

Two Stage Interleaved Boost Converter Design and Simulation in CCM and DCM

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Abstract— The concept of interleaving, or more generally that of increasing the effective pulse frequency of any periodic power source by synchronizing several smaller sources and operating them with relative phase shifts, has several advantages. We have a source and a load and the converter in between can have many stages in parallel. Among these the Interleaved Boost Converter has many applications. Here the concept of interleaving and the design and simulation of the Interleaved Boost Converter in both the CCM and DCM modes are discussed.

Keywords—Interleaving, Boost Converter, CCM, DCM.

I. INTRODUCTION

In the field of power electronics, application of interleaving technique can be traced back to very early days, especially in high power applications. In high power applications, the voltage and current stress can easily go beyond the range that one power device can handle. Multiple power devices connected in parallel and/or series could be one solution. However, voltage sharing and/or current sharing are still the concerns. Instead of paralleling power devices, paralleling power converters is another solution which could be more beneficial. Furthermore, with the power converter paralleling architecture, interleaving technique comes naturally. Benefits like harmonic cancellation, better efficiency, better thermal performance, and high power density can be obtained. In earlier days, for high power applications, in order to meet certain system requirement, interleaving multi-channel converter could be a superior solution especially considering the available power devices with limited performance at that time. Interleaving technique was also investigated in the early days for the satellite or fuel cell applications [2][3], and was introduced as unconventional SMPS power stage architecture[1]. Interleaving technique can effectively reduce the filter capacitor size and weight.

Boost power supplies are popular for creating higher dc voltages from low-voltage inputs. As the power demands from these supplies increase, however, a single power stage may be insufficient. Interleaving is also called 'multiphasing' and is useful for reducing the filter components. It is equivalent to a parallel connection of 2 sets of switches,

diodes and inductors connected to a common filter capacitor and load. [4][5]

II. WORKING AND ANALYSIS OF INTERLEAVED BOOST CONVERTER

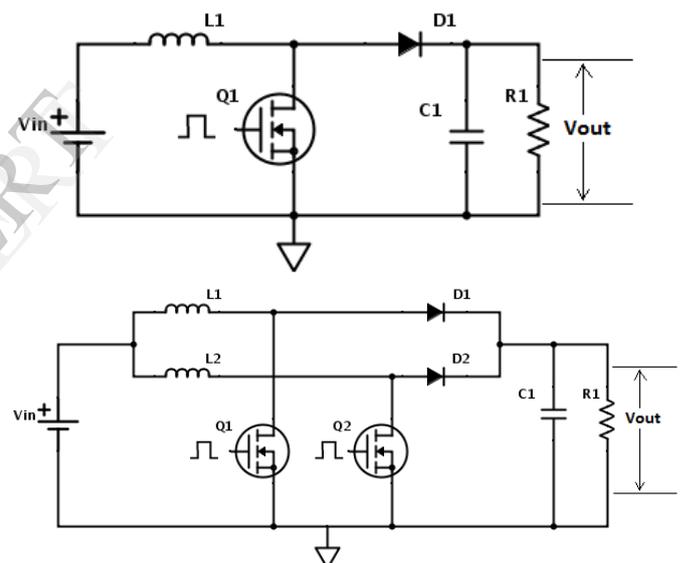


Fig 1: Single stage and Interleaved Boost converters

The diagram above shows a Single stage Boost Converter and Interleaved Boost Converter. We can see clearly that in the Interleaved topology, between the input and output stages, there are 2 stages of the power converter in parallel, thereby having 2 inductors, 2 switches and 2 diodes. [6]

In the single-phase design, applying a gate voltage to MOSFET Q_1 pulls the drain potential to ground, applying the input voltage across inductor L_1 and causing current to ramp up. During the ramp time, output capacitor C_1 must alone supply the load current. When Q_1 turns off, the voltage across L_1 reverses polarity to maintain current flow. This scenario forces the switch node more positive than the input voltage and forward-biases diode D_1 , charging output capacitor C_1 and supplying the output current. For each of the two switching states, the inductor's volt-microsecond product must balance. That is, $d/f_s * V_{IN} = (1-d)/f_s * (V_{OUT} - V_{IN})$, yielding

the relation $V_{OUT}=V_{IN}/(1-d)$, where d is the duty ratio, f_s is the switching frequency, V_{IN} is the input voltage, and V_{OUT} is the output voltage. This expression is valid in CCM (continuous conduction mode), in which the inductor current remains positive at all times. Each phase of the interleaved-boost converter works in the same way that this single-phase-boost converter does. The two power stages operate 180 degree out of phase, cancelling the ripple current in the input and the output capacitors. The interleaved-boost approach uses forced current-sharing between the power stages to equalize the power that the stages deliver. Without this feature, one power stage could deliver substantially more power than the other, which would defeat the ripple cancellation.

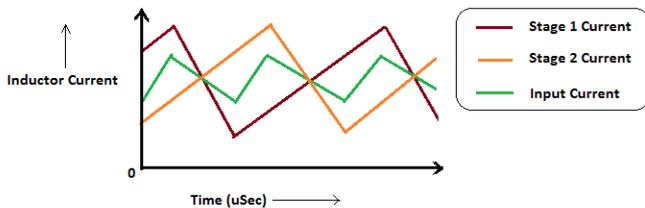


Fig 2: Currents of the 2 stages and the effective input current

Figure above shows that the two power stages are operating 180 degree out of phase provide a two-to-one reduction in peak-to-peak ripple current. The individual interleaved power stages operate at the same frequency as the single-phase design, 100 kHz, but the effective input- and output-ripple frequency is 200 kHz. The interleaved-design calculation used a frequency of 100 kHz and twice the ripple current of the single-phase design, yielding half the inductance. Since the same input current of the single stage is dividing into two in the interleaved design, the inductor specifications like current rating, LI^2 are greatly reduced [6]. The losses are also reduced considerably as the conduction losses are less compared to the single stage design.

III. DESIGN OF THE INTERLEAVED BOOST CONVERTER IN CCM MODE

The design of the Interleaved Boost Converter in Continuous Conduction mode (CCM) is similar to the design of the single stage normal boost converter with slight differences.

The design parameters are as below :

- Input Voltage (V_d) range – 90 – 264 V_{RMS}
- Output Voltage (V_o) - 400 V
- Output Power – 1.3 KW
- Switching frequency (of each MOSFET switch) – 100 KHz
- Voltage ripple – 200mV
- Current ripple – 40 % of load current [7]

The design is done for the ideal condition. Voltage drop across the diodes and switches is not considered. ESR (Equivalent series resistance) of Capacitor is not considered.

Calculation of the parameters:

A. Duty cycle (D)

Formula for the voltage conversion ratio is as below.

$$\begin{aligned} V_o / V_d &= 1 / (1-D) \\ D &= (V_o - V_d) / V_o \\ D_{max} &= (400 - 90) / 400 = 0.775 \\ D_{min} &= (400 - 264) / 400 = 0.34 \end{aligned} \quad (1)$$

B. Current Ripple (ΔI_L)

$$\begin{aligned} \text{Load current } I_o &= \text{Output power} / \text{Output voltage} \\ I_o &= 1300 / 400 = 3.25 \text{ A}_{RMS} = 4.6 \text{ A}_{Peak} \\ \Delta I_o &= 40 \% \text{ of load current (4.6A)} = 1.84 \text{ A} \end{aligned}$$

Relation between input and output currents is as below.

$$I_{IN} = I_o / (1-D) \quad (2)$$

$$\Rightarrow 2I_L = I_o / (1-D)$$

$$\Rightarrow I_L = (0.5) I_o / (1-D) \quad (3)$$

$$\Rightarrow I_L = (0.5)3.25 / (1 - 0.775) = 7.22 \text{ A}_{RMS} = 10.21 \text{ A}_{Peak}$$

$$\text{(Therefore } I_{IN} = 2I_L = 20.42 \text{ A}_{Peak})$$

$$\Delta I_L = 20 \% \text{ of } I_L (10.21 \text{ A})$$

$$\Delta I_L = 2.036 \text{ A}$$

C. Inductor value

For CCM, Output current (I_o) should be greater than the boundary current (I_{OB})

$$I_o > I_{OB}$$

$$V_o / R > T_s V_o D (1-D)^2 / 2L$$

$$L_{min} > RT_s D (1-D)^2 / 2 \quad (4)$$

$$\text{Load resistor } R = V_o / I_o = 400 / 3.25 = 123.08 \Omega$$

$$T_s (\text{Time period}) = 1 / f_s = 1 / 100 \text{ KHz} = 10 \mu\text{s}$$

$$V_d = 90 \text{ V}_{RMS} = 127.28 \text{ V}_{peak}$$

$$V_o = 400 \text{ V}_{RMS} = 565.68 \text{ V}_{peak}$$

The minimum value of inductance for CCM is given by the below formula:

$$L_{min} > RT_s D (1-D)^2 / 2$$

$$L_{min} > (123.08) (10 \times 10^{-6}) (0.775) (1 - 0.775)^2 / 2$$

$$L_{min} > 24.14 \mu\text{H}$$

If the inductance value is 24.14uH, it will result in boundary condition.

$$L = V_d D T_s / \Delta I_L \quad (5)$$

$$L = (127.28) (0.775) (10 \times 10^{-6}) / 2.036$$

$$L = 484.5 \mu\text{H}$$

As we can see, this is much greater than the boundary value resulting in CCM

D. Capacitance value

$$C = I_o D (T_s/2) / \Delta V \quad (6)$$

$$C = (3.25) (0.775) (10 \times 10^{-6} / 2) / 0.2$$

$$C = 63 \mu\text{F}$$

The major differences that we see in the design when compared to the single stage normal boost converter is in the calculation of the current ripple where the optimal value is chosen to be 40 % of the load current [7]. Hence the inductor current ripple should be chosen as half which is 20% of each inductor current. Another difference is that while calculating the capacitance value we consider $T_s/2$ as the switching frequency doubles and hence time period is halved.

IV. SIMULATION IN CCM

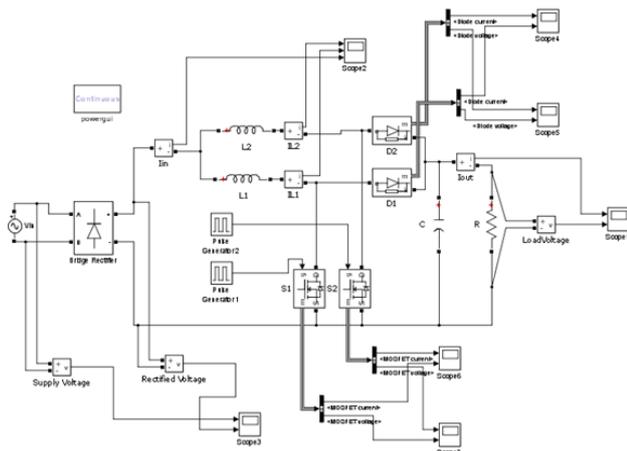


Fig 3: Simulation circuit of Interleaved Boost Converter in CCM

The inductances L_1 and L_2 have the same value of $484.5\mu H$. Capacitance is $63\mu F$. Duty cycle is 0.775. The values are the ones which have been calculated in the previous section.

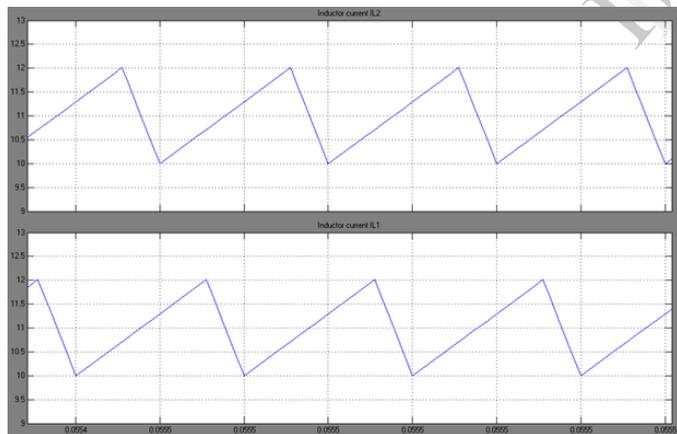


Fig 4: The inductor currents of the 2 inductors I_{L1} and I_{L2} in CCM

It can be seen in Fig 4 above that the inductor currents are operating at 180 deg out of phase that is while one is charging, the other is discharging. Both the inductor currents I_{L1} and I_{L2} are not reaching zero which means that the converter is in CCM. The average value of each of the inductor currents is 11A. The inductor current ripple is 2A.

Fig 5 shows the input current. When compared with the inductor currents, it can be seen that, for the same duty cycle, the switching frequency is doubled and the ripple is reduced. The ripple of the input current is 1.4 A which proves that there

is a natural cancellation of the ripple in the interleaved topology.

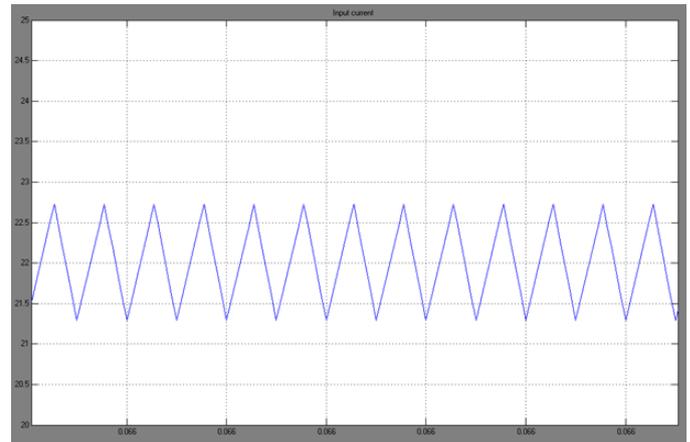


Fig 5 : The input current in CCM

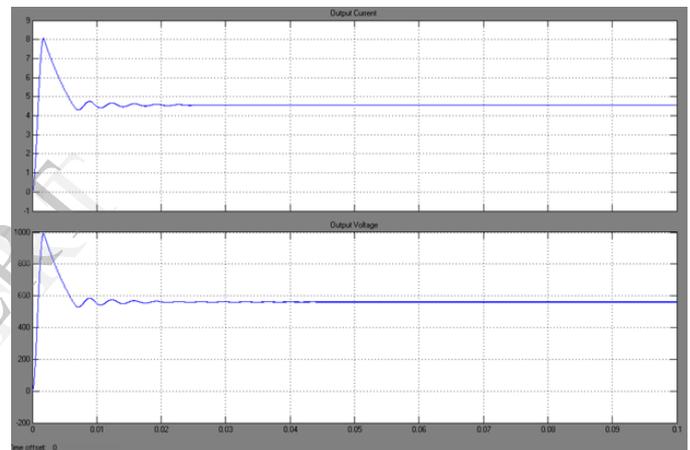


Fig 6 : The waveforms of load current and load voltage in CCM

As we can see the waveforms of the load current and load voltage are the same which indicates that the power factor of the circuit is very near unity or unity. The circuit can be used where Power factor correction is needed.

V. DESIGN OF THE INTERLEAVED BOOST CONVERTER IN DCM MODE

The design of the Interleaved Boost Converter in the Discontinuous conduction mode (DCM) is considerably different when compared to the CCM mode. Here also there are slight modifications to the design as compared to the single stage boost converter.

The design parameters are the same as in the CCM mode.

However when the calculation of the parameters is concerned, the same order as the CCM mode cannot be followed.

Calculation of the parameters:

A. Load current, load resistor, time period and peak values.

These calculations are the same as in CCM mode.

B. Inductor value

While calculating the inductance value in the CCM mode, we also calculated the minimum value of inductance L_{min} . Now if the value is equal to L_{min} , then we will have the boundary condition, where the inductor current just touches zero and then the next cycle begins immediately. We got L_{min} as $24.14 \mu H$. So it follows that if the inductor value is less than $24.14 \mu H$, then the converter will work in DCM.

So let the value of L be $15 \mu H$ (which is $< 24.14 \mu H$)

C. Duty Cycle

In DCM the formula for the duty cycle is given by

$$D = \sqrt{I_o 2L(V_o - V_d) / (T_s V_d^2)} \tag{7}$$

$$D = \sqrt{4.6 * 2 * 15 * 10^{-6} * (565.68 - 127.28) / 10 * 10^{-6} * 127.28^2}$$

$$D = 0.61$$

D. Δ_1 (Percentage of time period where the inductor discharges)

$$\Delta_1 = V_d / (V_o - V_d) * D \tag{8}$$

$$\Delta_1 = (127.28 / (565.68 - 127.28) * 0.61)$$

$$\Delta_1 = 0.117$$

E. Ripple Inductor current (ΔI_L)

$$\Delta I_L = V_d D T_s / L \tag{9}$$

$$\Delta I_L = 127.28 * 0.61 * 10 * 10^{-6} / (15 * 10^{-6})$$

$$\Delta I_L = 51.76 A$$

F. Output capacitor value

$$C = I_o D (T_s / 2) / \Delta V \tag{10}$$

$$C = (4.6) * (0.61) (10 * 10^{-6} / 2) / 0.2$$

$$C = 70.15 \mu F$$

VI. SIMULATION IN DCM

The circuit in DCM is shown by Fig 6.

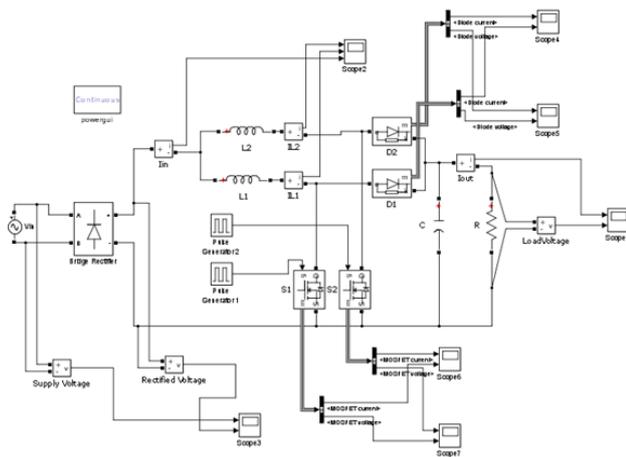


Fig 6: Simulation circuit of Interleaved Boost Converter in DCM

The circuit is the same as that of CCM. The inductances L_1 and L_2 have the same value of $15 \mu H$. Capacitance is $70.15 \mu F$. Duty cycle is 0.61 . The values are the ones which have been calculated in the previous section.

Fig 7 shows the inductor currents of the 2 inductors and the input current in the Discontinuous Conduction Mode. The 2 inductor currents remain at zero for some time during the time period and hence the DCM mode is confirmed. Both the converter stages operate at 180 deg phase difference. The effective input current does not reach zero as there is no instance where both the inductor currents are zero at the same time. The input current ripple is reduced as compared to the inductor currents. This also proves the natural ripple reduction property of the interleaving topology.

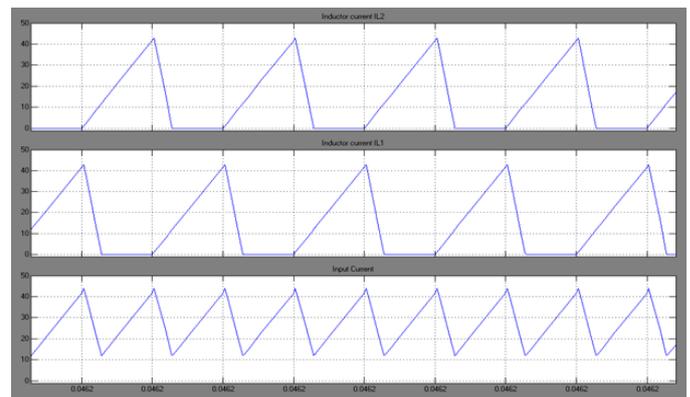


Fig 7: The inductor currents of the 2 inductors I_{L1} and I_{L2} and the input current in DCM

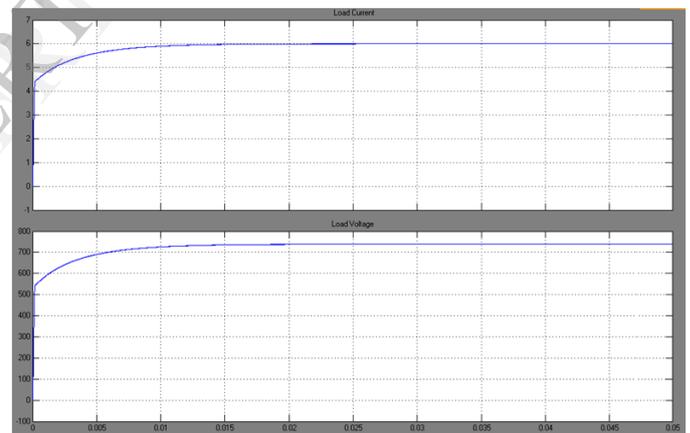


Fig 8: The waveforms of load current and load voltage in DCM

As we can see the waveforms of the load current and load voltage are the same which indicates that the power factor of the circuit is very near unity or unity. The circuit can be used where Power factor correction is needed.

The major differences that we see in the design when compared with the normal single stage boost converter are the same as that of CCM mode but when DCM design is compared to the CCM mode, the way we choose the inductor value is different, the formula for the duty cycle is different, and Δ_1 needs to be calculated. Also duty cycle depends on the load in DCM but not so in CCM.

VII. APPLICATIONS

The Interleaved Boost Converter is used widely in computer and telecom applications where SMPS (Switched Mode Power Supplies) are needed. Other applications are in photovoltaic fuel cells, hybrid electric vehicles and satellites.

DCM mode is used when the energy required by the load is very low i.e. in low power applications.

These can be used in power electronic equipments which require power factor correction (PFC).

VIII. CONCLUSION

The interleaved boost converter in both the continuous conduction mode (CCM) and in the discontinuous conduction mode (DCM) has been successfully designed and simulated to verify the design. The two-phase approach uses significantly less inductance than does the single-phase approach, and each inductor carries half the current. There is a natural reduction in the ripple of the input and output currents.

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