Analysis of High Frequency Multi-Phase Multi-Stage Boost Converter

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Abstract-A novel approach to achieve a high static gain in non-isolated dc-dc converter is presented in this paper. The conventional boost converter is cascaded to step-up the voltage to higher level and the first boost stage is multi-phased to avoid high input current stress on the switch. The multi-phase configuration significantly reduces the current ripple and the voltage ripple due to the operation of the parallel paths and hence reducing the filter size. This technique allows the operation with a high static gain and high efficiency, making possible to design a compact circuit. The operational principle, the design procedure and the simulation results obtained are presented for multi-phase, multi-stage and integrated multi-phase multi-stage boost converter.

Keywords: high step-up gain, multi-stage, multi-phase, ripple cancellation.

I. INTRODUCTION

With the growth of battery powered application, there is a huge demand for highly efficient, small size, low cost and high static gain dc-dc converter. Typical applications are hybrid vehicle, uninterruptable power supply [4] and renewable energy system such as solar.

The step-up stage normally is the critical point for the design of high efficiency converters due to the operation with high input current and high output voltage, thus a detailed study should be carried out, in order to define the topology for a high step-up application.

Magnetic coupled classic converter such as flyback or push-pull converter can be used to achieve high static gain [4]. However, volume of power transformer will greatly influence the size of converter. The leakage inductance can produce voltage stress; high switching frequency will bring down the efficiency of the transformer itself and will cause electromagnetic Interference (EMI), thereby reducing the converter efficiency. Non-isolated conventional boost converter, can provide high step-up voltage gain but with the penalty of high voltage and current stress, high duty cycle operation.

However, new non-isolated dc-dc converter topologies is proposed, showing that it is possible to obtain high static gain with low current stress and low losses, improving the performance with respect to conventional dc-dc converter. A new alternative for the implementation is proposed in this paper by cascading the boost converter to get high step-up [13] and multi-phasing to avoid current stress on semiconductor switches [9], thus designing a highly efficient converter with simpler structure. With increase in ripple frequency due to multi-phasing the filter size will reduce significantly.

II. MULTIPHASE BOOST CONVERTER

The concept of interleaving is that of increasing the effective pulse frequency of any periodic power source by synchronizing several smaller converters and operating them with relative phase shifts [10]. 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, parallelizing power converters is another solution which could be more beneficial. Furthermore, with the power converter parallelizing architecture, interleaving technique comes naturally. Benefits like harmonic cancellation, better efficiency, better thermal performance, and high power density can be obtained [13]. With these multi-modular converters the current stress can be divided to a level that can be handled by semiconductor switches and reduces the ohmic component of their conduction losses. In many applications, one major concern is the input and output filters rely almost exclusively on tantalum capacitors due to the highest available energy-storage-to-volume ratio [10]. However, the ESR of this filter capacitor causes high level thermal stress from the high switching pulsed current. The input and output filter capacitance is usually determined by the required number of capacitors sufficient to handle the dissipation losses due to the ripple current. Interleaving multiple converters can significantly reduce the switching pulsed current go through the filter capacitor. By properly choosing the channel number and considering the duty cycle, the ripple current may be reduced to zero. Furthermore, interleaving increases the ripple frequency to be \( n \) (\( n \) is the total number of phase) times the individual switching frequency.
The ESR of the tantalum capacitors is inversely proportional to the frequency. Interleaving technique can effectively reduce the filter capacitor size and weight. Another concern of this application is packaging. Due to the thermal management issues, the power loss of non-interleave converter exceeds the typical power dissipation capability. In addition, the substantial bulky converter usually requires a larger heat sink module. Interleaving technique can divide the power transfer into multiple modules, lighter and smaller. With the interleaving architecture, increased output power may be supplied by adding additional identical modules.

Use of multi-phase boost converter is an optimal solution for high input current dc-dc converter such as conventional boost where the current is shared among different phases [12]. The multi-phase booster can be achieved by adding more parallel legs to the conventional boost converter. The Fig.1 shows a three-phase boost converter, where two more legs connected in parallel with the conventional one. The multi-phase boost converter interleaves the clock signals of the paralleled power stages, reducing input and output ripple current without increasing the switching frequency. Because of the phase difference in clocking between the converters, the inductor ripple currents in the different phases tend to cancel each other, resulting in a smaller ripple current getting to the output capacitor. The frequency of the output ripple current is increased by the number of the phase.

Fig.1. Three-Phase boost converter

Fig.2. Phase-1, 2, 3 closed

Fig.3. Phase-2 Open, Phase-1 and phase-3 closed

Fig.4. Phase-3 Open, Phase-1 and Phase-2 closed

Fig.5. Phase-1 Open, Phase-2 and Phase-3 closed

Thus the factors, such as reduced ripple current, increased ripple frequency contribute to a smaller output filter capacitor for the same ripple voltage requirement, thereby reducing the size and cost of the filter components. This results in improved dynamic response to load transients [13].

A) Circuit description and operational analysis of Multi-Phase Boost Converter.

The basic structure of three-phase boost converter can be constructed by adding two parallel legs to conventional boost converter. It is possible to add more number of parallel legs to have more phases, where the input current is shared among different phases. The converter is operating in continuous conduction modes for better operational characteristics results. Thus, the different operational stages and the theoretical waveforms are represented for CCM and considering three phases only. Different stage operations can be explained with reference to the Figs.2 – 6. The three-phase boost converter operates in six stages. The Table no.1 figures out the status of the three-phase boost converter for different switching conditions.

In three-phase boost converter, the clock for the switches is phase shifted by 120 degree as shown in Fig.6. The three phase ripple current waveforms are shown with solid, dashed and dotted lines with reference to their clock signals, the ripple cancellation among different phase’s results in reduced magnitude and increase in frequency by three times [13].

The voltage transformation of three-phase boost converter is same as that of conventional boost converter. Due to interleaving of the clock pulses, all the three switches are closed for the duration \( \left( D - \frac{2}{3} \right) T \), three times a period with the interval of \( (1 - D)T \)

Where, D and T are duty ratio and switching period of the converter.
### B) Design Consideration for Multi-Phase Boost Converter.

The design equations for Multi-Phase Boost converter operating in continuous conduction mode is presented with an example. Considering the following specifications,

- **Input voltage**: $V_{\text{in}} = 12 \, \text{V}$
- **Output voltage**: $V_{\text{out}} = 40 \, \text{V}$
- **Output power**: $P = 1 \, \text{KW}$
- **Switching frequency**: $F = 100 \, \text{kHz}$
- The rated load for given output power: $R = 1.6 \, \Omega$

1) **Static gain**: The static gain of Multi-Phase booster is as that of conventional booster.

\[
V_{\text{out}} = \frac{V_{\text{in}}}{1-D}
\]  
(1)

Where $D$ is switch duty cycle ratio.

Therefore, the nominal duty cycle is 0.7

2) **Inductor current**: The inductor current through each phase is given by,

\[
I_{\text{L,phase}} = \frac{V_{\text{out}}}{N \times \Delta \text{phase}} = 27.78 \, \text{A}
\]  
(2)

$N$ – Number of phases.

$\Delta = 1 - D$

3) **Inductance**: Considering 70% peak to peak ripple,

\[
\Delta I_{\text{L,phase}} = 38.89 \, \text{A}
\]

Therefore, inductance in each phase is given by

\[
L_{\text{phase}} = \left( \frac{V_{\text{in}} D T}{\Delta I_{\text{L,phase}}} \right) = 2.16 \, \mu\text{H}
\]  
(3)

$T$ – Switching period.

The resultant peak-to-peak ripple current through the capacitor, is given by

\[
\Delta I_{\text{ripple}} = \frac{V_{\text{in}} D^2 T}{N \times \Delta \text{phase}} = 5.56 \, \text{A}
\]  
(4)

4) **Filter capacitance**: For 20% ripple voltage, the capacitance value is given by,

\[
C = \frac{V_{\text{out}} (\frac{D}{2}) T}{\Delta V_{\text{out,peak}}} = 1.04 \, \mu\text{F}
\]  
(5)

By considering the inductor copper loss and semiconductor loss [7], output voltage equation for three-phase booster is given by,

\[
\frac{V_{\text{o}}}{V_{\text{in}}} = \left( \frac{1}{D} \right) \left( 1 - \frac{D V_{\text{D}}}{V_{\text{in}}} \right) \left( \frac{1}{1 + \frac{R_{\text{D}}}{3 R_{\text{D}}}} \right)
\]  
(6)

Parasitic element values are same for all the phases, as it is identical multi-modular structure.

- $V_{\text{D}}$ – diode voltage drop
- $R_{\text{L}}$ – Inductor DC resistance
- $R_{\text{ON}}$ – Switch ON resistance

Similarly, the efficiency of three-phase booster can be computed as,

\[
\eta = \left( 1 - \frac{D V_{\text{D}}}{V_{\text{in}}} \right) \left( \frac{1}{1 + \frac{R_{\text{D}} + R_{\text{ON}} + D R_{\text{D}}}{3 R_{\text{D}}}} \right)
\]  
(7)

### C) Simulation result of Multi-Phase Boost Converter.

The design procedure that developed was verified with simulation results. The simulations include semiconductor and copper loss. The Fig.7 shows the phase inductor current and resultant ripple current waveforms. The output voltage and current waveforms are shown in Fig.8.
II. MULTISTAGE BOOST CONVERTER

In order to attain a higher boosting in conventional dc-dc converter the required duty cycle will be very high. The switch has to be closed for a long time so that the inductor will store energy. But the OFF time will be in fractions, compared to ON time. The inductor has to collapse, within the given OFF time. Very close to 100% duty cycle will always be a threat to the system such as when the load fluctuates or rises, the system tries to compensate the load by increasing the duty cycle which may lead to duty ratio of 1, means the switch has to be closed all the time, the current in the inductor and as well in switch will continue to increase. Thus, causing the semiconductor devices to get damaged as the rated power dissipation exceeds [3].

Multi-Stage boost converter is a cascaded boost converter that results in the output voltage increasing in a geometric progression [8]. The output voltage of one stage will act as input voltage to the next stage, and thus steps up. The Fig.9 shows the structure of three-stage boost converter to achieve a very high static gain.

A) Circuit description and operational analysis of Multi-Stage Boost Converter.

The structure of three-stage boost converter is achieved by cascading three discrete conventional boost converters. It is possible to add more stages for higher static gain. The converter circuit can be resolved for two conditions, ON and OFF time in one switching period, the same duty cycle is maintained for all the stages.

1) Switch ON [Fig.10]: During the ON duration of switching period, all the three switches are closed. The capacitor C1 and C2 are charged with voltage V1 and V2 respectively. Thus, the input voltage $V_{in}$ will cause the inductor current $I_{L1}$ to increase during the ON period, thereby storing the energy. Same with the inductor currents, $I_{L2}$ and $I_{L3}$, the voltages $V1$ and $V2$ cause the inductors $L2$ and $L3$ to store energy. The capacitor C3 will be supplying to load [8].

2) Switch OFF [Fig.11]: During the OFF duration of the switching period all the switches are made open, the voltage across the first stage inductor $L1$, $V1-Vin$, will cause the inductor current to decrease, thereby releasing the stored energy and charging the capacitor C1 through diode $D1$ [8]. Similarly, with the inductor currents $I_{L2}$ and $I_{L3}$, charging the capacitor C2 and C3 and supplying to load through diodes $D2$ and $D3$.

Thus for three-stage booster, the voltage transformation is given as:

$$V_3 = \left(\frac{1}{1-D}\right)V_2 = \left(\frac{1}{1-D}\right)^2V_1 = \left(\frac{1}{1-D}\right)^3V_{in} \quad (8)$$

Where, $V_1$, $V_2$, $V_3$ are output voltages of first, second and third stage respectively.

Similarly, the current relation is given by,

$$I_o = (1-D)I_{L3} = (1-D)^2I_{L2} = (1-D)^3I_{L1} \quad (9)$$

$I_o$ – output current
$I_{L1}$ – first stage inductor currents.
$I_{L2}$ – second stage inductor currents.
$I_{L3}$ – third stage inductor currents.
Fig. 12. Output voltage of each stage

**B) Design Consideration for Multi-Stage Boost Converter.**

The design equations for Multi-Stage Boost converter operating in continuous conduction mode is presented with an example. Considering the following specifications,

- Input voltage: $V_{in} = 12$ V.
- Output voltage: $V_{out} = 444$ V.
- Output power: $P = 1$ KW.
- Switching frequency: $F = 100$ kHz.
- The rated load for given output power: $R = 197.13$ Ω

1) **Static gain:** The static gain of Three-stage booster is given by,

$$V_{out} = \left(\frac{1}{1-D}\right)^3 V_{in}$$  \hspace{1cm} (10)

Where D is switch duty cycle.

Therefore, the nominal duty cycle is 0.7

2) **Intermediate Inductor currents and capacitor voltages:**

First stage output capacitance voltage,

$$V_1 = \left(\frac{1}{1-D}\right)^2 V_{in} = 40$ V $$ \hspace{1cm} (11)

Second stage output capacitance voltage,

$$V_2 = \left(\frac{1}{1-D}\right)^2 V_{in} = 133.33$ V $$ \hspace{1cm} (12)

First stage inductor current,

$$I_{L_{1}} = \left(\frac{1}{1-D}\right)^3 I_o = 83.33$ A $$ \hspace{1cm} (13)

Second stage inductor current,

$$I_{L_{2}} = \left(\frac{1}{1-D}\right)^2 I_o = 25$ A $$ \hspace{1cm} (14)

Third stage inductor current,

$$I_{L_{3}} = \left(\frac{1}{1-D}\right) I_o = 7.5$ A $$ \hspace{1cm} (15)

3) **Inductance:** Considering 70% peak to peak ripple, the inductor values are given by [7],

$$L_1 = \frac{V_{in}.D.T}{\Delta V_{1req}} = 0.72$ \mu H $$ \hspace{1cm} (16)

$T$ – Switching period.

$$L_2 = \frac{V_{1}.D.T}{\Delta V_{2req}} = 8.01$ \mu H $$ \hspace{1cm} (17)

$$L_3 = \frac{V_{2}.D.T}{\Delta V_{3req}} = 88.86$ \mu H $$ \hspace{1cm} (18)

4) **Capacitance:** For 20% ripple voltage [7], the capacitance value is given by,

$$C_1 = \frac{V_{1}.D.T}{\Delta V_{1req}} = 21.06$ \mu F $$ \hspace{1cm} (19)

$$C_2 = \frac{V_{2}.D.T}{\Delta V_{2req}} = 1.96$ \mu F $$ \hspace{1cm} (20)

$$C_3 = \frac{V_{3}.D.T}{\Delta V_{3req}} = 0.17$ \mu F $$ \hspace{1cm} (21)

C) **Simulation result of Multi-stage Boost Converter.**

The design procedure that developed was verified with simulation results. The Fig.12 shows the output voltage of every stage. The Fig.13 shows the inductor current of all the three stages.

### III. MULTI-PHASE MULTI-STAGE BOOST CONVERTER

Generally, the problem with high static gain dc-dc converter is very high input current, power equality law [1]. The high static gain dc-dc converter posses a high input current stress on the switch. Thus the power semiconductor device at the input side is always stressed by high current. In case of Multi-stage boost converter, the first stage power semiconductor switches are more stressed than any other. The multi-phase booster is integrated with multi-stage booster, in order to achieve the advantage of both modalities. Thus, the first stage in three stage boost converter can be multi-phased, so that the high input current can be shared among all the phases [13]. The Fig.14 shows a three-phase three-stage boost converter, the converter provides a high static gain and posses much less stress to the initial stage components. More than one stage can be multi-phased if required. Thus it makes possible to have low rated components to be used. The increase in the number of components in multi-phase multi-stage booster is compensated by better efficiency. The heat sink module required at high current input stage is considerably reduced.

The design procedure is the same as discussed above for multi-phase and multi-stage booster. The number of stages and the number of phase in each stage will depend on the application, the static gain and the duty cycle.
The simulation result for the integrated three-phase three-stage boost converter is shown in Fig. 15 and Fig. 16, the output voltage of each stage and first stage three-phase currents respectively.

IV. CONCLUSION

The shortcomings of conventional boost converter can be easily overcome by multi-phase and multi-stage boost converter. The high input current was divided by identical parallel modality in multi-phase boost converter. With average duty cycle very high static gain can be achieved by multi-stage boost converter. The above two advantage can be achieved by integrating multi-phase and multi-stage booster. The inductor current ripple cancellation leads to reduced ripple with increased frequency in multi-phase booster. This makes the way to have a smaller filter size, leading to a compact system. Thus, for the application requiring very high static gain, multi-phase multi-stage booster topology will be best suitable being an efficient system.

REFERENCES


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