

AN APPROACH TO OPTIMIZING NUMBER OF PHASES IN AN INTERLEAVED BOOST CONVERTER

Boris Šašić, László Nagy*

Curtis Instruments, New York, USA

*EE Dept., University of Novi Sad, Faculty of Technical Sciences,
Novi Sad, Republic of Serbia, lnadj@uns.ns.ac.yu

Abstract: This paper is an attempt to streamline the process in one of the critical initial parts of a multiphase converter design. It addresses multiphase boost converters. The basic equations for normalized input ripple current and output capacitor RMS current are presented in the first part of the paper. Then, it is shown that in some practical applications a number of phases may be optimized for minimum input current ripple and output capacitor RMS current. Simply increasing a number of phases in a multiphase design is not always an answer. Finally, the last section shows some practical results based on a 5kW design used as a fuel cell voltage regulator.

Key Words: DC-DC converter, multiphase boost, fuel cell, ripple cancellation, interleaved converter, design optimization

1. MULTIPHASE BOOST CONVERTERS

In applications where the output voltage needs to be higher than the input voltage and there are no isolation requirements, a boost converter offers the simplest and lowest cost solution. Simple design with low parts count increases the converter's reliability. In normal operation, at any moment within a switching cycle current flows through only one semiconductor part (it alternates between the switch and the rectifier). This operation results in a very high efficiency.

Connecting two power stages in parallel (both, input and output) and shifting drive signals by 180° results in an interleaved configuration. Benefits of interleaving are numerous: each stage handles half of the power, input and output effective frequency is doubled and, when the circuit operates at duty cycle of 0,5, there is an input ripple cancellation effect. It has been shown [1] that an interleaved converter may actually have lower physical volume and lower price than comparable single-phase unit. Adding more phases increases benefits of interleaving. Fig. 1. shows typical waveforms of two- and three-phase boost converter input current ripple.

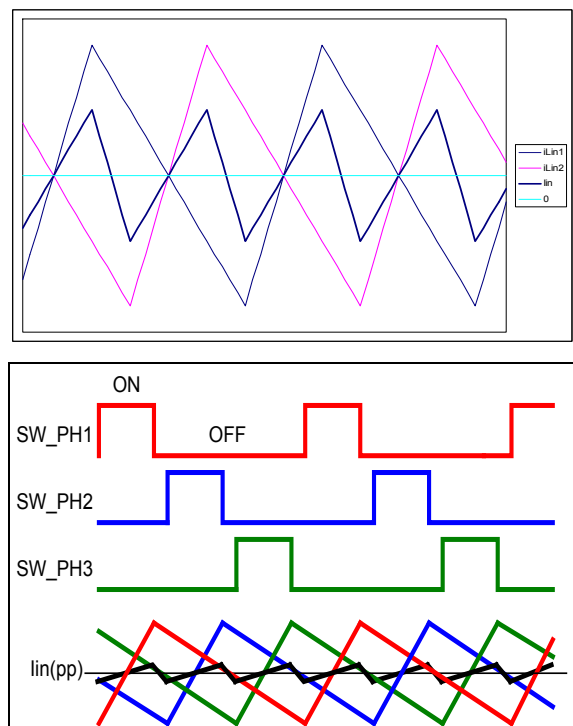


Fig. 1. Two- and three-phase boost converter waveforms

Each multiphase design is typically analyzed within duty cycle intervals that result in the input ripple cancellation. For a two-phase converter the intervals are 0-0,5 and 0,5-1,0. For a three-phase converter, there are three intervals of interest: 0-1/3, 1/3-2/3 and 2/3-1. This extends in a similar manner to any number of phases.

Most commonly used method for calculating RMS values of a typical power converter waveform is by splitting it into n piecewise segments and then adding squared RMS values of each individual segment (1) [2].

$$I_{RMS} = \sqrt{I_{RMS_1}^2 + I_{RMS_2}^2 + \dots + I_{RMS_n}^2} \quad (1)$$

This method works well for multiphase converters as well and is used in this paper to derive generalized expressions.

Input current ripple and output capacitor RMS current are two of the parameters that designers want to optimize when considering multiphase topologies.

2. INPUT CURRENT RIPPLE

Following the procedure outlined above, equations for the input current ripple were derived for most commonly used number of phases, then generalized and summarized in the Table 1.

Table 1. Interleaved boost converters' input current ripple

Number of phases (n)	Interval 1 $\delta < 1/n$	Interval 2 $1/n < \delta < 2/n$	Interval 3 $2/n < \delta < 3/n$	Interval 4 $3/n < \delta < 4/n$	...	Interval i $(i-1)/n < \delta < i/n$	...	Interval n $\delta > (n-1)/n$
1	$\delta(1-\delta)\frac{V_{out}T}{L_{in}}$							
2	$\delta(1-2\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{1}{2})(2-2\delta)\frac{V_{out}T}{L_{in}}$						
3	$\delta(1-3\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{1}{3})(2-3\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{2}{3})(3-3\delta)\frac{V_{out}T}{L_{in}}$					
4	$\delta(1-4\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{1}{4})(2-4\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{2}{4})(3-4\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{3}{4})(4-4\delta)\frac{V_{out}T}{L_{in}}$				
...
n	$\delta(1-n\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{1}{n})(2-n\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{2}{n})(3-n\delta)\frac{V_{out}T}{L_{in}}$	$(\delta-\frac{3}{n})(4-n\delta)\frac{V_{out}T}{L_{in}}$	...	$(\delta-\frac{i-1}{n})(i-n\delta)\frac{V_{out}T}{L_{in}}$	...	$(\delta-\frac{n-1}{n})(n-n\delta)\frac{V_{out}T}{L_{in}}$

Fig. 2 shows normalized graphs of the input current ripple for one through four-phase interleaved boost converters as a function of duty cycle.

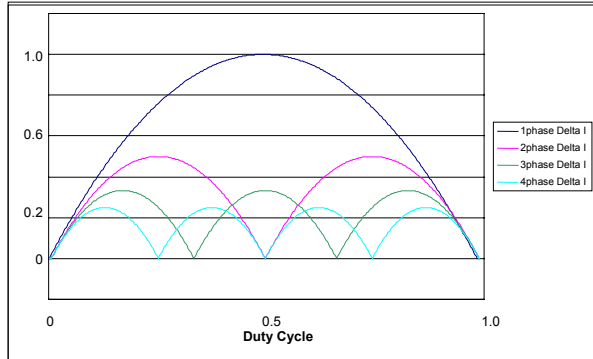


Fig. 2. Input current ripple vs. duty cycle

The effects of multiphase converters become clearly visible as the maximum ripple becomes progressively smaller and ripple cancellation effects occur (n-1) times (n being the number of phases). Note that duty cycles of zero (0) and one (1.0) are of theoretical value only, the ripple cancellation at those duty cycles is of no practical consequence.

Maximum value of the ripple current can be found by searching for the maximum of the function shown for n phases and interval 1 (Table 1, above):

$$\Delta I_{in} = \delta(1-n\delta)\frac{V_{out}T}{L_{in}} \quad (2)$$

The maximum is then found as (3)

$$\Delta I_{in(max)} = \frac{1}{4n}\frac{V_{out}T}{L_{in}} \quad (3)$$

3. OUTPUT CAPACITOR RMS CURRENT

For illustration purpose, the output capacitor current for a two-phase boost converter is shown in Fig. 3.

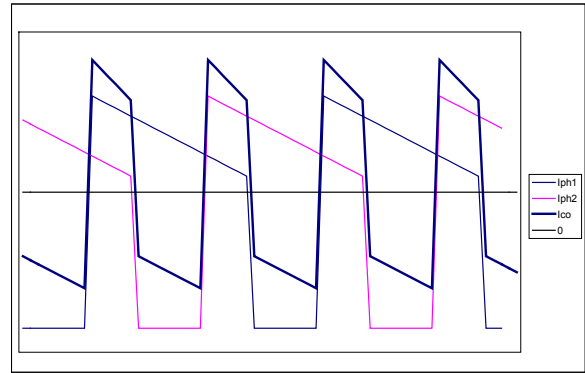


Fig. 3. Output capacitor current, $\delta < 0,5$

Closed form equations for the output capacitor RMS current in multiphase converters are sorted in the Table 2.

Even though the equations from the Table 2 are very practical for direct calculations, as they are related to the output current (I_{out}) which is typically a specified parameter, for our analysis it will be more convenient to substitute I_{out} for input current $I_{inAVG} = I_{out}/(1-\delta)$.

Table 2. Interleaved boost converters' output capacitor RMS current

Number of phases (n)	Interval 1 $\delta < 1/n$	Interval 2 $1/n < \delta < 2/n$	Interval 3 $2/n < \delta < 3/n$	Interval 4 $3/n < \delta < 4/n$	...	Interval i $(i-1)/n < \delta < i/n$	...	Interval n $\delta > (n-1)/n$
1	$\frac{I_{out}}{(1-\delta)} \sqrt{\delta(1-\delta)}$							
2	$\frac{I_{out}}{2(1-\delta)} \sqrt{\delta(1-2\delta)}$	$\frac{I_{out}}{2(1-\delta)} \sqrt{\frac{1}{2}(2\delta-1)(2-2\delta)}$						
3	$\frac{I_{out}}{3(1-\delta)} \sqrt{\delta(1-3\delta)}$	$\frac{I_{out}}{3(1-\delta)} \sqrt{\frac{1}{3}(3\delta-1)(2-3\delta)}$	$\frac{I_{out}}{3(1-\delta)} \sqrt{\frac{1}{3}(3\delta-2)(3-3\delta)}$					
4	$\frac{I_{out}}{4(1-\delta)} \sqrt{\delta(1-4\delta)}$	$\frac{I_{out}}{4(1-\delta)} \sqrt{\frac{1}{4}(4\delta-1)(2-4\delta)}$	$\frac{I_{out}}{4(1-\delta)} \sqrt{\frac{1}{4}(4\delta-2)(3-4\delta)}$	$\frac{I_{out}}{4(1-\delta)} \sqrt{\frac{1}{4}(4\delta-3)(4-4\delta)}$				
...
n	$\frac{I_{out}}{n(1-\delta)} \sqrt{\delta(1-n\delta)}$	$\frac{I_{out}}{n(1-\delta)} \sqrt{\frac{1}{n}(n\delta-1)(2-n\delta)}$	$\frac{I_{out}}{n(1-\delta)} \sqrt{\frac{1}{n}(n\delta-2)(3-n\delta)}$	$\frac{I_{out}}{n(1-\delta)} \sqrt{\frac{1}{n}(n\delta-3)(4-n\delta)}$	...	$\frac{I_{out}}{n(1-\delta)} \sqrt{\frac{1}{n}(n\delta-(i-1))(i-n\delta)}$	...	$\frac{I_{out}}{n(1-\delta)} \sqrt{\frac{1}{n}(n\delta-(n-1))(n-n\delta)}$

The general equation for n-phases and interval 1 then becomes

$$I_{CoRMS} = \frac{I_{inAVG}}{n} \sqrt{\delta(1-\delta)} \quad (4)$$

Fig. 4 shows graphs of the normalized output capacitor RMS current for one through four-phase boost converters as a function of duty cycle.

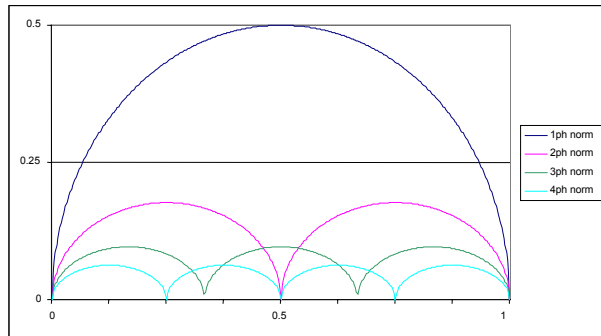


Fig. 4. Normalized output capacitor RMS current

Similarly to the input current ripple, the Fig. 4 indicates that the ripple cancellation effects on the output side are also very pronounced. However, it should be noted that, with the output capacitors, there is no complete cancellation - there is always a ripple current present - minimum ripple current equals input inductor's current ripple. In our analysis the inductor ripple current was neglected. Even though it is relatively small it never cancels at the output and zero values in Figure 3 should be considered points with the minimum, not zero, ripple.

4. A PRACTICAL APPLICATION - 5kW CONVERTER FOR HYBRID FUEL CELL SYSTEM

A practical value of equations shows in a design of a 5kW DC/DC converter for fuel cell application. Fuel cells are finding their way in a multitude of industrial applications and several topologies are being examined worldwide. Small sampling of the work being done is

given in [3-5]. Minimizing current ripple is an important issue, as investigated in [6].

Our converter was designed to operate in a system designed to replace forklift's lead-acid batteries. The system consists of a fuel cell, DC/DC converter and small battery. Battery provides peak load handling capability while DC/DC converter maintains battery fully charged and regulates fuel cell's output.

The converter specification lists very wide input voltage range (24-40V). This covers fuel-cell output voltage from no load to overload conditions. By examining this particular application it was found that in steady-state operation the output voltage varies very little and is typically around 28V.

Output voltage specification also covers very wide range: 40-60V. However, the battery is always kept at 41V (slightly below the fully charged state to ensure that it can absorb recuperative braking energy).

Based on the specified wide input and output ranges, nominal duty cycle range can be calculated as 0,03-0,60. With the practical considerations listed above, the converter's steady-state operating point is, therefore

- Input voltage: 28V
- Output voltage: 41V
- Steady-state duty cycle: 0,32.

Fig. 5 shows three and four-phase normalized input current ripple with nominal duty cycle range and steady-state value (centered around 0,32) superimposed.

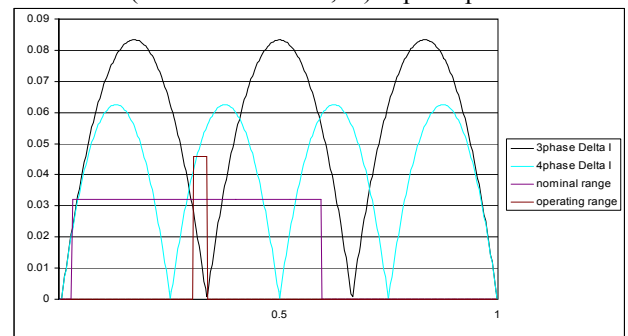


Fig. 5. Normalized input current ripple as a function of duty cycle

By examining Fig. 5, an interesting conclusion can be reached: for the actual steady-state duty cycle range the input current ripple is significantly lower in the three-phase design. Identical conclusion can be drawn by investigating output capacitor RMS currents. During certain events - system start, initial battery charging, transient conditions, etc., the converter will work over much wider range, leaving this narrow steady-state area. It will then work in suboptimal mode. However, these events are relatively rare and short in duration and will not overstress the unit for any significant amount of time that may adversely affect its life.

Without considerations detailed in this paper such conclusion would be considered counterintuitive. In this case, for the real-life, application dictated operating conditions the three-phase design (Fig. 6) offers significant benefits compared to the four-phase design. It also yields lower cost unit with reduced complexity and anticipated higher reliability.

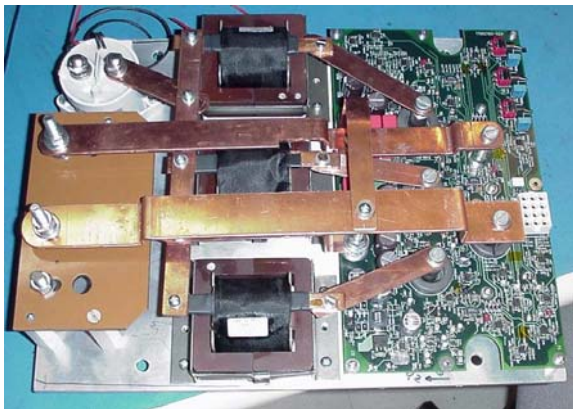


Fig. 6. Photograph of the converter prototype

5. CONCLUSION

The boost converter is one of the most commonly used power converter topologies covering wide range of input and output voltages, power levels and applications. Development of high performance, low cost semiconductors helped commercialize multiphase

topologies offering multiple benefits at only a small price premium.

This paper addresses two of the most critical aspects of a multiphase boost converter: (1) input current ripple and (2) output capacitor RMS current. Equations for both parameters are listed in closed form. Generalized equations make it easy to find exact values for any number of phases employed.

By analyzing one practical application - a 5kW fuel cell regulator, an interesting and somewhat surprising conclusion is reached: a three-phase converter operates with lower input current ripple and output capacitor stress than an equivalent four-phase design. Simply increasing number of phases does not always yield reduced component stress.

6. REFERENCES

- [1] J. Betten and R. Kollman, "Interleaving DC/DC converters boost efficiency and voltage", EDN magazine, October 13, 2005, pp. 77-86
- [2] R. W. Erickson and D. Maksimovic, "Fundamentals of Power Electronics", second edition, Kluwer Academic Publishers, 2001
- [3] X. Kong and A. M. Khambadkone, "Analysis and Implementation of a High Efficiency, Interleaved Current-Fed Full Bridge Converter for Fuel Cell System", IEEE Transactions on Power Electronics, Vol. 22, No. 2, March 2007, pp. 543-550
- [4] J. L. Duarte, M. Hendrix and M. G. Simoes, "Three-Port Bidirectional Converter for Hybrid Fuel Cell Systems", IEEE Transactions on Power Electronics, Vol. 22, No. 2, March 2007, pp. 480-487
- [5] Z. Jiang and R. A. Dougal, "A Compact Digitally Controlled Fuel Cell/Battery Hybrid Power Source", IEEE Transactions on Industrial Electronics, Vol. 53, No. 4, August 2006, pp. 1094-1104
- [6] G. Fontes, C. Turpin, S. Astier and T. A. Meynard, "Interactions Between Fuel Cells and Power Converters: Influence of Current Harmonics on a Fuel Cell Stack", IEEE Transactions on Power Electronics, Vol. 22, No. 2, March 2007, pp. 670-678