence the problem of tracking the maximum power point reduces to an impedance matching problem. There are many types of algorithm to track the maximum power. The algorithm used here is the Perturb and Observe algorithm [2]. It is the simplest algorithm of all. The algorithm is shown in Figure 5. The complete block diagram is shown in Figure 6. The specification of the PV panel is shown in Table 2.

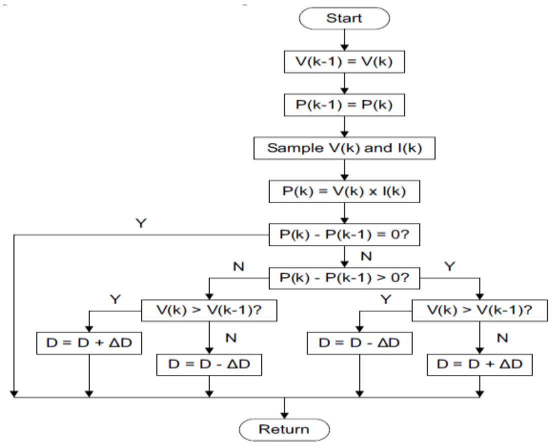


**Figure 5.** Flowchart of Perturb & Observe alogrithm

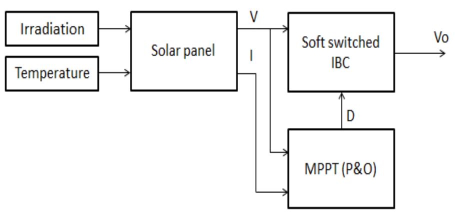


**Figure 6.** Block diagram of soft switched IBC with PV and MPPT

**TABLE 2.** Simulation parameters for PV

| Parameter | Value |
|---|---|
| Open circuit voltage ($V_{OC}$) | 21.16V |
| Short circuit current ($I_{SC}$) | 5.87A |
| Voltage at maximum power point ($V_{MPP}$) | 17.53V |
| Current at maximum power point ($I_{MPP}$) | 5.43A |
| Maximum power | 95.187W |

## 4 SIMULATION OF SOFT SWITCHED IBC WITH PV MODULE AND MPPT

**4. 1. Simulation Results of PV Panel Characteristics** Using the simulation parameters as in Table 2, the simulation results of the PV panel characteristics is shown in Figures 7 and 8 [1]. From the above curves, it can be seen that the maximum attained power is 95W at a voltage of 21V.

**4. 2. Simulation Waveforms of Soft Switched IBC** Various waveforms obtained as a result of simulation of the soft switched IBC are shown in Figures 9-16.

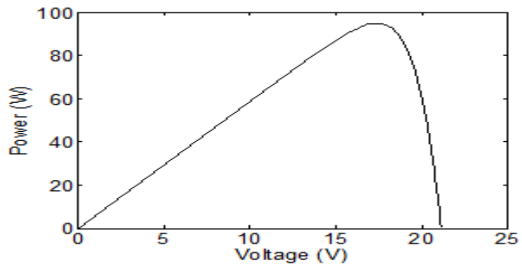


**Figure 7.** P-V curve of panel

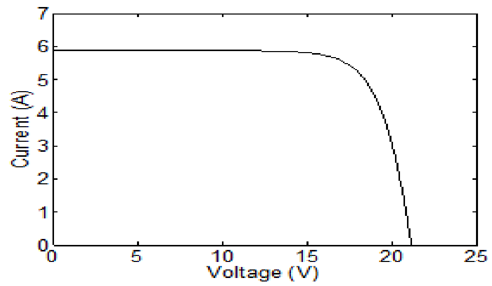


**Figure 8.** I-V curve of panel

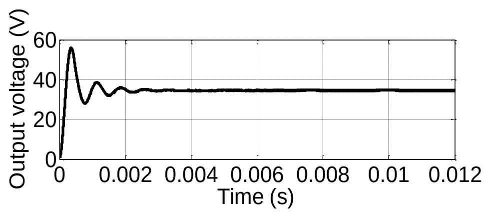


**Figure 9.** Output voltage waveform of the IBC

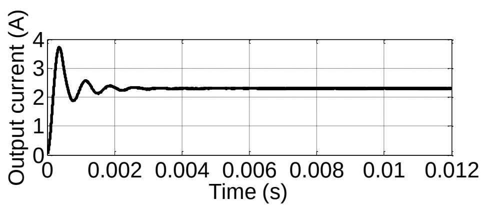


**Figure 10.** Output current waveform of the IBC

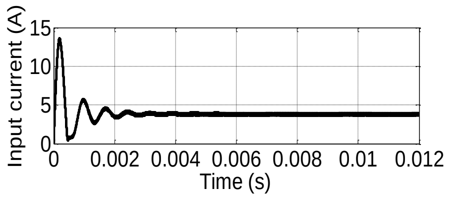


**Figure 11.** Input current waveform of the IBC

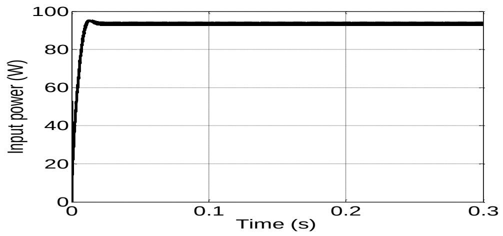


**Figure 12.** Input power to IBC from PV panel

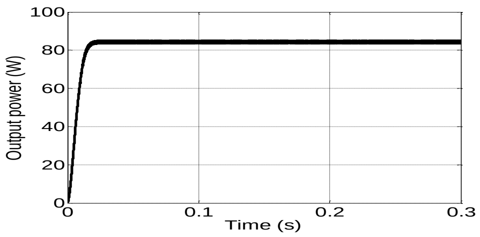


**Figure 13.** Output power from the IBC

### 4. 3. Steady State Ripple Waveforms of IBC

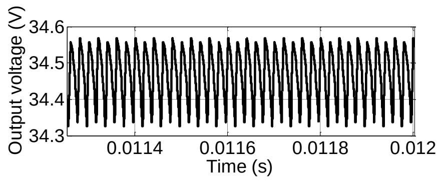


**Figure 14.** Output voltage ripple waveform of the IBC

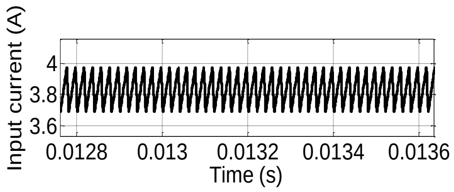


**Figure 15.** Input current ripple waveform of the IBC

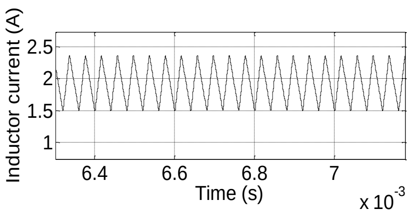


**Figure 16.** Inductor current ripple waveform of the IBC

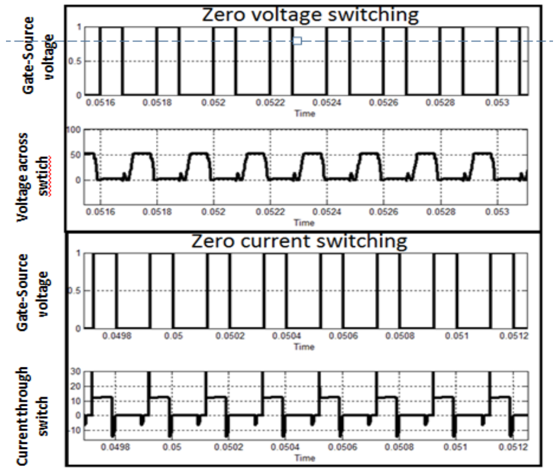


**Figure 17.** ZVS and ZCS waveforms for IBC

**TABLE 3.** Ripple calculation

| Parameter | Soft switched IBC | Conventional IBC |
|---|---|---|
| Output voltage ripple | 0.144V | 2.33V |
| Input current ripple | 0.0779A | 1.234A |
| Inductor current ripple | 0.4416A | 0.845 A |

### 4. 4. Calculation of Ripple Value

The ripple values are calculated from the simulation. Waveforms and its comparsion with conventional IBC are shown in Table 3. From Table 3, it is found that, the proposed soft-switched IBC gives a reduced output voltage and input current ripple compared to the conventional one.

### 4. 5. Calculation of Losses in Switching Devices

The losses for the proposed IBC [3, 4] is calculated by finding the conduction and switching losses of the switches as discussed below:

- **Switching loss**

$$P_{sw} = 0.5 * V_{DS} * I_D * f_s * t_{sw}$$

where $V_{DS}$ is the drain to source voltage
$I_D$ is the drain current
$f_s$ is the switching frequency
$t_{sw}$ is the sum of the rise time and fall time

- **Conduction loss**

$$P_c = I^2 * R_{d(on)} * D$$

where $I$ is the current through the device, $R_{d(on)}$ is the on state resistance.
The switching and conduction losses for both the switches $S_{S1}$ and $S_{S2}$ are as follows:
Switching loss for $S_{S1}$ and $S_{S2}$: 0.157092W
Conduction loss for $S_{S1}$ and $S_{S2}$: 1.1859W

Total device losses=Switching losses+Conduction Losses. Total losses for individual switches are as follows:

Switch $S_{S1}$=0.157092W+1.1859W=1.342992W

Switch $S_{S2}$=0.157092W+1.1859W=1.342992W

Total losses=2.685984W

**4. 6. Calculation of Efficiency of IBC** From Figures 12 and 13, the input power and output power of the IBC are input power, $P_{in}$=95.09W and output power, $P_{out}$=89.5 W

Efficiency=$P_{out}/P_{in}$=(89.5/95.09)*100=94.11%.

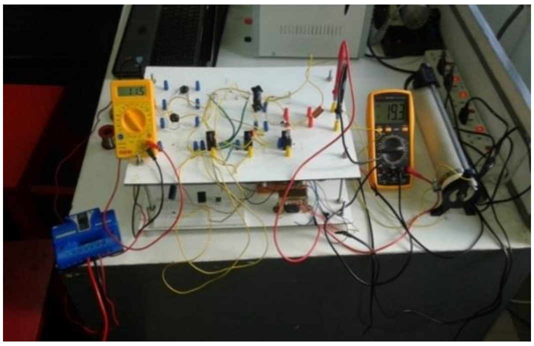

**Figure 19.** Input and output voltage of the IBC

## 5. HARDWARE IMPLEMENTATION

The entire hardware consists of the gate drive, the converter circuit and a PV panel to provide input voltage to the converter. Here the implementation is done without the use of an MPPT algorithm. For the switches, MOSFETs are used and to provide isolation between the drive circuit and the switches, optocouplers are used. The output pulse from the optocoupler is used to trigger the switches.

The output voltage from the PV panel is not a constant one. It keeps varying with temperature and irradiance. So, the converter is not directly fed from the PV panel. Instead, it is used to charge a battery using a charge controller and this output is given to the converter as shown in Figure 18. The charge controller maintains proper charging voltage on the batteries. It also blocks reverse current and also prevents battery overcharge.

Here, a 12V battery is charged from the PV panel using a charge controller. This 12V is fed as input to the IBC circuit. The input voltage fed to the IBC is 11.5V. The duty cycle of operation is 40%. Thus, using the relation $V_{out}=V_{in}/(1\text{-}D)$, we can find that, $V_{out}$=11.5/(1-0.4)≈19.3V which is shown in Figure 19. From the hardware, the losses of the device was found to be 2.978W and the output voltage ripple was 0.144V. Therefore, the proposed IBC is a better topology for PV applications.

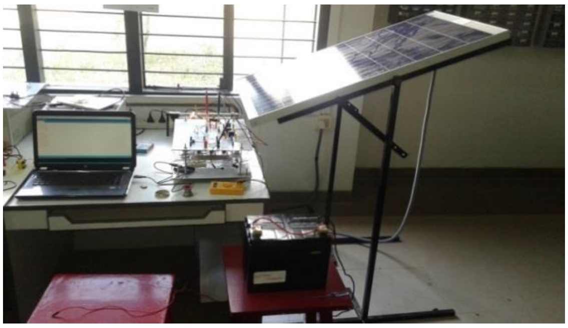

**Figure 18.** Hardware arrangement of soft switched IBC

## 6. CONCLUSION

This paper provides an insight to the use of soft switching technique for an interleaved boost converter (IBC) for photovoltaic (PV) applications. The primary objective is to reduce switching losses and switching stress on the main switches. This is achieved using ZVS (zero voltage switching) and ZCS (zero current switching) methods operating in lower and higher duty cycles. By using the concept of impedance matching between the resonant tank circuit and output capacitor, the circuit can drive heavy loads with high efficiency. In order to use the converter for photovoltaic applications, it is coupled with a PV panel since solar energy is freely available. Thus by implementing soft switching, the voltage stress on the main switches is reduced, the losses are reduced and also the ripples in the voltage and current waveforms are less. Additionally, the efficiency of the converter is also increased. Hence, the proposed soft switched IBC is an ideal choice for PV applications.

## 7. ACKNOWLEDGEMENT

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Photovoltaic

**چکیده**

منابع انرژی متداول به سرعت در حال اتمام هستند که این مساله به شیوه های حفاظت ضعیف و استفاده بیش از حد از این منابع مربوط می شود در حالی که تقاضای انرژی در جهان به صورت لحظه ای در حال افزایش است. علاوه بر این، هزینه تولید انرژی متعارف در حال افزایش است که منجر به افزایش آلودگی زیست محیطی می شود. از این رو، لازم است تا نگاهی به منابع انرژی جایگزین مانند خورشید، آب و باد داشت. فتوولتائیک (PV) یک گزینه بسیار امیدبخش است چرا که از انرژی نور خورشید که به طور طبیعی در دسترس است و در سراسر زمین توزیع شده است استفاده می کند که نه تنها آلودگی ندارد بلکه رایگان، فراوان و قابل بازیافت درطبیعت است. از میان مبدلهای DC-DC مختلف ارائه شده در متون، مبدل بوست لایه بهترین گزینه برای PV و دیگر کاربردهای چگالی توان بالا است. مبدل های بوست متداول دچار تلفات سوئیچ و تنشهای سوئیچ در طول دوره روشن و خاموش شدن می شوند که علت آن سوئیچینگ سخت است. به منظور حذف اتلاف توان در دستگاه های مبدل، مبدلهای IBC در این مقاله ارائه شده است. سوئیچینگ نرم با استفاده از یک مدار مخزن رزونانس LC به دست می آید. مدار مخزن مسئول ولتاژ سوئیچینگ صفر (ZVS) و سوئیچینگ جریان صفر (ZCS) است، که به میزان زیادی موجب حذف اتلاف توان در سوئیچ می شود. از آنجا که منبع فتوولتائیک به عنوان ورودی به مبدل استفاده می شود، الگوریتم MPPT برای استخراج حداکثر توان در دسترس از پانل PV استفاده شده است. علاوه بر این، اتلاف دستگاه، موج دار شدن و به اشتراک گذاری جریان بر اساس ویژگی های ورودی و خروجی ثبت و مورد بررسی قرار می گیرد. مطالعه شبیه سازی از طرح با استفاده از نرم افزار MATLAB / SIMULINK softwareانجام می شود. نمونه سخت افزار با ماژول PV برای ارزیابی نتایج شبیه سازی توسعه داده شده است.

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