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Using Single-Phase Online Design Calculator To Analyze Stability Of Interleaved Power Stage Designs

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Single-output multiphase converter topologies can achieve higher output currents while managing thermal performance. However, the stability analysis of stacking multiple converter phases presents a more difficult challenge than that of a single-phase converter.

That's because online design calculators such as Texas Instruments' Power Stage Designer,[1] which generate Bode plots for assessing converter stability, are typically designed to work with single-phase power stages. Consequently, the power supply designer must run simulations to determine loop response, and these simulations take more time than using the design calculator. This scenario comes into play often with TI's stackable controllers, which have their own design calculators as well.

Fortunately, even multiphase designs can be adapted for use with the aforementioned tools by performing a few simple calculations. In this article, I'll describe how to take a single-output multiphase design and modify it to a single-output, single-phase equivalent circuit. You can then use the equivalent model's results to simplify stability analysis or use them in a single-phase online design calculator. In addition to explaining this approach, I'll also validate its accuracy using simulation.

Benefits Of Interleaved Designs

When using a single-phase buck controller design such as one based on the LM5148[2] from TI in high-current applications, the ability to manage thermals becomes a challenge as the output current increases. The required current-sense resistor also decreases in value, which can compromise stability because of the signal-to-noise ratio.

As I mentioned earlier, single-output interleaved designs offer several advantages for high-current buck converters. Fig. 1 shows a typical single-output two-phase interleaved design using the LM5148. Stacking multiple single-phase converters enables the use of higher-value current-sense resistors while achieving the desired output current. This approach also boasts improved efficiency and thermal performance.

Note that you can use this approach for stability analysis and to calculate losses. This approach does not consider ripple current cancellation, which is a major benefit of a single-output interleaved design.

Equivalent Single-Phase Circuit

Fig. 1 shows a two-phase single-output interleaved buck converter. Since these phases function in parallel, each phase effectively supplies half of the total load current, with half the total capacitance at its output. The goal is to reduce the converter in Fig. 1 to a single-output single-phase equivalent circuit.

Fig. 2 shows a simplification of a single-output interleaved controller design.

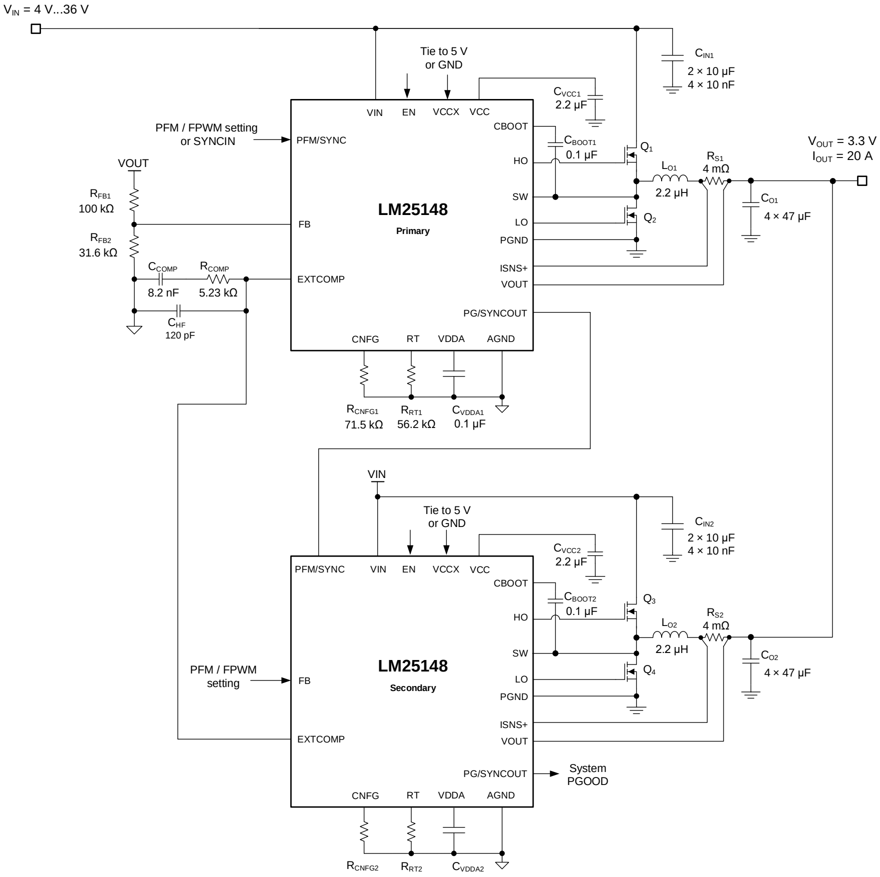

Fig. 1. The LM25148 configured as a two-phase single-output interleaved controller design.

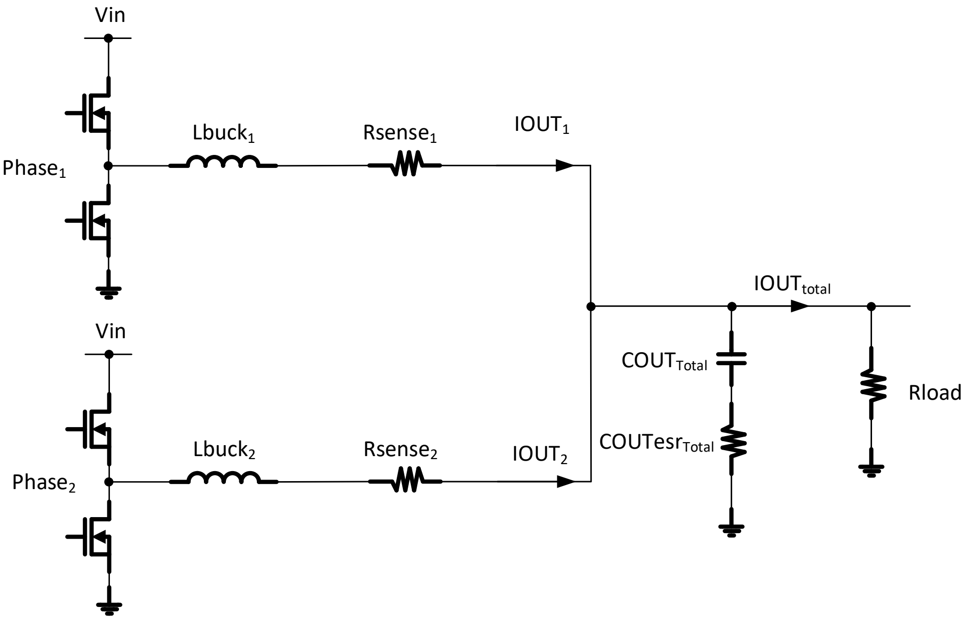

Fig. 2. Single-output two-phase interleaved controller design example.

By observation, you can reduce the total capacitance by the number of phases, as shown in equations 1 and 2:

$$\mathrm{COUT_{Total}} = \mathrm{COUT_1} + \mathrm{COUT_2} \qquad (1)$$

$$\mathrm{COUT_{Total}} = \mathrm{COUT_1} + \mathrm{COUT_2} = 200\mu\mathrm{F} \qquad (2)$$

Assuming that the output capacitors are the same value, equation 3 calculates the total equivalent series resistance (ESR) of the capacitor by also assuming that the number of parallel resistances is equal to the number of phases for a single-output two-phase design:

$$\mathrm{COUTesr_{Total}} = \frac{\mathrm{COUTesr_1} \times \mathrm{COUTesr_2}}{\mathrm{COUTesr_1} + \mathrm{COUTesr_2}} \qquad (3)$$

The LM5148 design calculator[3] only accommodates stability and loss calculations for a single-phase controller design. To analyze this design using this single-phase calculator, you need to simplify it into an equivalent circuit representing a single phase. Each phase will handle a proportion of the total load current.

The total load current is

$$\mathrm{IOUT_{Total}} = \frac{\mathrm{Vout}}{\mathrm{Rload}} \qquad (4)$$

Equation 5 divides the total current by the number of phases (n) for parallel operation of $\mathrm{IOUT_n}$ per phase:

$$\mathrm{IOUT_n} = \frac{\mathrm{IOUT_{Total}}}{\mathrm{n}} \qquad (5)$$

You’ll need to multiply the load resistance by 2 in order to halve the load current. Therefore, equation 6 expresses Rload per phase as

$$\mathrm{Rload_{Phase}} = \mathrm{Rload} \times \mathrm{n} \qquad (6)$$

Similarly, the proportion of the total capacitance divided by the number of phases (n):

$$\mathrm{COUT_{phase}} = \frac{\mathrm{COUT_{Total}}}{\mathrm{n}} \qquad (7)$$

A proportion of the ESR must also be determined. Equation 8 deduces the ESR of $\mathrm{COUT_{phase}}$:

$$\mathrm{COUTesr_{phase}} = \mathrm{COUTesr_{Total}} \times \mathrm{n} \qquad (8)$$

Equations 9, 10 and 11 surmise the rule to follow for n phases. The phase components are the values that you’ll enter into a single-phase calculator spreadsheet to obtain accurate stability results from the interleaved design.

$$\mathrm{COUT_{phase}} = \frac{\mathrm{COUT_{Total}}}{\mathrm{n}} \qquad (9)$$

$$\mathrm{COUTesr_{phase}} = \mathrm{COUTesr_{Total}} \times \mathrm{n} \qquad (10)$$

$$\mathrm{Rload_{Phase}} = \mathrm{Rload} \times \mathrm{n} \qquad (11)$$

To convert the example in Fig. 2 to a single-phase equivalent, use equations 9, 10 and 11.

Fig. 3 illustrates the single-phase equivalent.

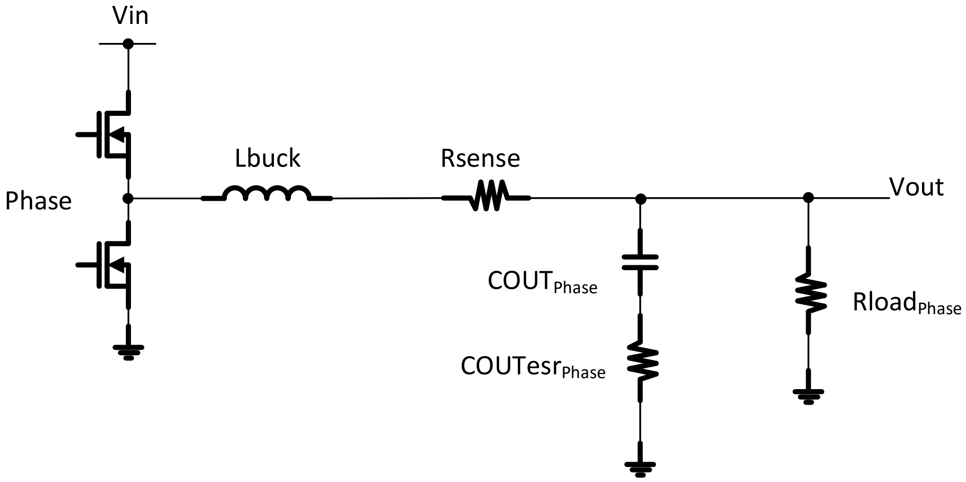

Fig. 3. Equivalent single-phase model with modified calculated values for COUTphase, COUTesrphase and RloadPhase.

Example

Consider a 12-V input, single 5-V at 10-A output, two-phase interleaved design where each phase delivers 5 A per phase. The values are LBuck = 12 µH, Rsense = 12 mΩ, $COUT_{Total}$ = 200 µF, $COUT_{esrTotal}$ = 500 µΩ and Rload = 0.5 Ω.

Referring to equations 9, 10 and 11 and inserting the equivalent values for $COUT_{phase}$, $COUTesr_{phase}$ and $Rload_{Phase}$ in the calculator, you can obtain an accurate frequency response for the single-output interleaved design, where the values are Lbuck = 12 µH, Rsense = 12 mΩ, $COUT_{phase}$ = 100 µF, $COUTesr_{phase}$ = 1 mΩ and $Rload_{Phase}$ = 1 Ω (5 V at 5 A).

SIMPLIS Model Frequency Response

Let's look at the frequency response of a single-phase buck converter compared to a single-output two-phase interleaved design using a SIMPLIS model of the LM5148. I'll also compare the frequency response of a single-output two-phase design with a single-phase equivalent model using the approach outlined in this article, and use the values of the single-phase equivalent circuit in the LM5148 design calculator.

Fig. 3 depicts the single-phase equivalent circuit of Fig. 2, with component values determined using equations 9, 10 and 11. The SIMPLIS simulation results in Figs. 4 and 5 show an exact match between the single-phase equivalent circuit and the single-output two-phase design, respectively.

Fig. 6 shows the correlation between the SIMPLIS results in Fig. 4 and the results of the design calculator using equations 9, 10 and 11. Note that the minor discrepancies in the crossover frequency and phase margin between the SIMPLIS models and the online calculator are due to slight differences in the programmed slope compensating ramp I used and the insignificant resistance in the power path.

You can also use the equivalent model results when performing mathematical modeling of the frequency response by using the equivalent values in the power-stage transfer function.

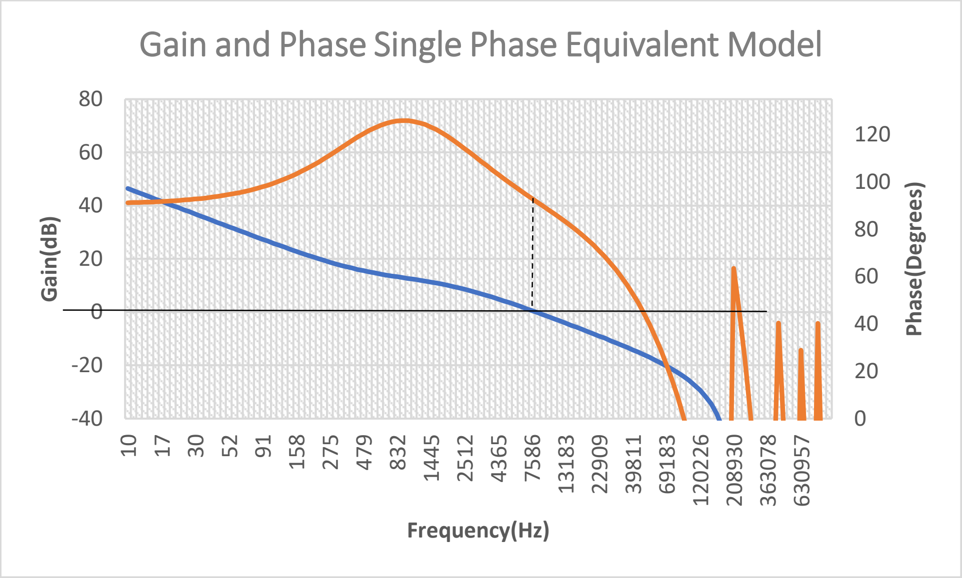

Fig. 4. SIMPLIS simulation: Gain and phase for single-phase equivalent model showing a crossover frequency of 8.1 kHz and a phase margin of 92 degrees.

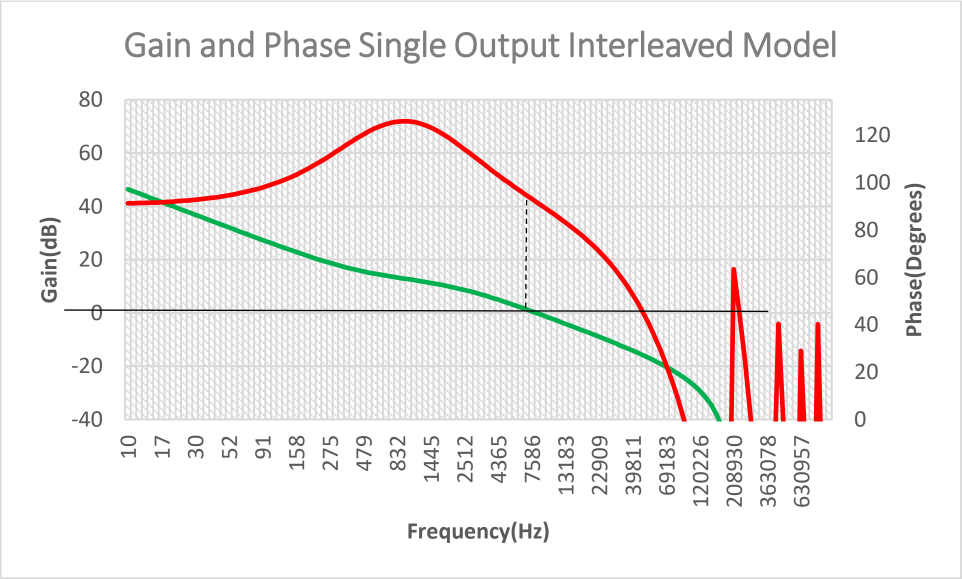

Fig. 5. SIMPLIS simulation: Gain and phase for single-output interleaved model showing a crossover frequency of 8.1 kHz and a phase margin of 92 degrees.

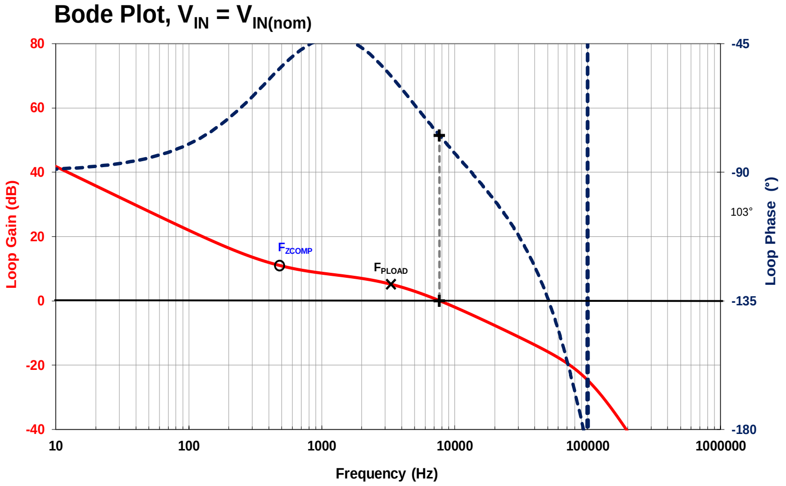

Fig. 6. Design calculator gain and phase for a single-phase equivalent model showing a crossover frequency of 7.7 kHz and a phase margin of 103 degrees.

Conclusion

In high-current applications, transforming the power stage of a single-output interleaved controller design into an equivalent single-phase model is easy to do. The modified values can then be used in a single-phase design calculator to obtain accurate results. Without this method, you would need to either use a dedicated single-output interleaved design calculator or use simulation to obtain accurate stability analysis. The approach described in this article saves the designer time and effort, avoiding these other, more-complex methods.

References

1. TI's Power Stage Designer page.
2. LM5148 3.5-V to 80-V, current mode synchronous buck controller product page.
3. LM5148-LM25148DESIGN-CALC, LM5148 and LM25148 controller quickstart design tool.

For Further Reading

1. "Under the Hood of a Multiphase Synchronous Rectified Boost Converter" Texas Instruments Power Supply Design Seminar SEM 2100 Topic 4, SLUP324, 2014. Also see TI's Power Supply Design Seminar page.
2. "Benefits of a Multiphase Buck Converter" by David Baba, Texas Instruments, Analog Applications Journal, Q1 2012.
3. "Benefits of Multiphasing Buck Converters – Part 1" by Tim Hegarty, EE Times, November 17, 2007.
4. "Switch-Mode Power Converter Compensation Made Easy" by Robert Sheehan and Louis Diana, Texas Instruments, September 2016. Also see the presentation.

About The Author

David Baba serves as a senior applications engineering manager at Texas Instruments where he has over 28 years of experience in dc-dc power-supply design. He holds a bachelor of engineering (BEng (hons)) degree from the University of Surrey in the United Kingdom.

For more on dc-dc converter design, see How2Power's Design Guide, locate the "Power Supply Function" category and select "DC-DC Converters". Also see the "Design Area" category and select "Stability".