

# Design of Interleaved Converter for Renewable Energy Sources

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**ABSTRACT:** Renewable energy is derived from natural resources that are replenished constantly. The commonly used renewable energy systems include photovoltaic cells and fuel cells. A suitable DC-DC converter is proposed for highly efficient renewable energy systems. Interleaved Boost Converter (IBC) topology is discussed for renewable energy applications. The advantages of IBC compared to the classical boost converter are low input current ripple, high efficiency and faster transient response, reduced electromagnetic emission and improved reliability. Three cases of interleaved boost converter are considered and analyzed. The output voltage of the three types of the converters is compared. The wave forms of the output voltage are obtained using MATLAB/SIMULINK. The design equations for IBC are presented. Using the results obtained from the simulation the best of the three IBCs is inferred.

**KEYWORDS:** Interleaved Boost Converter (IBC), renewable source, photovoltaic (PV), inductor, duty cycle.

## I. INTRODUCTION

Today photovoltaic power systems are becoming more and more popular, with the increase of energy demand and the concern of environmental pollution around the world. Generally three types of inverter systems except the centralized inverter system can be employed as small-scale distributed generation (DG) systems, such as the one for residential power applications.

The most important design constraint of the PV DG system is to obtain a high voltage gain. For a typical PV module, the open-circuit voltage is about 21V and the maximum power point (MPP) voltage is about 16 V and the utility grid is at 220 or 110 V ac. Therefore, the high voltage amplification is obligatory to realize the grid-connected function and achieve the low total harmonic distortion (THD). The conventional system requires large numbers of PV modules in series, and the normal PV array voltage is between 150 and 450 V, and the system power is more than 500 W. This system is not applicable to the module-integrated inverters because the typical power rating of the module-integrated inverter system is below 500 W and the modules with power ratings between 100 and 200 W are also quite common. The other method is to use a line frequency step-up transformer and the normal PV array voltage is between 30 and 150 V. But the line frequency transformer has the disadvantages of larger size and weight. In the grid-connected PV system, power electronic inverters are needed to realize the power conversion, grid interconnection, and control optimization.

## II. PRINCIPLE OF INTERLEAVED BOOST CONVERTER

In order to achieve the requirement of small volume, light weight and reliable properties, a high power IBC is constructed, as shown in figure 1. The principle of IBC is as follows: Each phase is a boost/buck DC-DC converter, which is composed of a bridge of power switches and storage energy inductor.

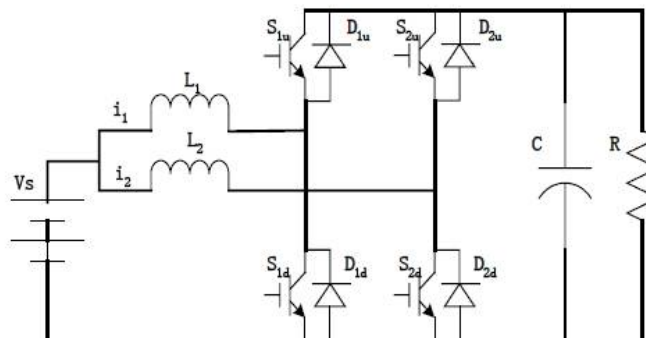


Fig. 1 The topology of the Interleaved Boost Converter

When  $S_{1u}=S_{2u}=OFF$ ,  $S_{1d}$  and  $S_{2d}$  switch on and off, the system works in the BOOST mode as shown in table 1.

Table. 1 The state of the power device in BOOST mode

S1u=OFF	S2u=OFF	D1u= ON / OFF	D2u= ON / OFF
S1d= ON / OFF	S2d= ON / OFF	D1d=OFF	D2d=OFF

From the table 1, it can be seen that in Boost mode, only the power devices ( $S_{1d}, S_{2d}, D_{1u}, D_{2u}$ ) have switching commutation, the power devices ( $S_{1u}, S_{2u}, D_{1d}, D_{2d}$ ) have no commutation. The power switches  $S_{1d}$  and  $S_{2d}$  have 180-degree phase difference of driving pulses in a cycle. The current fluctuation of input power supply is reduced greatly because the two 180-degree phase difference inductor currents minify the fluctuation of each other. In one switching cycle  $T_s$ , considering the commutation of power switches and diodes ( $S_{1d}, S_{2d}, D_{1u}, D_{2u}$ ), there are eight kinds of running states as shown in table 2.

Table. 2 The eight running states in interleaved BOOST mode

	S1d=on	S2d=on	D1u=on	D2u=on
S1d=on	State 2	State 7	*	State 1
S2d=on	State 7	State 5	State 4	*
D1u=on	*	State 4	State 3	State 8
D2u=on	State 1	*	State 8	State 6

IBC mainly used for renewable energy sources has a number of boost converters connected in parallel which have the same frequency and phase shift. These IBC's are distinguished from the conventional boost converters by critical operation mode, discontinuous conduction mode (DCM) and continuous conduction mode (CCM) so that the devices are turned on when the current through the boost rectifier is zero. In the CCM, the design becomes tedious as the critical point varies with load. In the DCM, the difficulties of the reverse recovery effects are taken care but it leads to high input current and conduction losses and it is not best suited for high power applications. CCM has lower input peak current, less conduction losses and can be used for high power applications. By dividing the output current into 'n' paths higher efficiency is achieved and eventually the copper losses and the inductor losses are reduced.

Firstly when the device S1 is turned ON, the current in the inductor  $i_{L1}$  increases linearly. During this period energy is stored in the inductor L1. When S1 is turned OFF, diode D1 conducts and the stored energy in the inductor ramps down with a slope based on the difference between the input and output voltage. The inductor starts to discharge and transfer the current via the diode to the load. After a half switching cycle of S1, S2 is also turned ON completing the same cycle of events. Since both the power channels are combined at the output capacitor, the effective ripple frequency is twice than that of a single-phase boost converter. The amplitude of the input current ripple is small. This advantage makes this topology very attractive for the renewable sources of energy.

The gating pulses of the two devices are shifted by a phase difference of  $360/n$ , where n is the number of parallel boost converters connected in parallel. For a two-phase interleaved boost converter  $n=2$ , which is 180 degrees and it is shown in figure 2.

The two phases of the converter are driven 180 degrees out of phase, this is because the phase shift to be provided depends on the number of phases given by  $360/n$  where n stands for the number of phases.

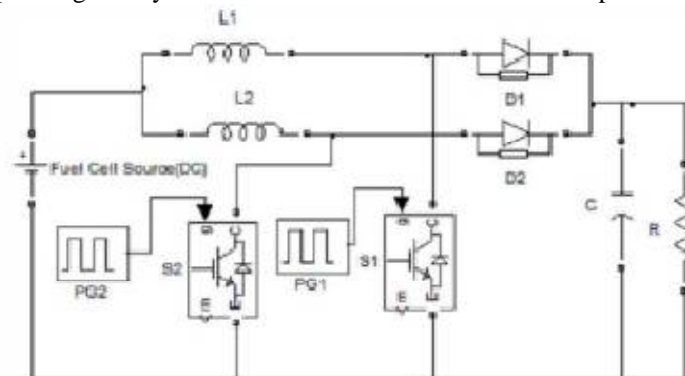


Fig. 2 Circuit diagram of a two phase uncoupled IBC

Since two phases are used the ripple frequency is doubled and results in reduction of voltage ripple at the output side. The input current ripple is also reduced by this arrangement. When gate pulse is given to the first phase for a time  $tJ$ , the current across the inductor rises and energy is stored in the inductor. When the device in the first phase is turned OFF, the energy stored is transferred to the load through the output diode D. The inductor and the capacitor serve as voltage sources to extend the voltage gain and to reduce the voltage stress on the switch. The increasing current rate across the output diode is controlled by inductances in the phases. Gate pulse is given to the second phase during the time  $t1$  to  $t2$  when the device in the first phase is OFF. When the device in the phase two is ON the inductor charges for the same time and transfers energy to the load in a similar manner as the first phase. Therefore the two phases feed the load continuously. Fig.3.3 to 3.5 shows the schematic diagrams of the two phase interleaved boost converter with uncoupled, directly coupled and inversely coupled IBC. As the output current is divided by the number of phases, the current stress in each transistor is reduced. Each transistor is switched at the same frequency but at a phase difference of  $\pi$ . Switching sequences of each phase may overlap depending upon the duty ratio (D). In this case the input voltage to the IBC is 20V and the desired output voltage is 40V, therefore D has to be chosen as 0.5.

### III. DESIGN METHODOLOGY OF IBC

The design methodology for IBC's require a selection of proper values of inductor, capacitor and proper choice of the power semiconductor devices to reduce the switching losses. The steps involved in designing IBC are as follows:

- Decision of duty ratio and number of phases
- Selection of Inductor values
- Selection of power semiconductor switches
- Design of output filter

#### (A) Selection of duty ratio and number of phases

Two phase IBC is chosen since the ripple content reduces with increase in the number of phases. If the number of the phases is increased further, without much decrease in the ripple content, the complexity of the circuit increases very much, thereby increasing the cost of implementation. Hence, as a trade off between the ripple content and the cost and complexity, number of phases is chosen as two. The number of inductors, switches and diodes are same as the number of phases and switching frequency is same for all the phases.

$$\frac{V_{in}}{L} \left( \frac{2-3D}{D'} \right) \frac{T}{N} d \quad (0.34 < D < 0.66)$$

The input current ripple can be zero at specific duty ratios which are multiples of N, where N stands for the no of phases. Here the number of phases is two. Therefore the duty ratio is taken as 0.5.

#### (B) Selection of Inductors

In switching regulator applications the inductor is used as an energy storage device. When the semiconductor switch is on, the current in the inductor ramps up and energy is stored. When the switch turns off energy is released into the load. The amount of energy stored is calculated by the formula Energy =  $\frac{1}{2}LI^2$  (Joules), where L is the inductance in Henrys and I is the peak value of inductor current

For the selection of the proper inductor and capacitor the design equation part for all the three converters are given below:

##### 1. Uncoupled inductor

The value of the inductance is given by equation

$$L = \frac{V_{in}DT}{\Delta I_{ph}}$$

##### 2. Coupled inductor

The equivalent inductance expression for directly coupled IBC is

$$L = \frac{V_{in}DT}{\Delta I_{ph}}$$

Where  $V_{in}$  represents input voltage, D represents duty ratio. The phase current ripple which is decided by L is given by

$$\Delta I_{phase} = \frac{V_{in}DT}{L} \frac{1+\alpha+2\alpha\frac{D}{D-1}}{1+\alpha-2\alpha^2}$$

To find out the values of mutual inductance, the input current is calculated using the input voltage and power. With a coupling coefficient of 0.61, the minimum self- inductance of the coupled inductor is found as

$$L = \frac{1 + \alpha \frac{D}{1-D}}{1 + \alpha - 2\alpha^2} L_{eq}$$

The value of  $L_m$  is calculated as

$$L_m = \alpha.L$$

Therefore, the overall input current ripple is derived as

$$\Delta I_{in} = \frac{V_{in}DT}{L} \left( \frac{(1-\alpha)(1-\frac{2D}{1-D})}{1 + \alpha - 2\alpha^2} \right)$$

From the above equations it is clear that increasing the value of the coupling coefficient can effectively reduce the input current ripple, but the phase current ripple is increased. Therefore, the value of coupling coefficient is carefully chosen as 0.61, so that the input current ripple is reduced and the phase current ripples are within the limits.

### (C) Inversely coupled inductor

The self-inductance value for inversely coupled is obtained from the equation

$$L \geq \frac{1 + \alpha \frac{D}{1-D}}{1 + \alpha^2}$$

The mutual inductance value is given by

$$L_m = -\alpha.L$$

### (D) Selection of Power Devices

A power semiconductor device is a semiconductor device used as a switch or rectifier in power electronics; a switch-mode power supply is an example. Such a device is also called a power device or when used in an integrated circuit, a power IC. A power semiconductor device is usually used in commutation mode and therefore has a design optimized for such usage; it should usually not be used in linear operation. The semiconductor device chosen for constructing the two phase interleaved boost converter is the IGBT. The main benefits of IGBT are lower on state resistance, lower conduction losses and high switching operation. The maximum voltage across the switching devices is given by

$$V_{switch} = V_{in} \frac{1}{1-D}$$

where  $V_{in}$  is the input voltage  $D$  is the duty ratio of the converter. The diode has less forward voltage, high reverse breakdown voltage and less reverse recovery current which results in reduced switching loss. Due to absence of reverse recovery current, there is no need of active snubber circuit for protection. Hence the circuit complexity is reduced. Circuit reliability is improved and design of the converter is simplified.

### (E) Output Filter

A capacitor filter is needed at the output to limit the peak to peak ripple of the output voltage. The capacitance of the output filter is function of the duty cycle, frequency and minimum load resistance during maximum load. Determining the value of the filter components is a process of trial and error and may require a few calculations to optimize the LC filter. Another thing to consider is the LC filter resonant top that is created at the cut off frequency. The resonant top must be damped to not affect the stability of the converter.

For 5% output voltage ripple, the value of the capacitance is given by the formula

$$C = \frac{V_0DT}{R\Delta V_0}$$

Where  $R$  represents the load resistance,  $V_0$  represents the output voltage and  $T$  represents the switching period.

By putting a resistor in parallel with the inductor, the damping of the resonant can be eliminated. The value of the resistor can be equal to the impedance of the inductor. If the resistor is not put there, it can create resonant problems due to high  $Q$ .

## IV. SIMULATION AND RESULTS

As per the design equations, a two phase interleaved boost converter with uncoupled, directly coupled inductors and inversely coupled inductors are simulated in MATLAB / SIMULINK. The values for uncoupled IBC are  $L = 2.5\text{mH}$ ,  $C = 78\mu\text{F}$ ,  $F = 2\text{kHz}$  and  $R = 3.2\Omega$ . The output voltage is  $V_o = 38\text{V}$  for an input  $V_{in} = 20\text{V}$ . The values used for directly and inversely coupled IBC are summarized as  $V_{in} = 20\text{V}$ ,  $R = 3.2\Omega$ ,  $C = 78\mu\text{F}$ ,  $F_s = 2\text{kHz}$ ,  $L_m = 7\text{mH}$ ,  $L_{k1} = L_{k2} = 4.3\text{mH}$ ,  $V_o = 37\text{V}$ ,  $D = 0.5$  and  $\alpha = 0.61$  for directly coupled. Figure 4 shows the output voltage waveform of

uncoupled IBC. Figure 6 shows output voltage waveforms of a Inversely Coupled IBC. Figure 8 shows output voltage waveforms of a directly coupled IBC under steady-state condition.

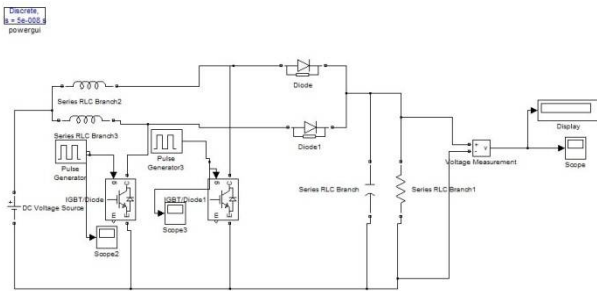


Fig. 3 Uncoupled IBC

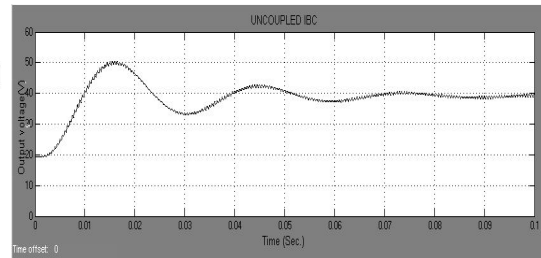


Fig. 4 Output Graph for Uncoupled IBC (Time Vs Voltage)

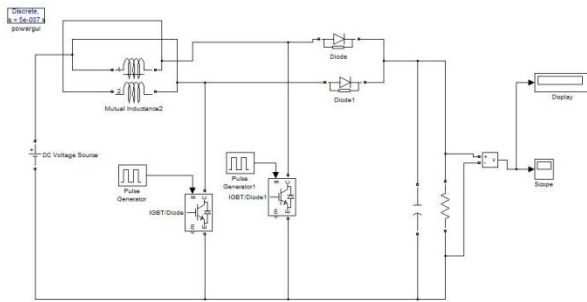


Fig. 5 Inversely Coupled IBC

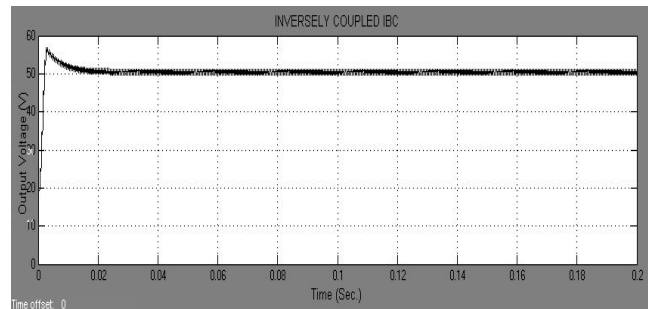


Fig. 6 Output graph for Inversely Coupled IBC

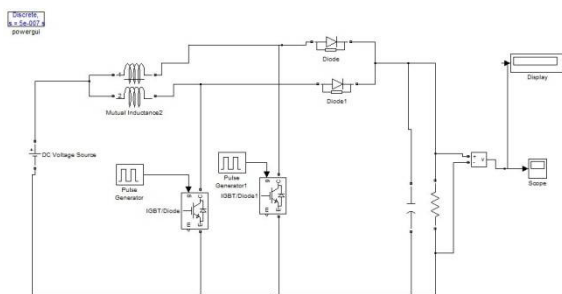


Fig. 7 Directly Coupled IBC

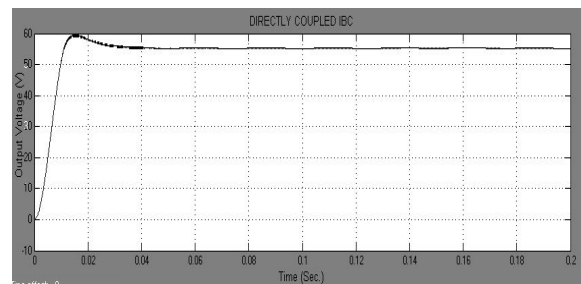


Fig. 8 Output Graph for Directly coupled IBC

### V. CONCLUSION

Interleaved boost converter has so many advantages and is a suitable converter for renewable energy applications. Three cases of IBC using uncoupled, directly coupled and inversely coupled inductor have been analyzed for renewable energy applications. Their design equations have been presented and performance parameters of all three cases have been compared using simulation. It is demonstrated that the directly coupled interleaved DC-DC converter effectively improves the output voltage compared to that of uncoupled inductors. Therefore directly coupled IBC is a suitable choice for fuel cells.

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