SEPIC Converter Benefits from Leakage Inductance

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The SEPIC converter's popularity is due to its ability to operate from an input voltage that is greater or less than the regulated output voltage. This capability allows it to be used in many non-isolated applications such as automotive, medical, security systems, and LED lighting. Once the choice is made to use a SEPIC, you need to decide if you want to use a dual-winding inductor or two separate inductors. A single-coupled inductor is often selected due to its reduced component count 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. They can choose to design their own inductor, requiring all pertinent electrical parameters to be specified in the process. One parameter that is critical to the SEPIC's operation is leakage inductance, but its role is often overlooked or misunderstood. This article explores leakage inductance and the impact it has on the SEPIC converter's operation, and demonstrates how the presence of leakage inductance can be beneficial to circuit operation.

Figure 1 shows the SEPIC converter in its most basic form with idealized continuous conduction mode (CCM) waveforms shown in **Figure 2**. Circuit operation is this: The primary FET (Q2) turns on during time D. With input voltage imposed across the primary winding, current ramps in the positive direction. The secondary winding also has the input voltage across it due to the 1:1 turn ratio of the coupled inductor. The AC coupling capacitor then charges to a DC voltage equal to Vin. Current flow in both windings is through Q2-to-ground, with the secondary current flowing through the AC capacitor. The FET current during time D is the sum of the primary current (the average input current) plus the secondary current (the output current).

During the off time, or 1-D period, polarities across both windings reverse to maintain current flow. The secondary winding voltage is clamped to Vout (ignoring the diode drop), and sources current through D1 and into the output. The primary winding voltage is also clamped to Vout, while current flows through the AC capacitor, D1 and into the output. With Vout impressed across both windings, and the AC coupling capacitor held to a constant voltage of Vin, the FET sees a potential equal to Vin + Vout during this period. It is interesting to note that while the AC coupling capacitor maintains a DC voltage across it; both sides are switching and AC current flows through it. The current through D1 is pulsating with a "flat top" equal to Iout/(1-D),or In + Iout. The output capacitor filters this large pulsating current and provides a DC output voltage.

The specifications in **Table** 1 are used as the starting points to design a prototype and verify the circuit's performance. A coupled inductor with an inductance of 22 uH and an

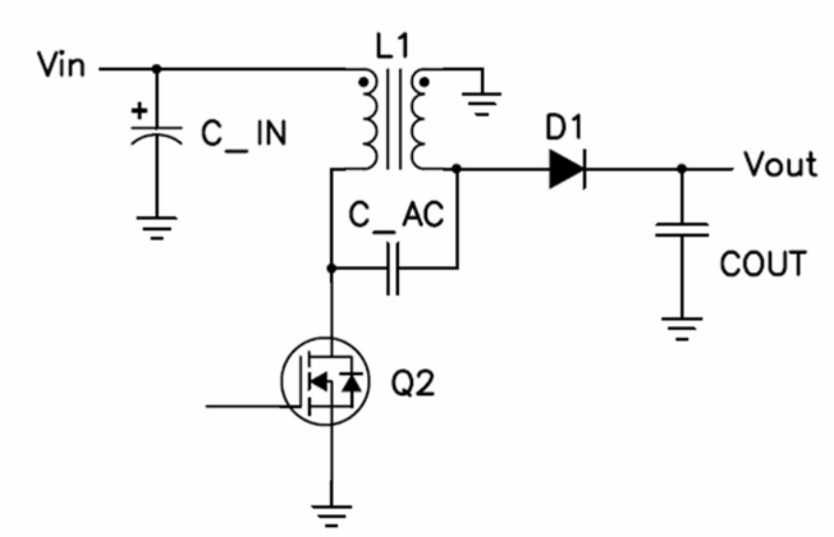

Figure 1: The basic coupled inductor SEPIC converter.

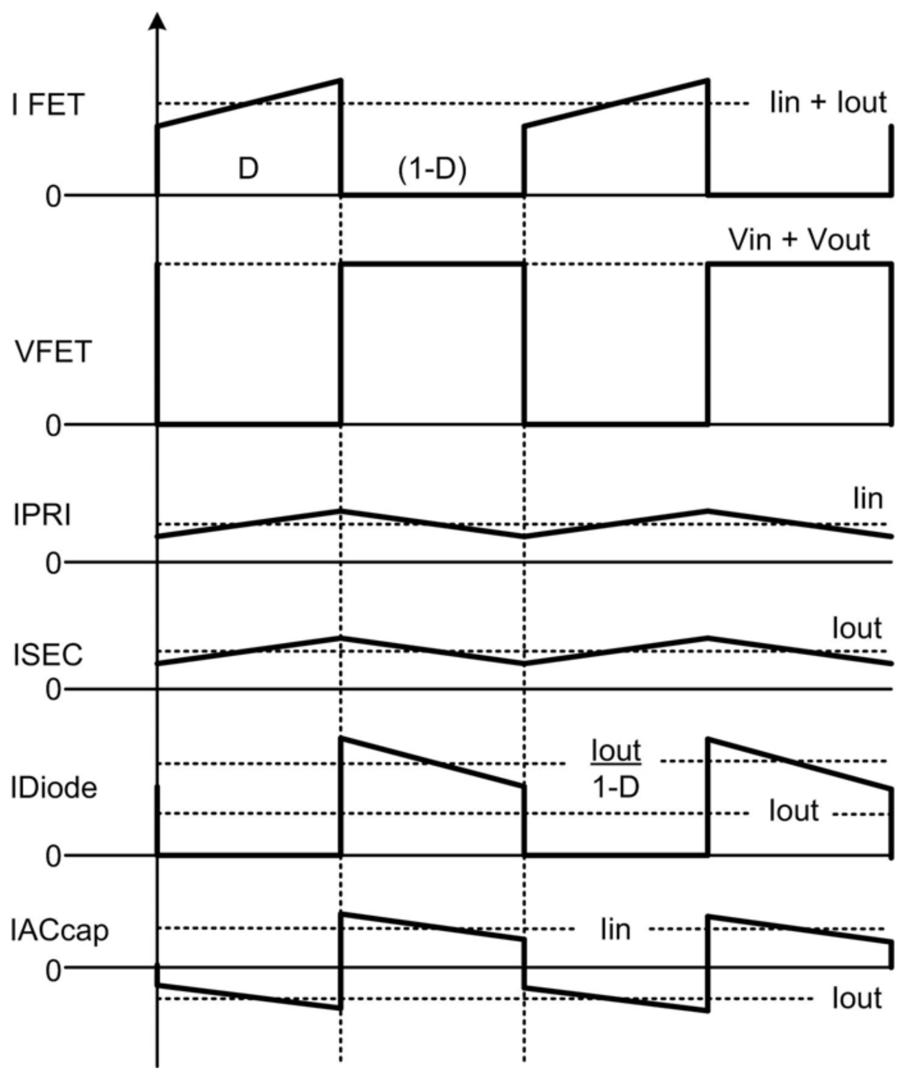

Figure 2: Key waveforms for a continuous conduction mode SEPIC.

Parameter	Specification
Input Voltage	10V - 40V
Output Voltage	12V
Max Output Current	4A
Ripple	1%
Efficiency (max load)	90% Goal

Table 1: Prototype SEPIC electrical specification.

average DC current rating of ~10 A is required. An off-the-shelf toroid inductor with comparable specifications was used for the design, although a custom design would have been somewhat smaller in size. Two variations of this toroid were tested, one tightly-coupled with bifilar windings and the other loosely-coupled with split windings. A model of a coupled inductor showing parasitic parameters is shown in **Figure 3**. For the tightly-coupled inductor, the magnetizing inductance is equal to 22 uH, while the loosely-coupled magnetizing inductance was 17 uH. The leakage inductances of the two inductors are quite different. The total tightly-coupled inductor leakage measures a mere 250 nH, while the total loosely-coupled leakage is a whopping 9 uH – about half the primary inductance. The primary and secondary winding resistances of each of the inductors measures 12 milliOhms. Core loss is determined by the Volt-uS product applied and the core material used. It can be modeled electrically in the first order as a resistor in parallel with the magnetizing inductance. **Figure 4** shows the complete SEPIC converter schematic with the tightly-coupled inductor parasitics included. Since the transformer construction is symmetrical in both cases the leakage can be split equally between the primary and secondary.

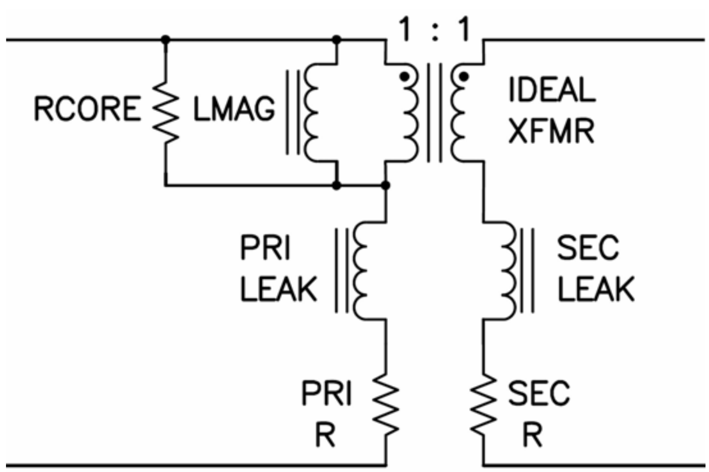

Figure 3: Non-ideal coupled inductor model.

Simulations of the primary and secondary currents with the tightly-coupled inductor (see **Figure 5**) reveal a picture much different than the ideal waveforms shown in **Figure 2**. The waveform's averages are correct, but there is additional circulating current flowing. The current flows in a loop including the AC capacitor, the primary and secondary leakages, the ideal transformer, and the input capacitor. The voltage across the AC capacitor contains an AC ripple voltage component along with its DC voltage, since its capacitance is not infinite. This AC ripple voltage is effectively imposed across the leakage inductance. For a given AC capacitor ripple voltage, the lower the leakage inductance, the larger the change in current will be. Conversely, for a large leakage inductance, the ripple current will be small. It is desirable to have the AC capacitor induced ripple current be comparable in size to the ripple current produced by the magnetizing inductance.

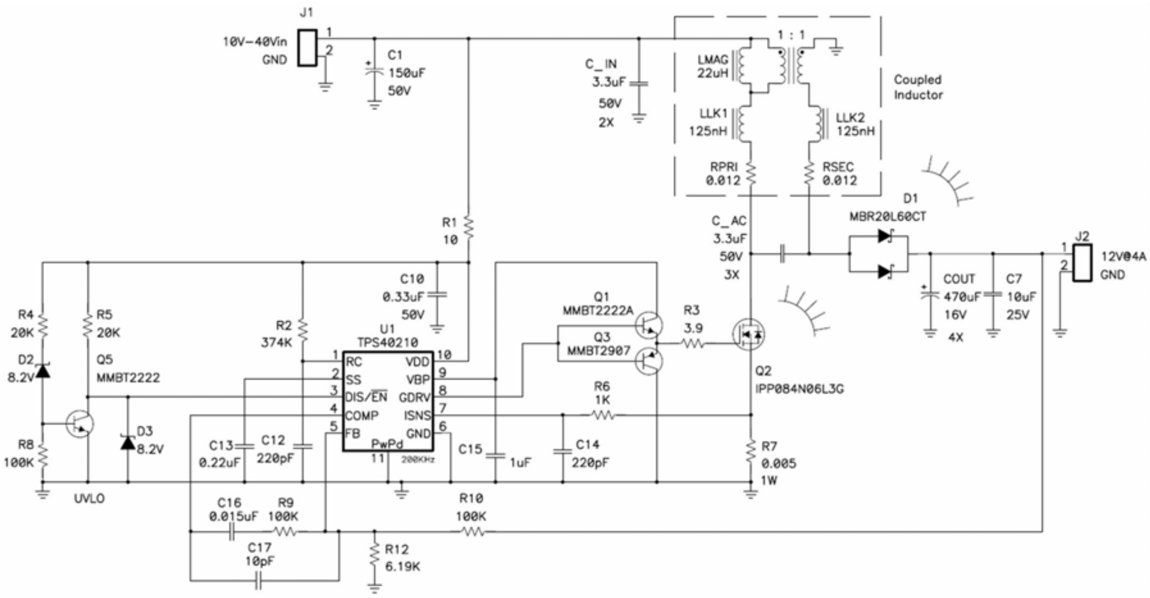

Figure 4: 12V@4A SEPIC converter schematic.

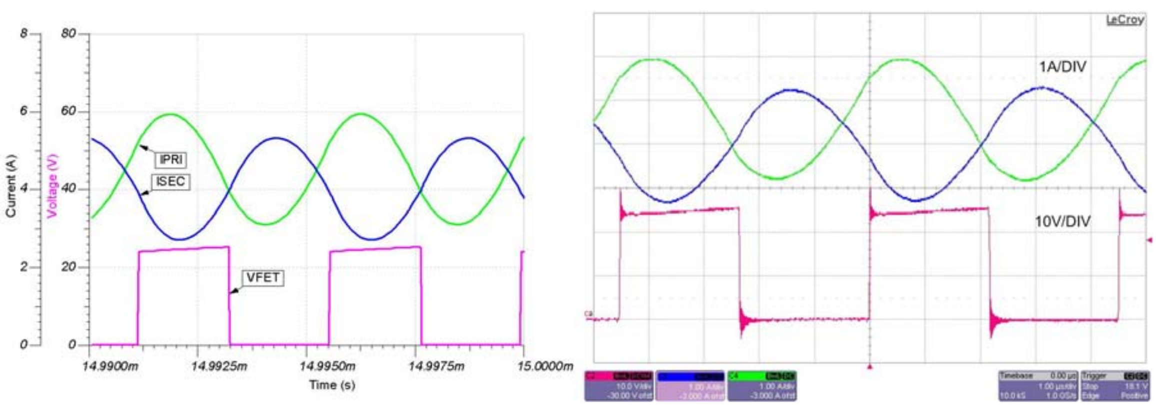

Figure 5: Inductor ripple currents for tightly-coupled magnetics may be much larger than expected. Simulation (left) and actual (right).

This can be done by either raising the leakage inductance or increasing the capacitance of the AC capacitor. In doing so, circulating AC current losses are reduced. However, increasing the capacitance generally increases size and cost, and the designer must ultimately make that decision. A starting point for determining a leakage inductance is expressed by **Equation 1**. This expression produces a leakage current approximately equal to the magnetizing current. This is by no means definitive and the designer can vary the amount as desired.

$$L_{lk} := \frac{I_{out} \cdot L_{pri} \cdot t_{on}}{C_{AC} \cdot V_{in}}$$ **Equation 1**

Additionally, output current is equal to the average current in the secondary winding, which can be monitored by adding a series ground referenced current sense resistor. This may be beneficial if you are using the converter as a battery charger or load current information is required at a system level. **Figure 6** shows the simulated and measured coupled inductor currents. These waveforms approach the expected “ideal” shapes in **Figure 2**.

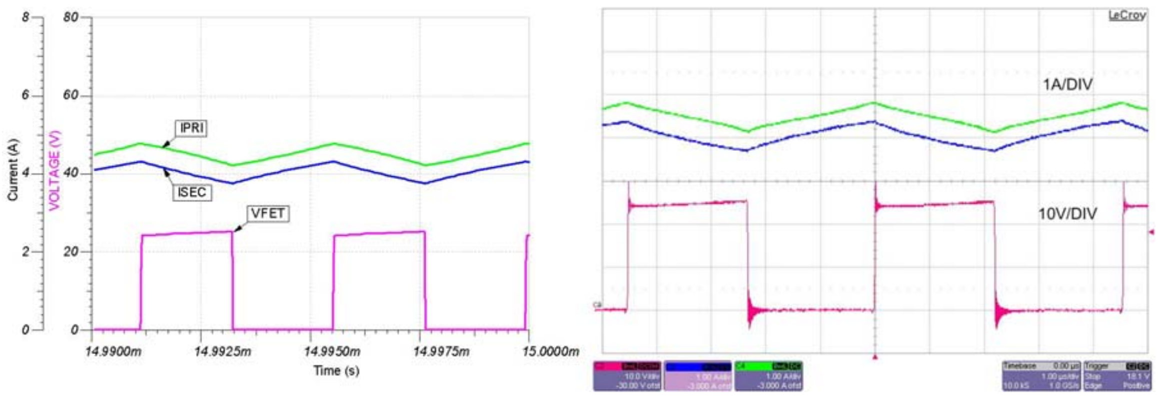

Figure 6: Leakage inductance produces well-behaved inductor currents. Simulation (left) and actual (right).

One benefit of the SEPIC converter is that the input ripple current in the input capacitor is continuous. This reduces the amount of input capacitance necessary for low-ripple voltage, which reduces EMI and prevents interference with sensitive upstream electronics. In certain noise susceptible applications, it may be desirable to further reduce the input ripple current. This can be accomplished by making the ratio of primary to secondary leakage large. Additional leakage, in the form of an external inductor, can be added in series with the primary winding. Alternately, it is possible to construct a coupled inductor where the leakage appears on only one winding [1] [2]. With either approach, this causes the AC capacitor’s ripple voltage to largely appear across the low leakage inductance on the secondary side, and steer the ripple current to the secondary winding. The ripple current, normally split evenly between the two windings, is now redistributed in proportion to the leakages. The input ripple current, as shown in **Figure 7**, is significantly smaller, producing a ripple voltage less than 10 mVpp.

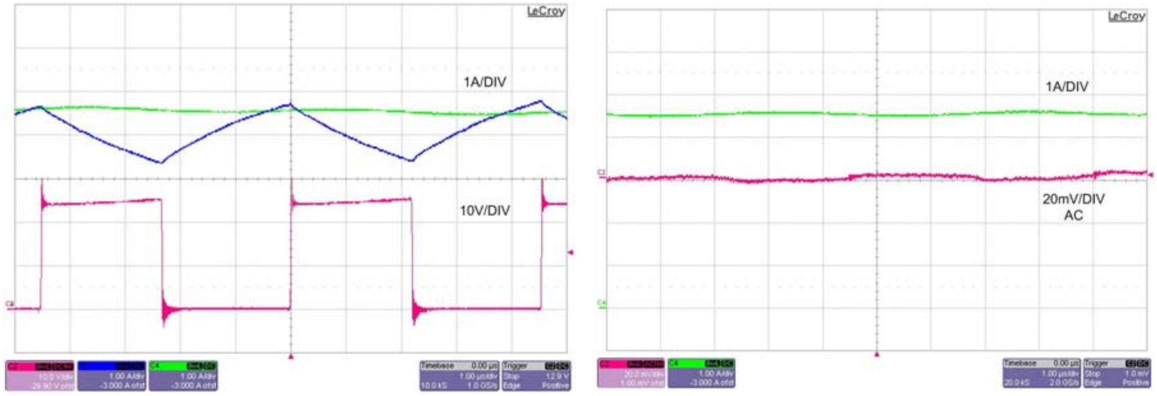

Figure 7: Ripple current is steered to the output, minimizing input ripple. inductor ripple currents (left) and input ripple voltage (right).

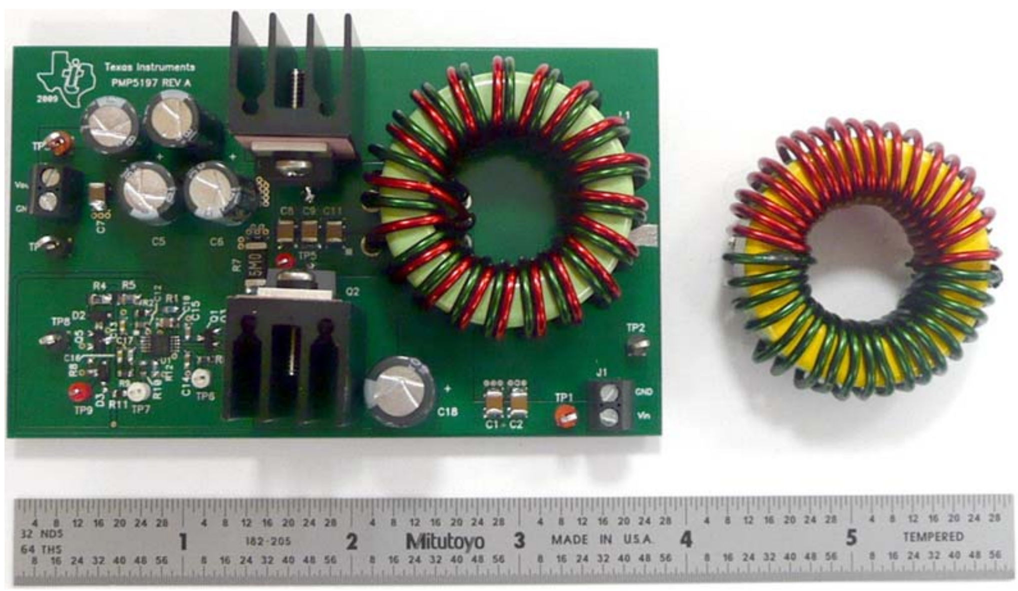

Figure 8: Evaluation hardware with tightly-coupled (left) and high-leakage split-winding inductors (right).

Figure 8 shows the evaluation board with the tightly-coupled inductor mounted and the loosely-coupled inductor alongside the board. The tightly-coupled inductor was bifilar wound, whereas the high-leakage inductor was section wound. **Figure 9** shows the converter's measured efficiency for both tightly and loosely-coupled inductors. The efficiency of the loosely-coupled inductor was approximately one percent higher overall. The high AC current content of the tightly-coupled inductor reduces efficiency by increasing core and resistive losses.

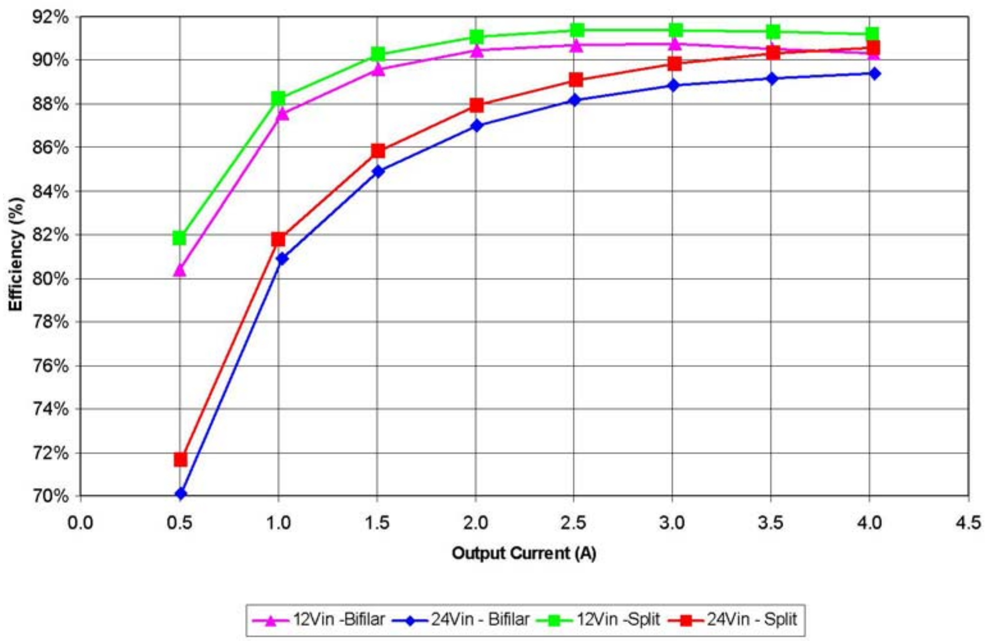

Figure 9: A loosely-coupled SEPIC provides better efficiency.

The SEPIC converter with a coupled inductor provides an excellent, highly-efficient solution. Purposely introducing some leakage into the design of the coupled inductor can benefit circuit operation and possibly improve efficiency. You can also reduce input ripple voltage by steering it with strategically placed leakage inductance.

References

[1] L.H. Dixon, "Coupled Inductor Design," Unitrode Power Supply Design Seminar, Seminar 900, Topic 8, May 1993, pp 8-1 to 8-4.

[2] L.H. Dixon, "High Power Factor Preregulator Using the SEPIC Converter," Unitrode Power Supply Design Seminar, Seminar 900, Topic 6, May 1993, pp 6-1 to 6-12.

To learn more about this SEPIC converter and other power solutions, visit: www.ti.com/power-ca.

About the Author

John Betten is an Applications Engineer and Senior Member of Group Technical Staff at Texas Instruments, and has more than 23 years of AC/DC and DC/DC power conversion design experience. John received his BSEE from the University of Pittsburgh and is a member of IEEE.