Benefits of a coupled-inductor SEPIC converter

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The single-ended primary-inductor converter (SEPIC) is capable of operating from an input voltage that is greater or less than the regulated output voltage. Aside from being able to function as both a buck and boost converter, the SEPIC also has minimal active components, a simple controller, and clamped switching waveforms that provide low-noise operation. The SEPIC is often identified by its use of two magnetic windings. These windings can be wound on a common core, as in the case of a coupled dual-winding inductor, or they can be the separate windings of two uncoupled inductors. Designers are often unsure of which approach is best and whether there is any real difference between the two. This article looks at each approach and discusses the impact each has on a practical SEPIC design.

Circuit operation

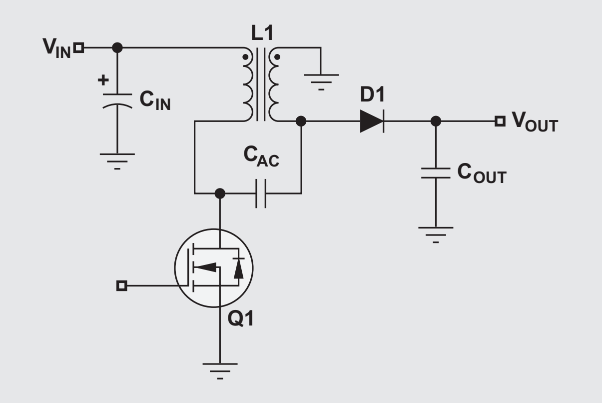
Figure 1 shows the basic SEPIC with a coupled inductor. When the FET (Q1) turns on, the input voltage is applied across the primary winding. Since the winding ratio is 1:1, the secondary winding is also imposed with a voltage equal to the input voltage; but, because of the polarity of the windings, the anode of the rectifier (D1) is pulled negative and reverse-biased. With the rectifier biased off, the output capacitor is required to support the load during this ON time, which forces the AC capacitor (C_{AC}) to be charged to the input voltage. While Q1 is on, current flow in both windings is through Q1 to ground, with the secondary current flowing through the AC capacitor. The total FET current during the ON time is the sum of the input current and the output secondary current.

When the FET turns off, the voltage on the windings reverses polarity to maintain current flow. The secondary-winding voltage is now clamped to the output voltage when the rectifier conducts to supply current to the output. Through transformer action, this clamps the output voltage across the primary winding. The voltage on the drain of the FET is clamped to the input voltage plus the output voltage. Current flow during the FET OFF time for both windings is through D1 to the output, with the primary current flowing through the AC capacitor.

Balancing volt-microseconds

The circuit operates similarly when the coupled inductor is replaced with two uncoupled inductors. For the circuit to operate properly, volt-microsecond balance must be maintained across each magnetic core. That is, for the two uncoupled inductors, the products of each inductor's voltage and time must be equal in magnitude and opposite in polarity during the FET ON and OFF times. It can be algebraically shown that the AC capacitor voltage for uncoupled inductors is also charged to the input voltage. See the Appendix for details. The output-side inductor is clamped to the output voltage during the FET OFF time, as was the secondary winding of the coupled inductor. During the FET ON time, the AC capacitor imposes a potential equal to the input voltage but opposite in polarity across the inductor. With defined voltages clamped across the inductor for each interval, balancing the volt-microseconds determines the duty cycle (D). This is simply

Figure 1. The basic coupled-inductor SEPIC



$$D = \frac{V_{OUT}}{V_{OUT} + V_{IN}},$$

for continuous-conduction-mode (CCM) operation. The voltage imposed across the input-side inductor is equal to the input voltage when the FET is on. When the FET is off, volt-microsecond balance is maintained by clamping V_{OUT} across it. It is easy to remember that when the FET is on, the input voltage is applied across both inductors; and when the FET is off, the output voltage is imposed across both. The voltage and current waveforms of the two uncoupled-inductor SEPICs are quite similar to those of the coupled-inductor version, so much so that it would be difficult to tell them apart.

Two versus one?

If there is little difference in circuit operation between the SEPIC types, does it matter which one to use? A coupled inductor is often selected due to its reduced component count, better integration, and lower inductance requirement compared to using two single inductors. However, the limited selection of higher-power off-the-shelf coupled inductors poses a problem for power-supply designers. If they choose to design their own inductors, they must specify all pertinent electrical parameters as well as deal with longer lead times. Coupled-inductor SEPICs can benefit from leakage inductance, which reduces AC current losses.[1] Coupled inductors must have a 1:1 turns ratio for volt-microsecond balance. Choosing to use two separate uncoupled inductors typically offers a much broader selection of off-the-shelf components. Since the currents and even the inductances for each inductor are not required to be identical, different component sizes can be selected for each, providing greater flexibility.

Equations 1 through 3 show the calculations for inductance for both coupled and uncoupled inductors.

$$L_{\text{Coupled}} = \frac{V_{\text{IN(max)}}^{2} \times d_{\text{min}}^{2}}{2 \times f_s \times P_{\text{OUT(min)}} \times \left(1 + d_{\text{min}} \times \frac{1-\eta}{\eta}\right)} \tag{1}$$

$$L_1 = \frac{d_{\text{min}} \times V_{\text{IN(max)}}^{2} \times \eta}{2 \times f_s \times P_{\text{OUT(min)}}} \tag{2}$$

$$L_2 = \frac{(1 - d_{\text{min}}) \times V_{\text{OUT}}^{2}}{2 \times f_s \times P_{\text{OUT(min)}}} \tag{3}$$

The equations determine the minimum inductance necessary for CCM operation at maximum input voltage and minimum load. Comparing these equations at 50% duty-cycle operation (which occurs when V_{IN} equals V_{OUT}) and unity efficiency, the value calculated for the coupled inductor in Equation 1 is twice that of the uncoupled inductors. Since the converter will certainly have losses, and most input voltage sources vary quite a bit, this simplified inductance generalization is usually false; but it is often adequate for all but extreme cases. It usually means that the converter will enter discontinuous-conduction-mode (DCM) operation slightly sooner (or later) than expected, which in most cases is still acceptable. As previously mentioned, with uncoupled inductors it is not necessary that the output-side inductor be the same value as the input-side inductor, as is often assumed; but this can certainly be done for simplicity's sake. The output-side inductor's value can simply be determined by scaling the input-side inductor by V_{OUT}/V_{IN}. The benefit of using a lower-value output-side inductor is that it is typically smaller and costs less.

Example designs

The specifications shown in Table 1 are the basis for a design comparison. The first design uses a coupled inductor, and the second uses two uncoupled inductors.

The design using a coupled inductor is typical of an automotive input-voltage range with an output power of 64 W. Equation 1 determines that the coupled inductor requires an inductance of 12 µH, with a combined current rating of 13 A (based on $I_{IN} + I_{OUT}$). This design poses a particular challenge because of the limited selection of off-the-shelf inductors. Therefore, a custom inductor from Renco was specified and designed. This inductor was wound on a split bobbin to intentionally introduce leakage inductance to minimize circulating AC currents that can induce losses. These losses are due to the AC capacitor's ripple voltage being imposed across the leakage inductance. For designs of lower power, coupled inductors from Coilcraft (MSS1278 series) and Coiltronics (DRQ74/127 series) offer good off-the-shelf alternatives.

For the design with uncoupled inductors, a 33-µH Coilcraft SER2918 was used for L1, and a 22-µH Coiltronics HC9 was used for L2. Each was chosen based on winding resistance, current rating, and size. When selecting the inductors, the designer must take care to also consider core and AC winding losses. These losses reduce the inductor's allowable DC current, but not all vendors provide adequate information to calculate this. Failure to properly calculate this could greatly increase core temperature beyond the typical 40°C rise. It could also decrease efficiency and hasten premature failure.

Table 1. Prototype SEPIC electrical specifications

PARAMETER	SPECIFICATION
Input voltage	8 to 32 V
Output voltage	16 V
Maximum output current	4 A
Ripple	1%
Minimum efficiency (maximum load)	91%

Figure 2. SEPIC (16 V at 4 A) with coupled inductor

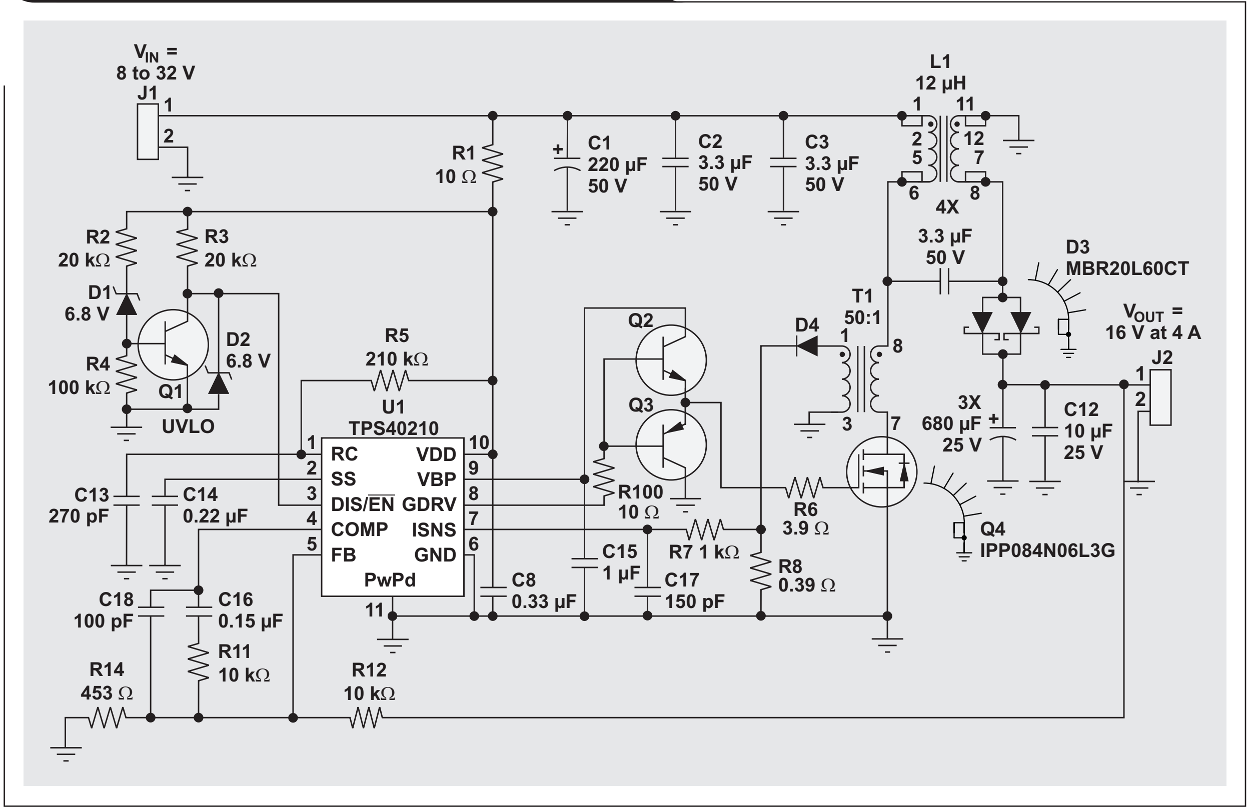
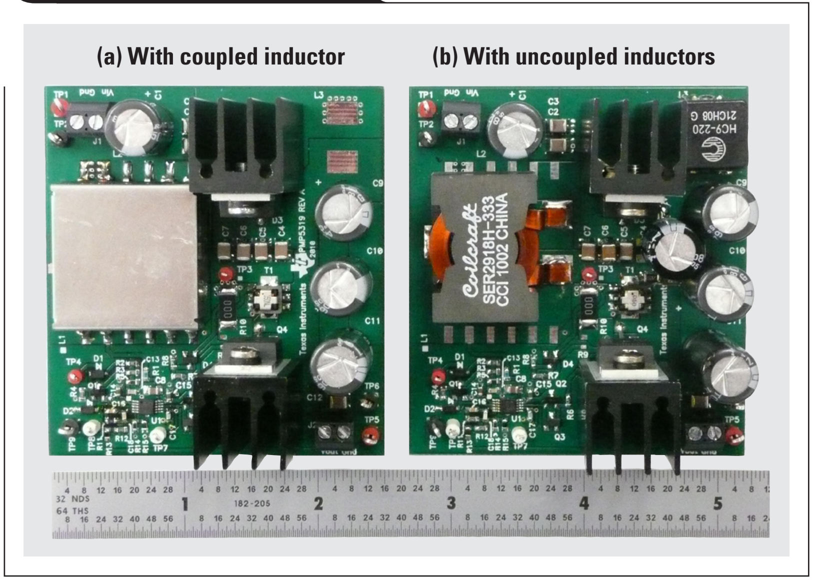


Figure 2 shows a schematic of the prototype SEPIC with a coupled inductor. To implement the uncoupled inductors in the design, the coupled inductor was simply replaced with two inductors on the same PWB. Figure 3 shows both prototype circuits. In Figure 3b, L1 occupies the space of the coupled inductor, and L2 is in the upper right corner.

As expected, both circuits operated in a nearly identical fashion, with the switching voltage and current waveforms being essentially the same. But there were several key differences in performance. While the control loop for the coupled-inductor design was quite benign, the design with uncoupled inductors was initially unstable. Measurement

Figure 3. SEPIC prototypes


(a) With coupled inductor

(b) With uncoupled inductors

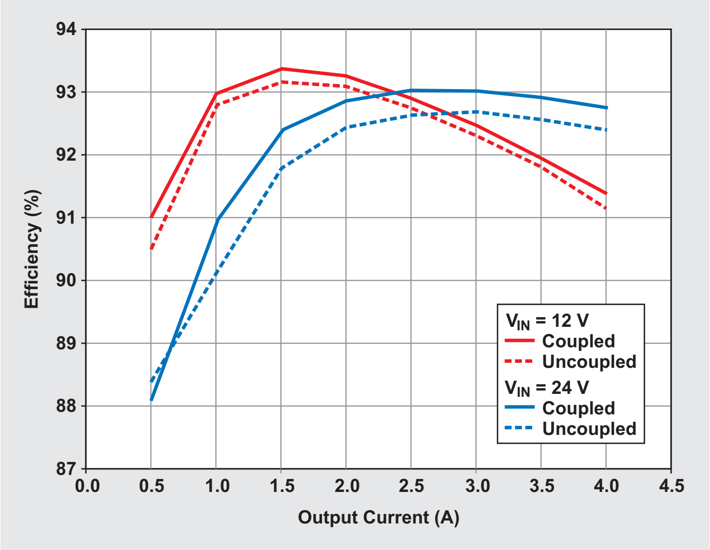
of the loop gain determined that a high-Q, low-frequency resonance was the culprit, requiring the addition of an R/C damping filter in parallel with the AC capacitor. The resonant frequency, while greatly simplified, appeared to be approximately

$$\frac{1}{2\pi\sqrt{C_{AC}\times(L1+L2)}}.$$

The SEPIC circuit has quite complex control-loop characteristics, necessitating the use of mathematical tools for detailed analysis because the analytical results are often difficult to interpret. Adding this R/C damping filter(220 µF/2 Ω) increases the cost, circuit area, and losses. This is in addition to the extra 10% area required for two uncoupled inductors versus a single coupled inductor.

Figure 4 shows the measured efficiency for both circuits. It can be seen that there is an across-the-board boost in efficiency of up to 0.5% for the coupled-inductor design. This is likely due to lower overall core losses in the coupled-inductor design, since its DC wiring losses were actually higher than those in the design with uncoupled inductors. L2 uses a powdered-iron core material, which tends to have higher losses than the ferrite material used for L1 and the custom Renco coupled inductor.[2] While ferrite material for L2 could have been used, it would have resulted in a larger area.

Figure 4. Both coupled and uncoupled inductors achieve good efficiency



Conclusion

The SEPIC can be successfully implemented with either a coupled inductor or two uncoupled inductors. Improved efficiency, reduced circuit area, and more benign control-loop characteristics are benefits realized in the prototype hardware when a properly wound custom coupled inductor is used. While custom components are less desirable than off-the-shelf parts, many coupled inductors are readily available, albeit in smaller sizes. If time to market is critical, uncoupled inductors provide greater flexibility to the designer.

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Appendix: Algebraic proof for $V_{IN} = V_{Cap}$ with uncoupled inductors

The following two equations are used to balance the volt-microseconds for L1 and L2:

$$D\times V_{IN} = (1-D)(V_{Cap}+V_{OUT}-V_{IN}) \quad \text{(for L1)}$$

$$(1-D)\times V_{OUT} = D\times V_{Cap} \quad \text{(for L2)}$$

$$\text{or } V_{OUT} = \frac{V_{Cap}\times D}{1-D}$$

The following sequence uses substitution and simplification techniques with these two equations to obtain the result:

$$D\times V_{IN} = (1-D)\times\left[V_{Cap}+\frac{V_{Cap}\times D}{1-D}-V_{IN}\right]$$

$$D\times V_{IN} = (1-D)\times V_{Cap}+V_{Cap}\times D-(1-D)\times V_{IN}$$

$$D\times V_{IN} = (1-D)\times V_{Cap}+V_{Cap}\times D-V_{IN}+D\times V_{IN}$$

$$V_{IN} = (1-D)\times V_{Cap}+V_{Cap}\times D$$

$$V_{IN} = V_{Cap}-D\times V_{Cap}+V_{Cap}\times D$$

$$V_{IN} = V_{Cap}$$

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