SEPIC - regulator with zero input ripple current

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The SEPIC topology offers a constant output voltage over a wide input voltage range - the input voltage can be lower than, equal to or higher than the output voltage.

In the case of coupled inductors on the same core, board space can be saved and the "zero-input-ripple-current" condition can be reached. Generated EMI noise is minimised and so the input filtering can be simplified.

A single-ended primary inductance converter (SEPIC) is a combination of buck and boost regulator topologies which are coupled through the capacitor Cc.

At turn-on, C_c will charge to V_g. When power-switch S turns on, the left end of Cc is connected to ground and its right-plate voltage $-V_c$ (= $-V_g$) is applied to the undotted end of the secondary winding. The voltage at the secondary side has the same polarity that the V_g source (at the converter input) is applied to the primary. Each winding attempts to induce the same voltage into the other. During the off time of S, D1 conducts, applying the output voltage (plus diode drop) to the primary winding through the secondary. This voltage induced across the primary winding happens to be the same voltage applied to it by the algebraic addition of the input source and V_c in series with $V_{out} + V_{d1}$.

For an ideal transformer, this would cause an over-constrained electrical indeterminacy, like connecting current sources in series or voltage sources in parallel.

What will the winding currents actually be in the coupled case?

Remember that the leakage inductance values (Llp/ Lls) of the SEPIC or Cuk transformer windings are much smaller than the mutual (magnetising) inductance, M.

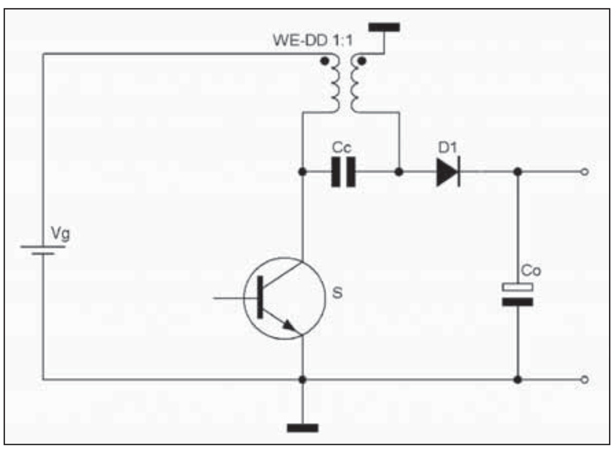

Fig. 1: SEPIC topology.

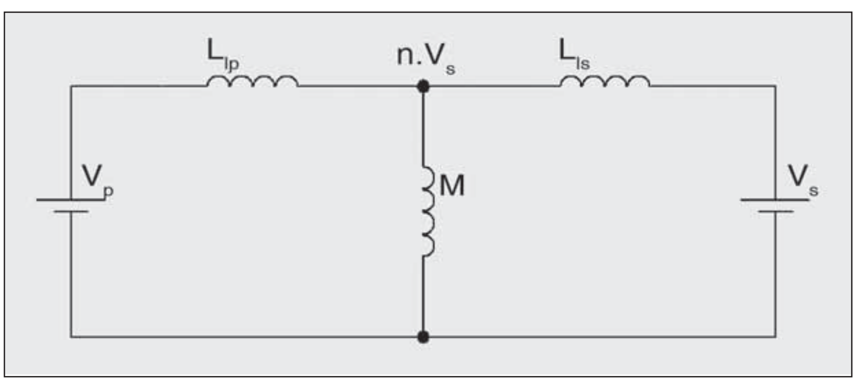

Fig. 2: Transformer model.

The secondary voltage source, V_s, induces n • V_s into the primary, as shown across the magnetising inductance. For the interesting case, $V_s = V_p = V_g$, if the turns ratio, n, is increased slightly from unity, by 1/k (where $k < 1$ is the coupling coefficient between windings), then the voltage induced by Vs will increase the voltage at the centre node to n • V_g, thereby "bootstrapping" L_{lp}.

Because the voltage at each end of Llp is the same, its inductance is effectively infinite.

Consequently, all variations in magnetising current, (through M) due to a varying V_g is supplied from the secondary winding source. By symmetry, setting n = k causes the secondary-winding current to become constant while the primary source supplies the magnetising-current variations. This effect can be desirable because (for n = 1/k) it results in constant (DC) primary current. Noisy switching current does not appear at the converter input but is diverted instead to the secondary winding. However, typical values of k are slightly less than one, and turns ratios of nearly 1:1 may not be easy to wind.

SEPIC application

To get a better knowledge about the differences of a SEPIC regulator we analyse the solution with two (uncoupled) inductors and coupled inductor solution.

Duty cycle:

For continuous mode the duty cycle is:

$$D = \frac{U_{out}\ U_D}{U_{in}\ U_{out}\ U_D}$$

With U_D = diode forward voltage

If the input voltage Uin is same as output voltage the duty cycle will be around 50%.

The maximum possible output voltage is limited by the maximum duty cycle (D) of the regulator and is:

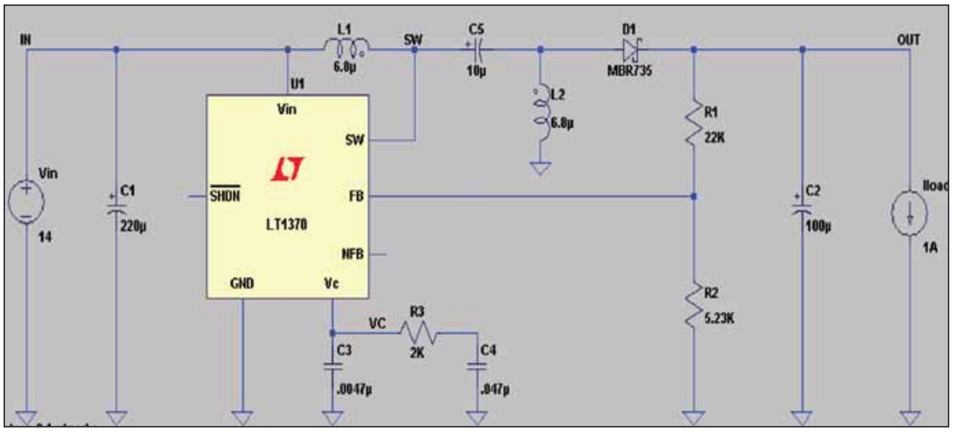

Fig. 3: SEPIC regulator with linear technology IC LT 1370.

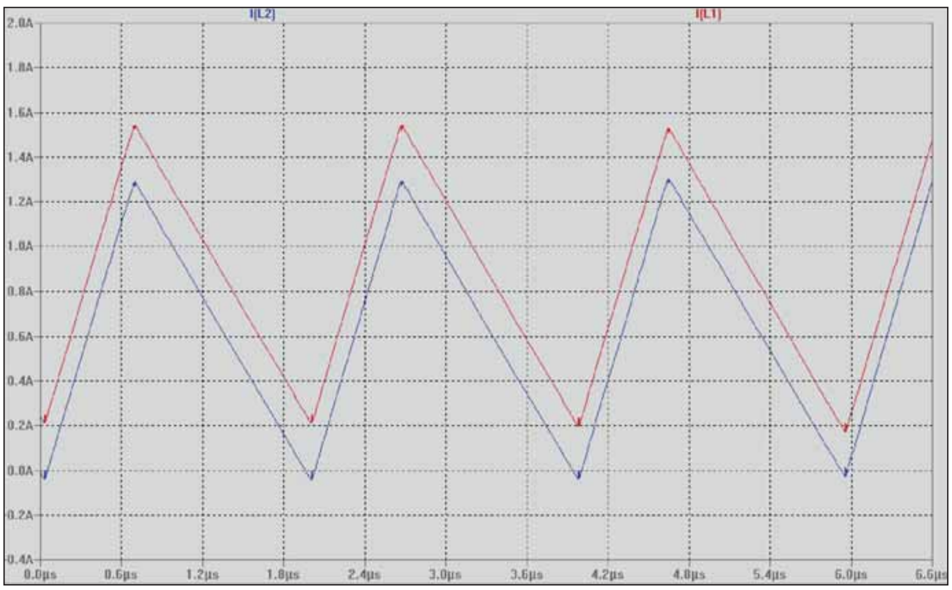

Fig. 4: Inductor ripple currents for uncoupled inductors. Ripple current primary: 1,25 App at Iout=1A

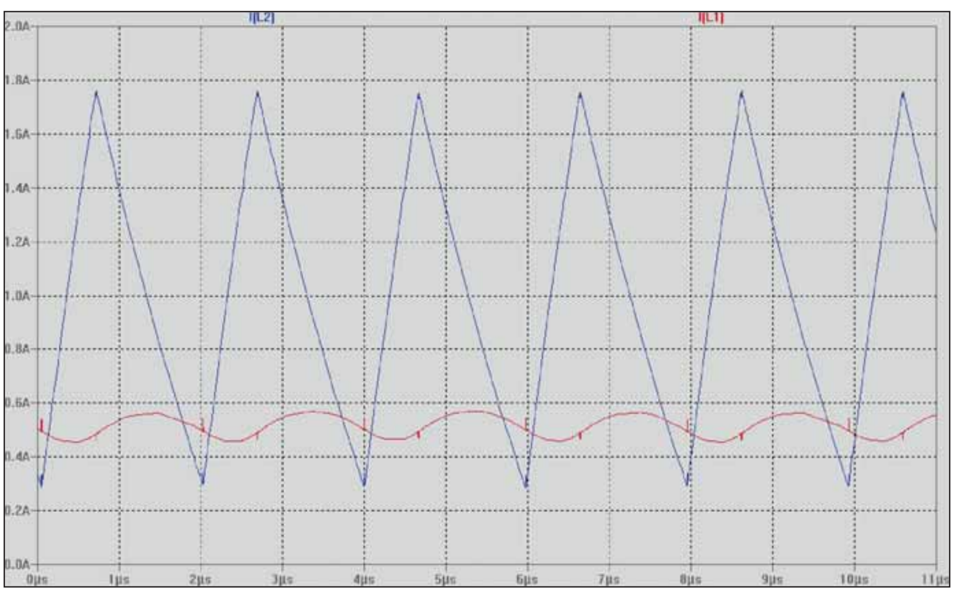

Fig. 5: WE-DD coupled inductor ripple current: primary: 100mApp bei Iout=1A.

$$U_{out(max)} = (U_{in}+U_D)\frac{D_{max}}{1-D_{max}} - U_D\frac{D_{max}}{1-D_{max}}$$

Inductance value and currents

as an example, both

output current 1 A, output voltage 6,5 V and input voltage range 6 … 20 V at switching frequency f= 500 kHz:

Calculate min. inductance:

$$D_{max}\ \frac{U_{out}\ \ U_D}{U_{in\,min} + U_{out} + U_D} = \frac{6{,}5V + 0{,}7V}{6V + 6{,}7V + 0{,}7V} = 0{,}53$$

$$L_1\ \ L_2\ \ \frac{U_{in(min)} \cdot D_{max}}{I_{out} \cdot f} = \frac{6V \cdot 0{,}537}{1A \cdot 500kHz} = 6{,}44\ \mu H$$

Chosen inductor value = 6,8 µH.

The ripple current at 14 V input is then:

$$\Delta I = \frac{U_{in} D_{14}}{L \cdot f} = \frac{14V \cdot 0{,}347}{6{,}8\mu H \cdot 500kHz} = 1{,}42A$$

The maximum currents through L1 and L2 can be calculated to:

$$I_{L1(max)} = I_{out(max)} + \frac{\Delta I}{2} \cdot \frac{U_{out}+U_D}{U_{in(min)}}$$

$$= 1 + \frac{0{,}917}{2} \cdot A \cdot \frac{6{,}5V + 0{,}7V}{6V} = 1{,}75A$$

$$I_{L2(max)} = \left(I_{out(max)} + \frac{\Delta I}{2}\right) \cdot \frac{U_{in(min)}\ \ U_D}{U_{in(min)}}$$

$$= \left(1 + \frac{0{,}917}{2}\right) \cdot A \cdot \frac{6V + 0{,}7V}{6V} = 1{,}62A$$

The saturation current of the inductor should be around 2 A for stable operation.

Coupled inductor operation (WE-DD):

If the inductors are built on one core theoretically the nductance can be lower and be set to L1=L2=L:

$$L = \frac{U_{in(min)} \cdot D_{max}}{2 \cdot I_{out} \cdot f} = \frac{6V \cdot 0{,}537}{2 \cdot 1A \cdot 500\ kHz} = 3{,}22\mu H$$

However in practical design you choose the same value as for uncoupled inductors to achieve lower ripple currents in general. Additionally, by coupling on the same core, tthe total ripple current will be smaller, as in uncoupled inductors.

Simulation

All simulations done here use the free software tool from Linear Technology “SwitcherCAD III” (or LTSpice, see www.linear.com for download), which has no limitations on number of nodes or components like other evaluation tools.

In both inductors the ripple current is around 1,5 A. This causes:

- Higher core loss in core material
- EMC noise problems if traces and current loops are to big

In the case of the usage of SEPIC-inductors like WE-DD, a dramatic decrease of ripple current can be found.

The ripple current on the output is still 1,5 A pp , but the input ripple current is reduced

to only 100 mA pp. This can also be shown and verified by measurements. This low ripple current through L1 minimises the filtering components in input filtering stage and saves costs in the total solution.

Efficiency

The efficiency measurement shows that the change to coupled inductors did increase the total efficiency of the SEPIC around 1,5 - 2% in the high output current range. Additionally, EMC noise problems are minimised by using coupled inductors. A practical measurement shows the total effect.

Conclusion

SEPIC regulators will become more and more important in battery-operated systems. By special design of the power inductors to coupled versions the noise in input current will be minimised and EMC problems reduced. At the same time, by using coupled inductors, the circuit will be more efficient.

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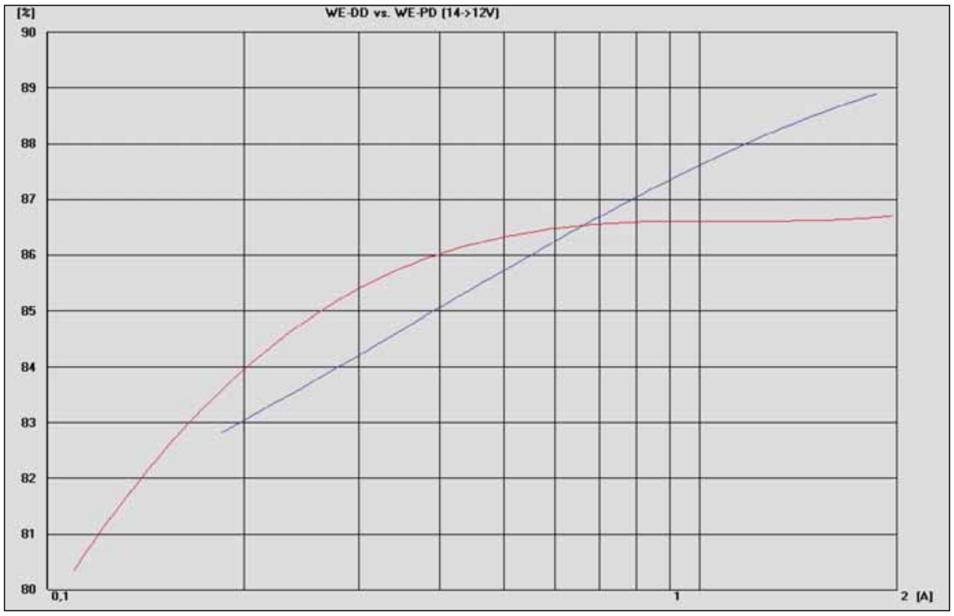

Fig. 6: Efficiency measurement.

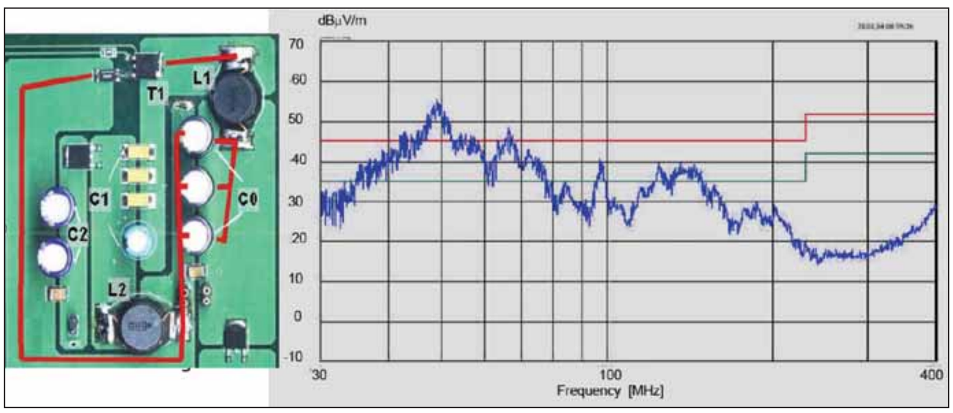

Fig. 7: SEPIC regulator with two inductors and big current-loops and EMI-noise-spectrum.

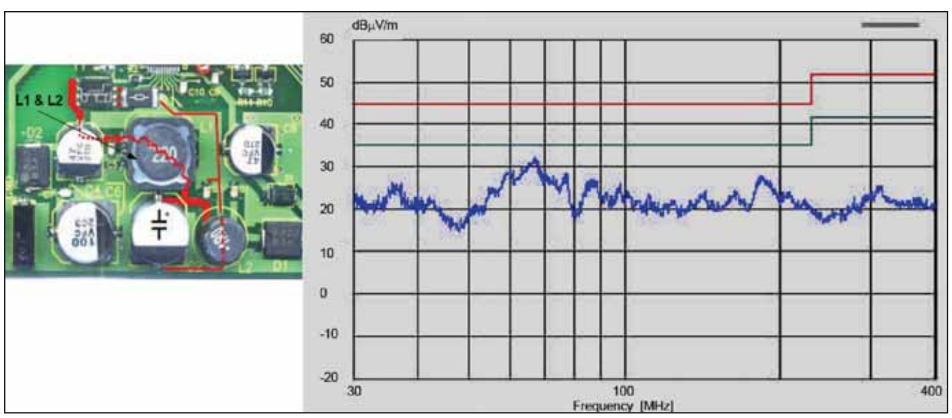

Fig. 8: SEPIC regulator with WE-DD coupled inductor and reduced EMI-noise-spectrum.