Design, Modelling and Simulation of Traditional DC - DC Boost Converter and Interleaved DC - DC Boost Converter

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Abstract

A DC-DC converter is an electrical circuit that employs switching techniques to convert a DC voltage input to the desired magnitude, which could be greater or lower, by momentarily holding input energy and then releasing it at a different voltage to the output. A DC-DC boost converter is a power converter that increases the magnitude of voltage from its input to its output. Boost converter finds many applications in battery power systems, photovoltaic systems, consumer electronics etc. A traditional DC-DC boost converter contains two semiconductors (a diode and a switch) and an energy storage element (inductor). Filters constructed from capacitors are added to the converter's output to reduce voltage ripple (load-side filters). This topology has certain limitations, therefore interleaving is a recommended approach for high-performance applications because it creates a harmonic circuit design by paralleling two or more identical converters. When compared to a traditional boost converter, the interleaved DC-DC boost converter (IBC) has higher efficiency, reduced size, and increased reliability. This work presents the design, development and modelling of the Traditional DC-DC boost converter and the Interleaved DC-DC boost converter (IBC) and compares their performance by simulating the mathematical models and circuits of the two converters using MATLAB/SIMULINK.

Keywords. Traditional Boost Converter, Interleaved Boost Converter, Current ripple, Voltage ripple, Continuous Conduction Mode, Efficiency.

1. INTRODUCTION

Batteries are frequently employed in energy storage systems to balance out power fluctuations between the generation and consumption of renewable energy sources. A step-up DC-DC converter is essential in applications requiring high dc voltage because battery voltage is often low and varies widely [2][7]. All modern systems require power converters that can deliver regulated voltages from a steady power source. The advantages of a simple circuit architecture and straightforward operation have led to a widespread use of the traditional boost converter for step-up applications[1][9]. However the Traditional DC-DC Boost Converter has quite a few limitations which include considerably high voltage and current ripples and a reduced output efficiency when compared to other topologies of the boost converter.[6] This paper proposes an interleaved converter with the intention of addressing the aforementioned issues and offering a superior solution. The method of interleaving, also known as multi phasing, is helpful for reducing the size of filter components, minimising the ripple in the input current, and it also has an impact on the converter's efficiency[4][8]. The optimal selection of the number of phases and the switching frequency results in a better efficient converter operation [3][5].

2. DC-DC BOOST CONVERTER

A boost converter is a device that boosts the output voltage in relation to the input voltage. The traditional DC-DC boost converter circuit is shown in Figure 2.1. It is a switching power converter that alternates between ON and OFF states on a regular basis. An input voltage source V_{in}, an inductor L, a diode D, a controlled semiconductor switch S that can be a MOSFET, an IGBT, or a BJT, an output capacitor C_{out} , and a load resistance R_{load} constitute a simple boost converter circuit. There are two modes of operation - Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM), which can be implemented for the boost converter. These modes can be computed by duty ratio and also be determined by the current inductor value. This work focuses on the continuous conduction mode (CCM) of the boost converter only.

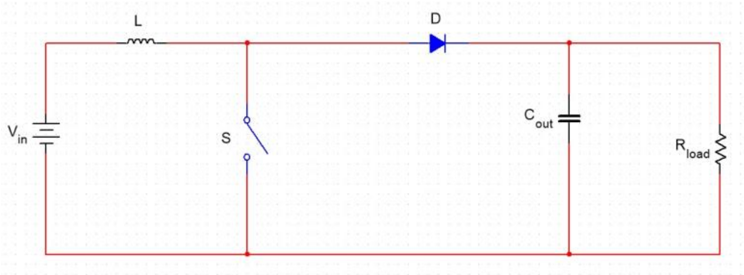

Figure 2.1. Traditional DC-DC Boost Converter Circuit Diagram

A traditional DC - DC boost converter has two modes of operation. **In the first mode** shown in Figure 2.2, the switch S is closed thus forming a path of least resistance for the current to flow. The inductor receives energy supplied from the input source, resulting in linear growth of current flowing in the inductor.

$$V_L = V_{in} \tag{2.1}$$

$$L\frac{diL}{dt} = V_{in} \tag{2.2}$$

$di_L = \Delta i_L$; $dt = DT$ when the switch is closed.

$$(\Delta i_L)_{closed} = \frac{Vin*D*T}{L} \tag{2.3}$$

Where D is duty cycle $(\frac{ton}{T})$, i_L and V_L are the inductor current and voltage respectively, T is the duration of a single switching cycle ($t_{on} + t_{off}$) and V_{in} is the input voltage.

In the second mode shown in Figure 2.3, the switch is opened and the stored energy in the inductor discharges through the diode (turned on), supplying the energy to the output capacitor and charges it to a voltage higher than the input voltage.

$$V_L = V_{in} - V_o \tag{2.4}$$

$$L\frac{diL}{dt} = V_{in} - V_o \tag{2.5}$$

$$(\Delta i_L)_{open} = \frac{(Vin - Vo)*(1-D)*T}{L} \tag{2.6}$$

At steady state operation:

$$V_o = \frac{Vin}{1-D} \tag{2.7}$$

where V_o is output voltage (V).

We can infer from the above equations 2.4 to 2.7 that the output voltage exceeds that of the input when the switch remains open (OFF). In order to obtain a more precise estimation of power for an ideal lossless converter, we can consider:

Input power = Output power

$$V_{in} I_{in} = \frac{Vo^2}{R} \tag{2.8}$$

Where R_{load} is the resistance considered as load.

The average value of inductor can be expressed as:

$$I_L = \frac{Vin}{(1-D)^2 * R} \tag{2.9}$$

The maximum and minimum inductor currents are calculated using the mean value and current ripples. The maximum current that can flow in the inductor is given by:

$$I_{max} = I_L + \frac{\Delta iL}{2} = \frac{Vin}{(1-D)^2 * R} + \frac{Vin * D * T}{L} \tag{2.10}$$

The minimum current of the inductor is given as:

$$I_{min} = I_L - \frac{\Delta iL}{2} = \frac{Vin}{(1-D)^2 * R} - \frac{Vin * D * T}{L} \tag{2.11}$$

In the above equation 2.11, the inductor current has been calculated such that the converter operates in continuous conduction mode, i.e., current is always positive. For I_{min} to be positive, this is a required condition. Therefore,the boundary between continuous and discontinuous inductor current is given by the equation,

$$I_{min} = 0 = \frac{Vin}{(1-D)^2 * R} - \frac{Vin * D * T}{L} \quad (2.12)$$

From the above equation 2.12, we can obtain the least inductance value of the inductor in traditional DC-DC boost converters.

$$L_{min} = \frac{D * (1-D)^2 * R}{2f} \quad (2.13)$$

where f is switching frequency (in kHz), I_{in} is input current (A), I_L is inductor current (A) and L_{min} is minimum value of inductor (H).

The L_{min} value calculated serves as a reference point and the selected inductor will have a slightly larger inductance value to ensure that the circuit operates in continuous conduction mode. It is beneficial to describe L in terms of a desired Δi_L.

$$L = \frac{Vin * D * T}{\Delta iL} = \frac{Vin * D}{\Delta iL.f} \quad (2.14)$$

The ripple factor (r) and the minimum capacitor value for continuous conduction mode is given as,

$$|\Delta Q| = \left(\frac{Vo}{R}\right) DT = C \Delta V_o \quad (2.15)$$

$$r = \frac{\Delta Vo}{Vo} = \frac{D}{RCf} \quad (2.16)$$

$$C_{min} = \frac{D}{R\left(\frac{\Delta Vo}{Vo}\right) f} \quad (2.17)$$

where ΔVo is change in output voltage (V), ΔQ is change in charge stored in the capacitor (C), r is ripple factor (%) and C_{min} is minimum capacitor value (F).

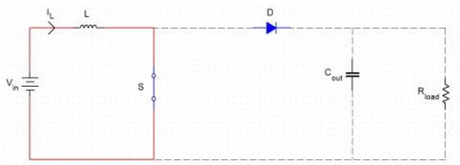

Figure 2.2. Mode-1 operation of Traditional DC-DC boost converter

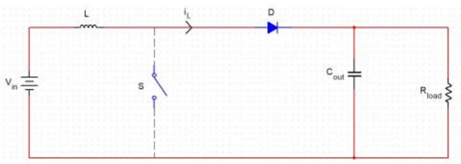

Figure 2.3. Mode-2 operation of Traditional DC-DC boost converter

2.1. Design of DC-DC Boost Converter

The design of the converter is done such that an output of 48 volts is obtained by supplying 12 volts to the circuit. The following parameters are considered while designing the traditional DC - DC Boost Converter: Inductor of 93.37 µH, Capacitor of 417 µF, Switching frequency of

100kHz, Voltage ripple of 2%, current ripple of 20% and output resistance of 48 Ω.

3. INTERLEAVED DC-DC BOOST CONVERTER

Two phase IBC comprises two identical Traditional boost converters in parallel with 180° phase delay and operating at the same frequency and duty cycles. Due to the parallel connection, the current is divided and I^2R losses are minimised and current stress is decreased. The interleaved DC-DC boost converter circuit is shown in Figure 3.1.

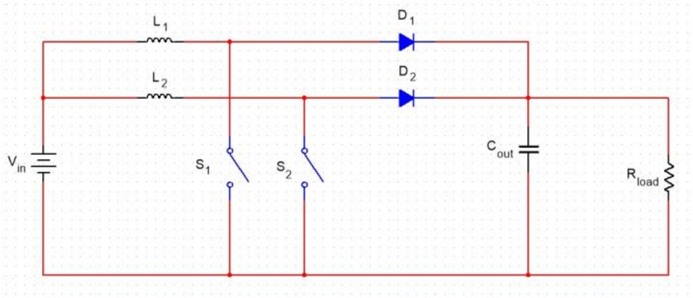

Figure 3.1. Interleaved DC-DC Boost Converter Circuit Diagram

IBC has four modes of operation. **In the first mode** shown in Figure 3.2, both the switches are closed. Thus the diodes are reverse biased (turned off). The current flowing in both the inductors builds up linearly and the energy is stored in the inductors.

$$V_{\mathbf{L1}} = V_{\mathbf{in}} \qquad (3.1)$$

$$V_{\mathbf{L2}} = V_{\mathbf{in}} \qquad (3.2)$$

where,

$V_{L1} = L_1\frac{di1}{dt}$ and $V_{L2} = L_2\frac{di2}{dt}$ (i_1 = current in Inductor 1 and i_2 = current in Inductor 2)

In the second mode shown in Figure 3.3, switch S_1 is closed and switch S_2 is opened. Diode D_1 is reverse biased (turned off) and the diode D_2 is forward biased (turned on). Current flowing in the first inductor increases as the supply is providing energy to that inductor. At the same time, the second inductor provides the load with energy resulting in lowering in the inductor current.

$$V_{\mathbf{L1}} = V_{\mathbf{in}} \qquad (3.3)$$

$$V_{\mathbf{L2}} = V_{\mathbf{in}} - V_o \qquad (3.4)$$

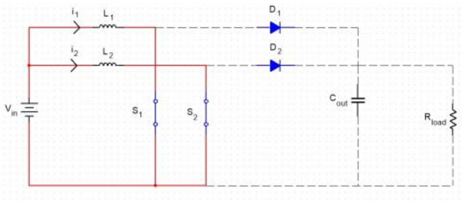

Figure 3.2. Mode-1 operation of IBC

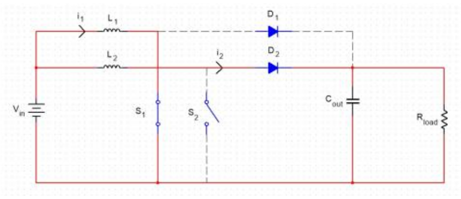

Figure 3.3. Mode-2 operation of IBC

In the third mode shown in Figure 3.4, switch S_1 is opened and switch S_2 is closed. Diode D_1 is forward biased (turned on) and the diode D_2 is reverse biased (turned off). The first inductor discharges current and thereby supplies energy to the load, leading to the decrease in inductor current. Simultaneously, the input source supplies the second inductor with energy causing the current flowing in that inductor to increase.

$$V_{\mathbf{L1}} = V_{\mathbf{in}} - V_o \qquad (3.5)$$

$$V_{\mathbf{L2}} = V_{\mathbf{in}} \qquad (3.6)$$

In the fourth mode shown in Figure 3.5, both switches are opened. Both the diodes are forward biased (turned on). This mode involves both inductors discharging and supplying the load with the energy and as a result both inductor currents decrease.

$$V_{\mathbf{L1}} = V_{\mathbf{in}} - V_o \qquad (3.7)$$

$$\frac{di1}{dt} = \frac{di2}{dt} = \frac{Vin - Vo}{L} \qquad (3.8)$$

It can be seen that, for the steady state operation of a boost converter:

$$V_o = \frac{Vin}{(1-D)} \qquad (3.9)$$

For interleaved configuration and Continuous Conduction mode, L_1 and L_2 need to be selected such that:

$$L_{1min} = L_{2min} = \frac{Vin*D*T}{2*\Delta iL} \qquad (3.10)$$

where L_{1min} and L_{2min} are the minimum values of Inductors L_1 and L_2. Capacitor value is given by,

$$C_{min} = \frac{D}{R*(\frac{\Delta Vo}{Vo})*f} \qquad (3.11)$$

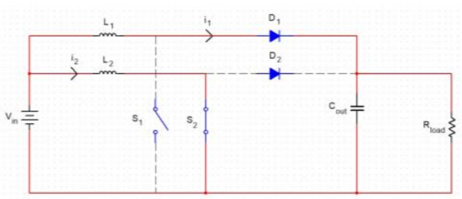

Figure 3.4. Mode-3 operation of IBC

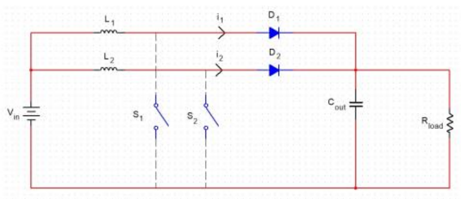

Figure 3.5. Mode-4 operation of IBC

3.1. Design of Interleaved DC-DC Boost Converter

The converter is designed to step-up a 12V input voltage to a 48V output voltage. Both inductor values used in IBC are equal. The following parameters are considered for the design of IBC: Inductors of 46.69 µH, Capacitor of 417 µF, Switching frequency of 100kHz, Voltage ripple of 2%, current ripple of 20% and output resistance of 48 Ω.

4. SIMULATION AND RESULTS

The simulation is done for the mathematical model developed for the Traditional DC-DC boost converter and the interleaved DC-DC boost converter and the circuits of the same in both open loop and closed loop configurations. The models and circuits of the simulations are developed on MATLAB/SIMULINK, version R2021a.

4.1. Mathematical Modelling

The Mathematical models of two different topologies of the DC-DC Boost converter are developed. These models are designed based on the design equations mentioned under Section 2 and Section 3 of the paper.

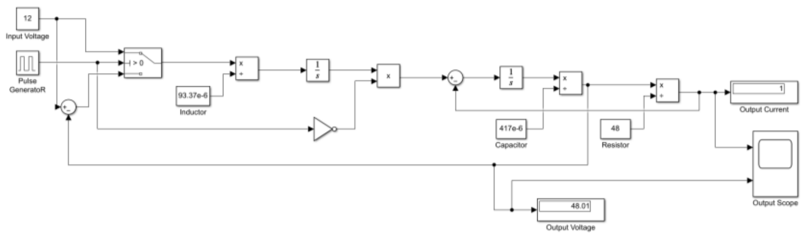

Figure 4.1 Mathematical model of Traditional DC-DC Boost Converter

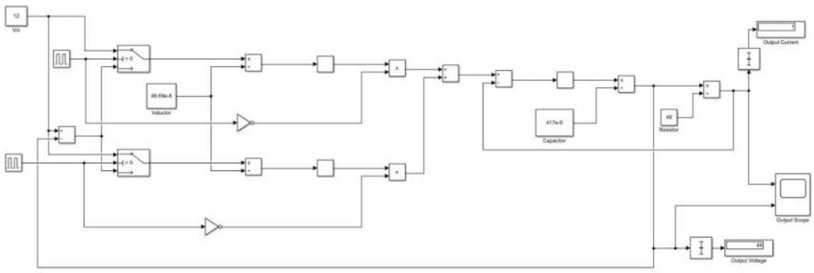

Figure 4.2 Mathematical model of Interleaved DC-DC Boost Converter

On simulation of the mathematical model we find that an output of 48V is obtained for the input of 12V with the following design parameters of the converter: Inductor of 93.37 µH (for Traditional Boost converter), Inductors of 46.69 µH (for IBC), Capacitor of 417 µF, Switching frequency of 100kHz, Duty cycle of 75%, Voltage ripple of 2%, current ripple of 20% and output resistance of 48 Ω.

4.2. Circuit Simulation

The input DC voltages vary from 9V to 12V. The results are shown by stepping up the voltage from 12V to 48V. The switching frequency of all switching elements is set at 100kHz. The main waveforms are shown with the horizontal axis and vertical axis depicting time and voltage/current respectively. The design parameters used in the simulation are the same as used for the mathematical modelling of the two converters as mentioned in section 4.1.

4.2.1. Traditional DC-DC Boost Converter

Figure 4.3 shows the simulated circuit for Traditional DC - DC Boost Converter without PI controller and Figure 4.4 depicts the obtained main waveforms for the output current is 1A, the output voltage is 48V and the input voltage is 12V.

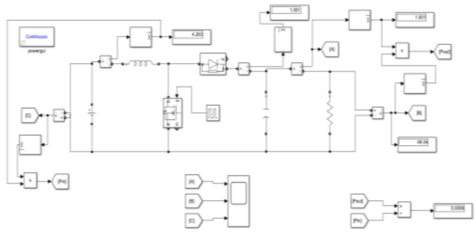

Figure 4.3 MATLAB/SIMULINK model of Traditional DC - DC Boost Converter

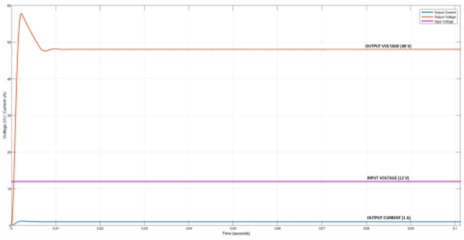

Figure 4.4 Simulation waveforms of output current (Blue), output voltage (Orange) and input voltage (Purple)

Figure 4.5 shows the simulated circuit for Traditional DC - DC boost converter with PI controller having values of P and I as 6 and 500 respectively and Figure 4.6 shows the obtained main waveforms for the output current is 1A , the output voltage is 48V, and the input voltage is varied in steps from 9V to 12V.

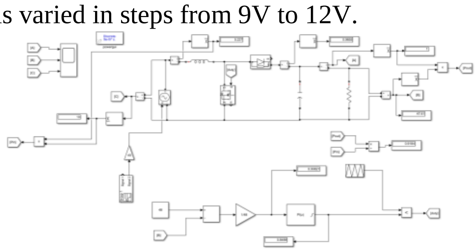

Figure 4.5 MATLAB/SIMULINK model of Traditional DC - DC Boost Converter (closed loop control)

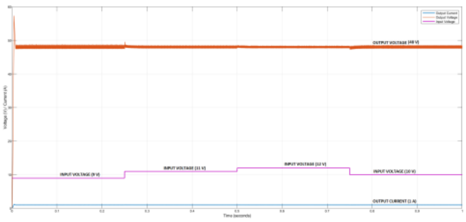

Figure 4.6 Simulation waveforms of output current (Blue), output voltage (Orange) and input voltage (Purple)

4.2.2. Interleaved DC-DC Boost Converter

Figure 4.7 shows the simulated circuit for Interleaved DC - DC Boost Converter without PI controller and Figure 4.8 shows the obtained main waveforms for the output current is 1A, the output voltage is 48V and the input voltage is 12V.

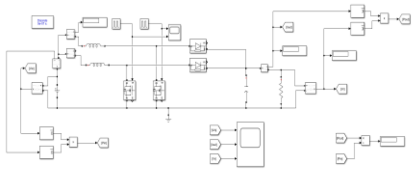

Figure 4.7 MATLAB/SIMULINK model of IBC

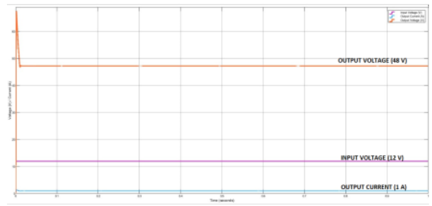

Figure 4.8 Simulation waveforms of output current (Blue), output voltage (Orange) and input voltage (Purple)

Figure 4.9 shows the simulated circuit for Interleaved DC - DC Boost Converter with PI controller having values of P and I as 6 and 1000 respectively and Figure 4.10 shows the obtained main waveforms for the output current is 1A , the output voltage is 48V, and the input voltage is varied in steps from 9V to 12V.

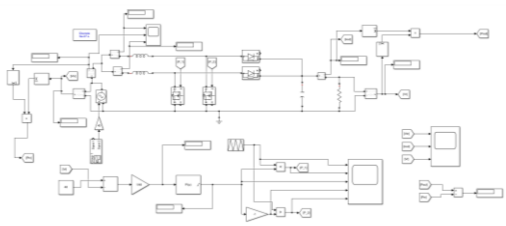

Figure 4.9 MATLAB/SIMULINK model of IBC (closed loop control)

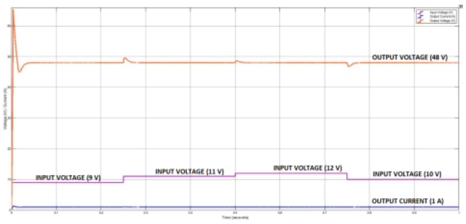

Figure 4.10 Simulation waveforms of output current (Blue), output voltage (Orange) and input voltage (Purple)

4.2.3. Current Ripple and Voltage Ripple

From Figure 4.11 and Figure 4.12 the values obtained for current ripple and voltage ripple of traditional DC - DC boost converter (closed loop control) is 20mA and 1.2V respectively.

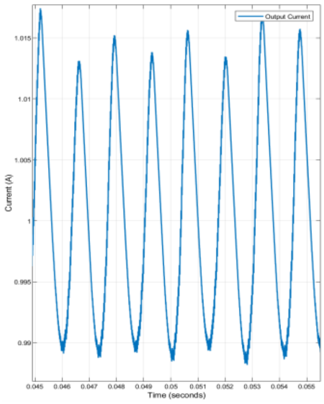

Figure 4.11 Current ripple in Traditional Boost Converter (closed loop control)

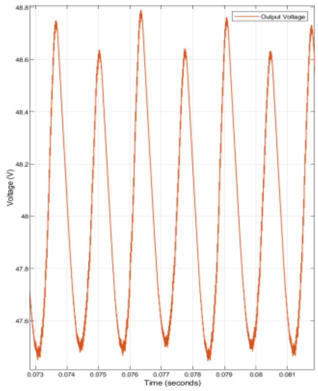

Figure 4.12 Voltage ripple in Traditional Boost Converter (closed loop control

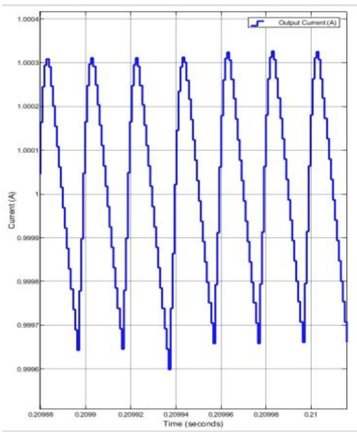

Figure 4.13 Current ripple in IBC (closed loop control)

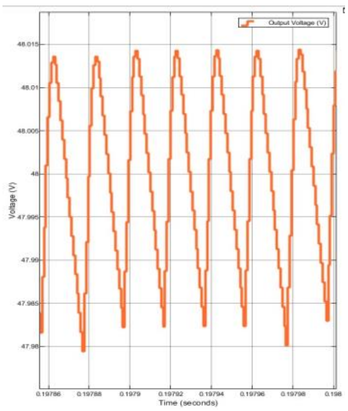

Figure 4.14 Voltage ripple in IBC (closed loop control**)**

From Figure 4.13 and Figure 4.14 the values obtained for current ripple and voltage ripple of Interleaved DC - DC Boost Converter (closed loop control) is 1mA and 30mV respectively.

For the given specification of stepping up the input voltage of 12V to an output voltage of 48V, it is observed that Interleaved DC - DC Boost Converter has better efficiency and lower current and voltage ripple content compared to Traditional DC - DC Boost Converter.

Table 1 shows the comparison of the simulation results of Traditional DC-DC Boost Converter and Interleaved DC-DC Boost Converter.

Table 1: Comparison of Traditional Boost Converter and Interleaved Boost Converter

Parameters	Traditional DC-DC Boost Converter	Interleaved DC-DC Boost Converter
Duty cycle	0.761	0.7575
Percentage Efficiency (open loop)	93.99%	94.43%
Percentage Efficiency (closed loop)	91.84%	93.42%
Output Current Ripple	20 mA	1 mA
Output Voltage Ripple	1.2 V	30 mV

5. CONCLUSION

Comparative analysis between the Traditional DC - DC Boost Converter and the interleaved DC - DC boost converter is performed only for continuous conduction mode (CCM). Both the converters were designed along with their mathematical models and simulated on MATLAB/SIMULINK to step up input voltage of 12V to an output voltage of 48V. Through the simulation results, IBC has reduced current and voltage ripple as a result IBC has better efficiency compared to the Traditional DC - DC Boost Converter. The input currents to inductor 1 and 2 are phase shifted by about 50%, the ripples produced by one inductor nullifies/reduces the ripples produced by the other. The same is the reason for the reduction of voltage ripples at the output of the IBC. Therefore, IBC is a more reliable topology than Traditional DC - DC Boost Converter. Finally, the results of the simulation points to IBC being implemented as a hardware model in the future.

6. REFERENCES

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