How To Model Coupled Inductors In A SEPIC Converter

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Converter designs based on the single-ended primary inductance converter (SEPIC) topology often opt to use a coupled inductor both to reduce the number of components and overall converter size, and to simplify control. However, this design choice complicates simulation: If the coupled inductor is not modeled correctly, the simulated result can be quite different from the bench result.

Unfortunately, there is not much guidance on this topic in the literature, particularly with regard to the SEPIC. This article discusses how to best model coupled inductors in a SEPIC design. Methods to build a proper model are introduced and the equations are included.

SEPIC Operation And Inductor Values

A SEPIC topology allows for the input to be higher, equal, or lower than the desired output voltage (Fig. 1). The conversion ratio as a function of duty cycle is shown in continuous conduction mode (CCM) in equation 1.

$$\frac{V_{OUT}+V_D}{V_{IN}}=\frac{\mathrm{D}}{1-\mathrm{D}} \quad (1)$$

In a SEPIC converter, no dc path exists between the input and output. This is an advantage over the boost converter for applications requiring the output to be disconnected from the input source when the circuit is in shutdown.

Compared to the flyback converter, the SEPIC converter has the advantage that both the power MOSFET and the output diode voltages are clamped by the capacitors (C1 and C_{OUT}), therefore there is less voltage ringing across the power MOSFET and the output diodes. The SEPIC converter requires much smaller input capacitors than those of the flyback converter. This is because, in the SEPIC converter, inductor L1 is in series with the input, and the ripple current flowing through the input is continuous.

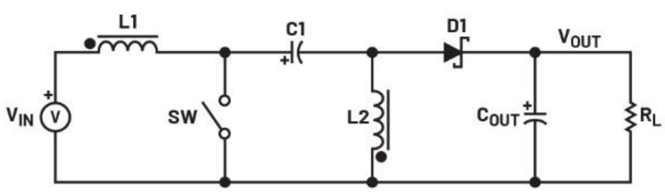


Fig. 1. A SEPIC converter.

Given an operating input voltage range, and having chosen the operating frequency and ripple current in the inductor, the inductor value (L1 and L2 are independent) of the SEPIC converter can be determined using equation 2.

$$L1=L2=\frac{V_{IN(MIN)}}{0.5\,x\,\Delta I_{SW}\times f}\times D_{MAX} \quad (2)$$

For most SEPIC applications, the equal inductor values will fall in the range of 1 µH to 100 µH.

By making L1 = L2, and winding them on the same core, the value of the inductance in equation 2 is replaced by 2L, due to the mutual inductance shown in equation 3.

$$L=\frac{V_{IN(MIN)}}{\Delta I_{SW}\times f}\times\ D_{MAX} \quad (3)$$

Coupled Inductors

Using a coupled inductor can simplify the design of the SEPIC converter by reducing the number of discrete components required and minimizing the complexity of the control circuitry. This can lead to cost savings, a smaller footprint, and a significant reduction of the complexity of the small-signal model, enabling higher bandwidth by eliminating the SEPIC resonances calculated in equation 4.

$$f_{SEPIC\_RESONANCE} = \frac{1}{2\pi\sqrt{(L1+L2)C1}} \qquad (4)$$

While the coupled inductor is superior in performance, the simulated inductor current waveforms in LTspice[1] don't always match the bench result. This is mainly due to the inaccuracy of the coupled inductor model from designers not knowing how to model this component.

When a coupled inductor is simulated in LTspice, careful attention must be paid to its model. For example, do not set K to 1 in a simulation without adding associated leakage inductors. Otherwise the simulated inductor currents become discontinuous, as shown in Fig. 2.

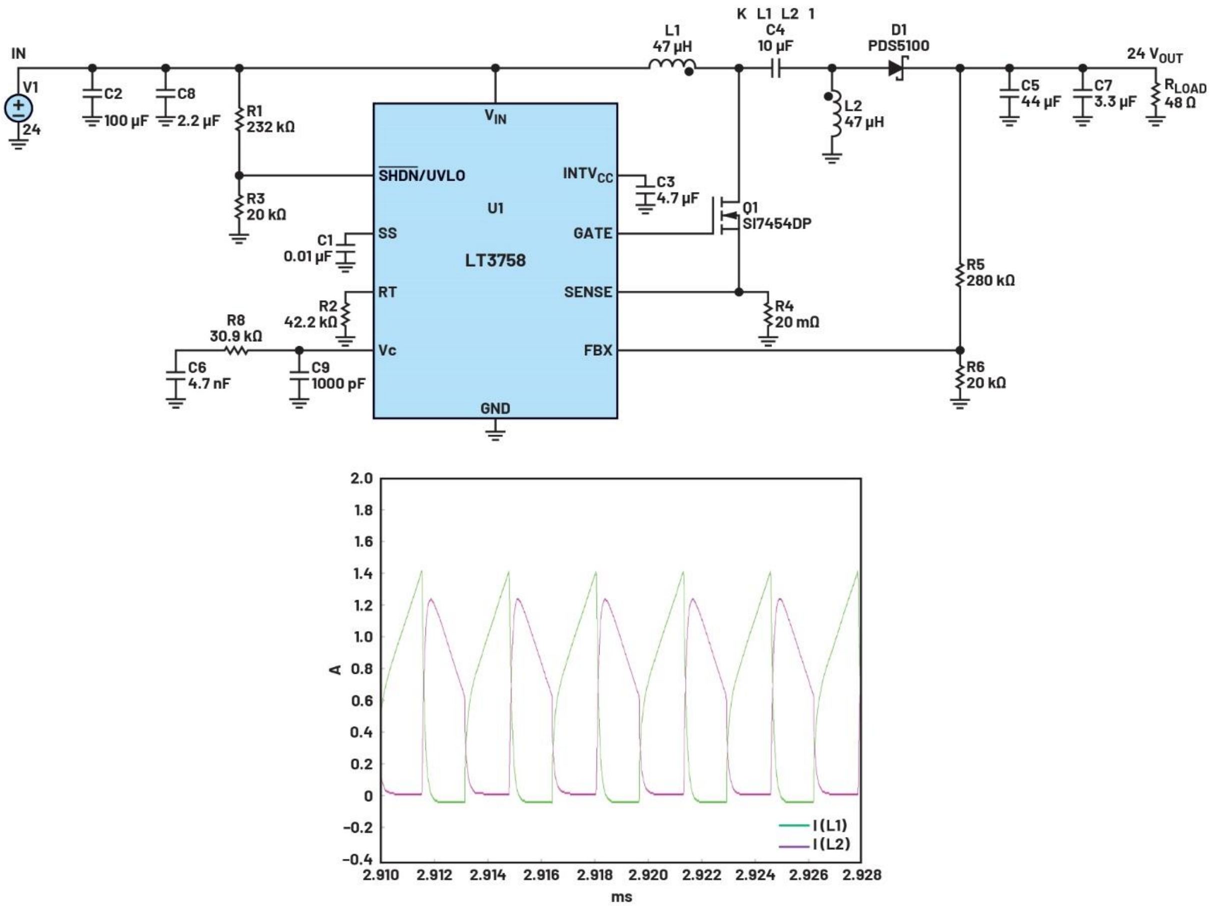


Fig. 2. An LT3758[2] SEPIC with K = 1 and its simulated current waveforms.

Modeling A Coupled Inductor

To properly model the coupled inductor, explicitly adding a leakage inductor is a must if K is set to be 1. Also, due to various winding structures, it's possible that the two magnetizing inductances are different. One of the coupled inductor models is shown in Fig. 3 and a bench test is necessary to obtain the values since inductor vendors typically do not provide the needed values.

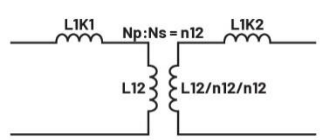


Fig. 3. A coupled inductor model.

Calculating these parameters based on the measured data is shown in equation 5.

$$L11 = L1k1 + L12$$

$$L22 = L1k2 + \frac{1}{n12^2} \times L12 \qquad (5)$$

$$L1k11 = L1k1 + n12^2 \times L1k2$$

$$L1k22 = L1k2 + \frac{1}{n12^2} \times L1k1$$

While L11 is the measured primary self-inductance with secondary open, L22 is the measured secondary self-inductance with primary open, L1K11 is the measured primary inductance with secondary shorted, and L1K22 is the measured secondary inductance with primary shorted.

In this example, the measured L11 is 46.66 μH, L22 is 45.78 μH, L1K11 is 0.725 μH, and L1K22 is 0.709 μH. Therefore, the calculated n12 is 1.011, L12 is 46.374 μH, L1K1 is 0.286 μH, and L1K2 is 0.429 μH. The completed coupled inductor model is shown in Fig. 4.

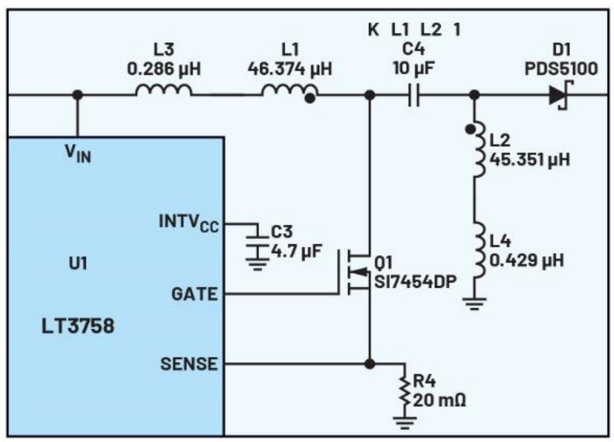


Fig. 4. A completed coupled inductor model assuming k =1.

The simulated results match the bench result well. See Fig. 5.

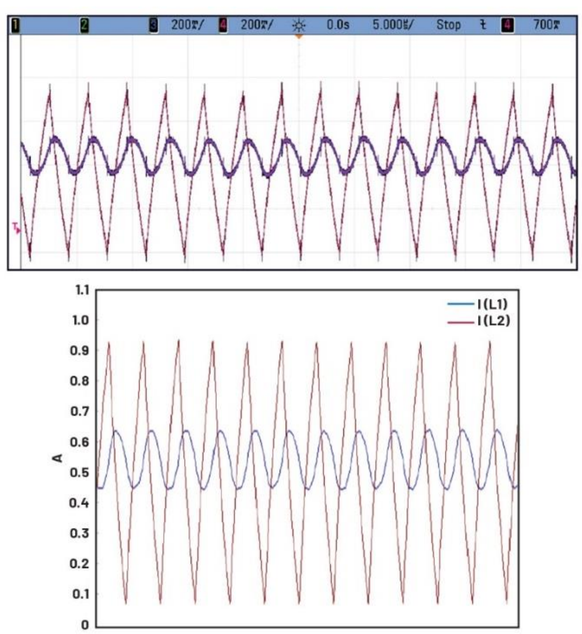


Fig. 5. Bench result vs. simulation results.

Another way to model the coupled inductor is to use the non-unit coupling factor. In this case, the leakage inductors do not need to be explicitly specified as shown in Fig. 6.

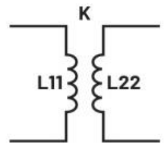


Fig. 6. A coupled inductor model with non-unit K.

The same bench test on the coupled inductor is performed to collect the information for calculating the K. Equations with two-port parameters are shown in Fig. 7.

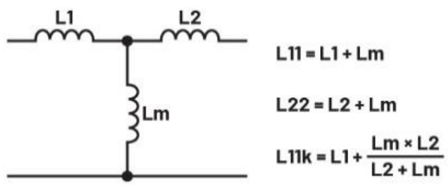


Fig. 7. Equivalent circuit and its equations.

In this example, the measured L11 is 46.66 µH, L22 is 45.78 µH, and L1K11. is 0.725 µH. The calculated Lm is 45.857 µH. The calculated K is 0.992.

$$k = \frac{L_m}{\sqrt{L11 \times L22}} \qquad (6)$$

The simulated result based on the model in Fig. 8 matches the bench result well with this inductor model too.

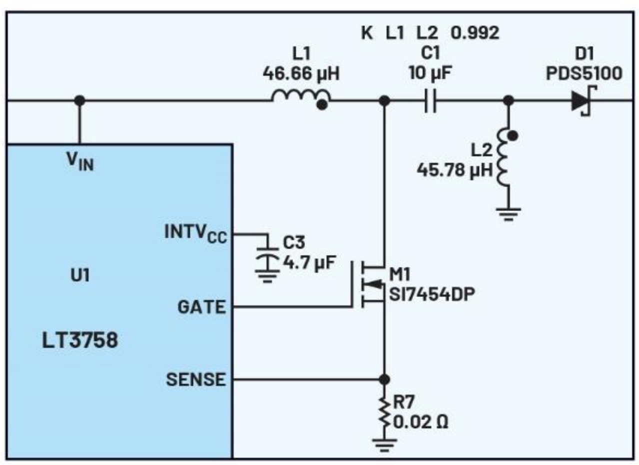


Fig. 8. A complete coupled inductor model with a non-unit K.

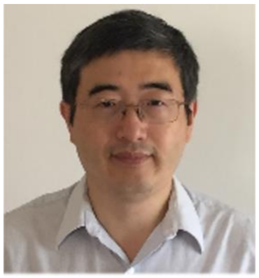
Conclusion

Power supply designers are sometimes confused by the nonideal inductor current waveforms obtained from LTspice simulation or bench test. With the proper coupled inductor model, the simulated inductor current waveforms match well with the bench result.

References

1. LTspice page, Analog Devices website.
2. LT3758 product page.
3. *Fundamentals of Power Electronics*, 2nd edition by Robert W. Erickson and Dragan Maksimović, Kluwer, January 2001.

About The Author



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