Optimized Design of a Coupled-Inductor Buck Converter, 48 to 12 V, 1 kW, Using Planar Magnetics and GaN-FETs for MHz-Range Operation

Track 6. Vehicle Electrification-related Technologies

Abstract—**The next generation of automotive vehicles and datacenters requires highly compact and efficient 48 V to 12 V point-of-load converters. This paper investigates the impact of coupling on the electrical properties of 2-phase buck converters operating in triangular current mode to achieve soft-switching. A novel planar inductor geometry with four poles and distributed air-gaps for operation beyond 1 MHz is presented that minimizes copper-losses from external proximity effect. An experimental prototype with 1 kW output achieves an impressive power density of 80 kW/l (1300 W/in³) and a peak efficiency of 96.5%, demonstrating the efficacy of the inductor structure.**

Index Terms—**coupled inductor, magnetic integration, planar inductor, triangular current mode**

I. Introduction

With a growing power demand, power distribution in both conventional and electric vehicles presents an increasing challenge. Traditionally, $12\,\mathrm{V}$ are used to distribute the power to all auxiliary devices which requires large cable diameters. Recently, many researchers proposed a $48\,\mathrm{V}$ distribution bus to reduce the cost of the wire assembly and/or reduce losses CITE. As most devices are still operating at $12\,\mathrm{V}$, highly compact and efficient point-of-load converters are required. This conversion stage is a critical part of distributed power architectures and its performance has a direct impact on system-level efficiency, thermal design, and spatial constraints.

This motivates the use of wide-bandgap semiconductors which offer lower $R_{ds,on}$ and faster switching speeds compared to traditional Si-devices. By increasing the switching frequency, magnetic components and filters can be shrunk significantly enabling very high power densities. Beyond $500\,\mathrm{kHz}$, hard-switched converters are generally unsuitable due to their large switching losses CITE. A lot of research has been done on resonant converters due to their high efficiency and compact design but those are unsuitable when a regulated output voltage is required over a wide input voltage range CITE.

This paper presents a highly compact interleaved buck converter for $48\,\mathrm{V}$ to $12\,\mathrm{V}$ conversion, delivering $1\,\mathrm{kW}$ of output power at a power density of $80\,\mathrm{kW/L}$ ($1300\,\mathrm{W/in}^3$). Using a custom planar inductor with distributed air-gaps, maximum power density is achieved while minimizing current crowding and inductor losses.

ToDo: Operation with soft-switching! Some waveforms and schematic!

II. Impact of the Coupling Factor

The symmetrical coupled inductor consists of two identical coils that are wound in a way, that the flux of one coil links with the flux of the second coil and vice versa with both coils connected on one side. This configuration can be described mathematically using

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} 1 & sblk \\ sblk & 1 \end{bmatrix} L_{self} \begin{bmatrix} \frac{di_1}{dt} \\ \frac{di_2}{dt} \end{bmatrix} \tag{1}$$

with self-inductance L_{self} and coupling-factor k. Note that k can be positive or negative; the impact of that will be analyzed later. In order to simplify the equations and provide a more intuitive understanding, the equivalent circuit in figure TODO is introduced. Both circuits are electrically equivalent for

$$\begin{aligned} L_{out} &= (1+k)\frac{L_{self}}{2} \\ L_m &= (1-k)\frac{L_{self}}{2}. \end{aligned} \tag{2}$$

The voltage at the virtual central node is now only dependent of the two leg voltages v_1 and v_2 decoupling the governing equations:

$$\begin{aligned} \frac{di_{out}}{dt} &= \frac{1}{L_{out}}(\frac{v_1+v_2}{2} - v_{out}) \\ \frac{di_m}{dt} &= \frac{1}{L_{out}}(\frac{v_1-v_2}{2}) \\ \text{with} \quad i_{out} &= i_1 + i_2 \quad \text{and} \quad i_m = i_1 - i_2 \end{aligned} \tag{3}$$

From this, the differential equations for each interval can be easily calculated and afterwards the important converter parameters. An effective dutycycle D_{eff} can be introduced with $D_{eff} = D$ for $D \leq 0.5$ and $D_{eff} = 1 - D$ for $D > 0.5$. The output ripple is described by

$$\frac{2V_{in}}{f_s(1+k)L_{self}} D_{eff}(\frac{1}{2} - D_{eff}). \tag{4}$$

The ripple in each leg which is important for soft-switching is given by

$$\Delta I_{leg} = \frac{V_{in} D_{eff}}{2 f_s L_{self}} \Big(\frac{2}{1+k}(0.5 - D_{eff}) + \frac{1}{1-k} \Big). \tag{5}$$

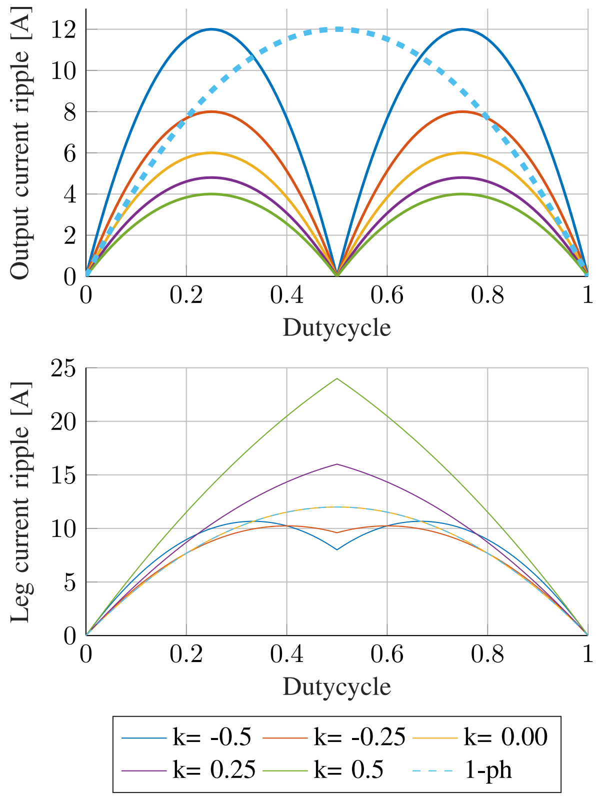

Fig. 1. Output current ripple and leg ripple for different coupling factors and constant input voltage. 1-ph for comparison. ToDo: Redo with normalized y-axis.

Both are shown in figure 1. There is a strong dependency of these parameters with dutycyle but interestingly, the leg ripple current is not that significantly influenced by the coupling-factor. As the coupling increases, L_{out} increases while L_m decreases causing a decrease in i_{out} but an increase in i_m.

As mentioned before, for soft-switching I_{neg} needs to be negative and generally needs to be below a certain value to guarantee a sufficiently short dead time which can be written as $\Delta I_{leg} \geq i_{out} + 2I_{neg}$. This is fulfilled for

$$f_s < \frac{V_{in} D_{eff}}{2L_{self}(i_{out} + 2I_{neg})} \left(\frac{2}{1+k}(0.5 - D_{eff}) + \frac{1}{1-k} \right). \tag{6}$$

III. Inductor Design

Four-pole introduced by [**?**].

IV. Experimental prototype

- Two LS-FETs due to large current. Switching losses don't matter
- Maybe list the key-components: F280049C, LT8418, IGC025S08S1
- Small 0805 capacitors due to resonance
- Incorporates internal vertical layout