

Topology Optimization of Coupled Inductors in Multi-Phase Buck Converters

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This study focuses on topology optimization of a coupled inductor for a multi-phase buck converter, addressing the challenges of achieving high efficiency and compact design. Using NGnet-based topology optimization, the cross-sectional area of the coupled inductor was optimized to achieve high system efficiency and minimize the volume. The optimization results highlight the importance of considering both coil and circuit losses in the design stage, providing a foundation for further optimization in multi-phase systems.

Index Terms—Coupled inductor, multi-phase buck converter, topology optimization.

I. INTRODUCTION

IN HIGH-END processors, such as CPUs and GPUs, the power requirement can reach approximately 1000 W, with currents exceeding 100 A due to their low operating voltage, which is typically less than several voltages. Therefore, multiphase buck converter (Fig. 1) is commonly used to efficiently distribute the current. However, an inductor is required for each phase. Inductors are the largest components of converters, and they exhibit significantly high loss densities. Therefore, the design of these inductors plays a crucial role in achieving miniaturization and improving the efficiency of the power circuits around processors.

Coupled inductors have been proposed to reduce the size and improve the efficiency of multiphase buck converters [1][2]. Coupled inductors exhibit a negative mutual inductance, which reduces ripples and helps achieve a faster transient response. As shown in the right side of Fig. 1, the current ripple in the inductors varies depending on the coupling ratio. Harmonic components are significantly influenced by the coupling ratio. Therefore, it is essential to evaluate an inductor by considering the circuit operation during the design stage. Furthermore, the optimal topology of a coupled inductor remains undefined because of the complexity of its operation.

In this paper, we present the topology optimization for a coupled inductor in a multiphase buck converter. The optimization aimed to maximize the efficiency of the buck converter and minimize the inductor volume. To allow the flexible determination of the inductor topology, a normalized Gaussian network (NGnet) [3] was employed. Through this optimization, the cross-sectional surface of the inductor was optimized, and we investigated how a coupled inductor should be optimized in a multiphase buck converter.

II. TOPOLOGY OPTIMIZATION OF COUPLED INDUCTORS IN MULTI-PHASE BUCK CONVERTERS

A. Coupled Inductor in a multi-phase buck converter

A schematic of an n th-phase buck converter is shown in Fig. 1. Inductors L_1 – L_n were coupled via negative coupling to reduce the ripples and achieve a fast transient response. A typical inductor for such a buck converter is shown in Fig. 2, where

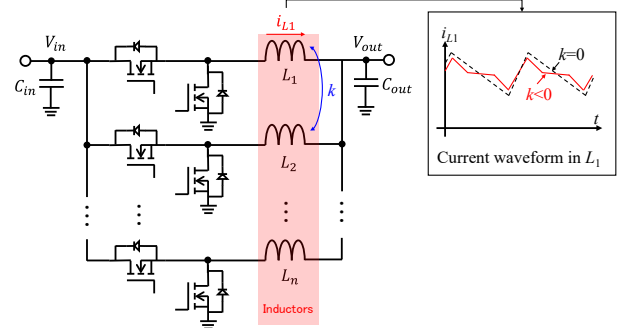
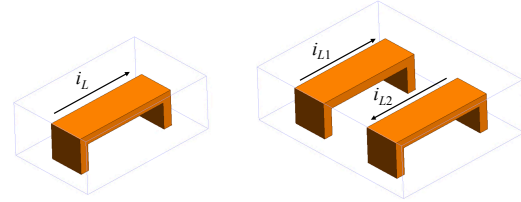


Fig. 1. Multi-phase buck converters.



(a) Typical inductor

(b) Coupled inductor

Fig. 2 Inductors for a buck converter with high current.

only a single-turn coil is used because of the high current flowing through each coil. However, this coil structure resulted in a low inductance. Since the switching frequency was set to more than hundred kHz, the AC losses caused by the skin and proximity effects must be considered during the design stage.

B. Topology Optimization of a Coupled Inductor

The topology optimization of a coupled inductor in a two-phase buck converter was conducted. The cross-sectional area of the coupled inductor was optimized using NGnet-based topology optimization [4], where 25 Gaussian functions were arranged around one phase, as shown in Fig. 3, and the structure was mirrored in the other phase. The coil size was defined as c_x and c_y . Based on this structure, the total number of design parameters is 27.

This optimization aimed to maximize the system efficiency and minimize the volume of the coupled inductor.

$$f(\mathbf{d}) = \alpha \frac{1}{\eta} + (1 - \alpha) \frac{V}{V_0}, \quad (1)$$

where η , V , and V_0 are the system efficiency of the buck converter and the volume and maximum volume of the inductor, respectively. α is the weight coefficient for the optimization. CMA-ES [2] was employed as the optimization strategy.

During CMA-ES, the system efficiency of the buck converter was computed using the following procedure:

1. FEA was performed under a static field to compute the self- and mutual inductances (L and M , respectively) and DC resistance R_{dc} .
2. Then, circuit analysis was performed using L , M , and R_{dc} to compute the current waveform flowing into the coupled inductor, as well as the input and output powers (P_{in} and P_{out} , respectively).
3. An FFT analysis was applied to the current waveform in the inductor to extract the current ripple at harmonic frequencies.
4. FEA was performed at the top five frequencies of the current ripple to compute the AC losses (P_{ac}).
5. The system efficiency was computed as $\eta = P_{out}/(P_{in} + P_{ac})$.

III. OPTIMIZATION RESULTS

The coupled inductor in the two-phase buck converter was optimized using CMA-ES. The input and output voltages of the buck converter were set to 12 and 1.2 V, respectively. The operating frequency and FET on-resistance were set to 500 kHz and 10 m Ω , respectively. The coefficient α in Equation (1) was set to 0.8 and 0.9.

The optimized topology of the coupled inductor is shown in Fig. 4. Table I summarizes the characteristics of each structure. According to the optimization results, the inductance of the optimized inductor decreases with α because of the reduced magnetic volume. Conversely, as the coil area increases, DC resistance decreases to maintain the efficiency despite the reduced magnetic volume.

The current waveforms flowing through each inductor are shown in Fig. 5. It is confirmed that the current ripple is suppressed at $\alpha=0.9$, which corresponds to a larger inductance.

From the loss breakdown shown in Fig. 6, the inductor loss and its ratio to the total system loss are lower when $\alpha=0.8$ compared to when $\alpha=0.9$. Furthermore, the loss structure underwent significant changes. At $\alpha=0.9$, the DC loss was higher, whereas the AC loss was suppressed. It is found that AC losses at $\alpha=0.8$ dominated due to the large current ripple. In addition, the circuit loss, which is primarily attributed to FET switching loss, was higher because of the low input impedance, which resulted from the reduced resistance and inductance at $\alpha=0.8$.

These preliminary optimization results indicate that the design concept changed significantly depending on the inductor volume. Therefore, it is necessary to consider not only the inductor loss, but also the circuit losses when designing a coupled inductor for a multiphase buck converter. This study will discuss the optimized topology and its impact on various losses in detail. Moreover, we will extend the optimization to a four-phase coupled inductor to further enhance the efficiency.

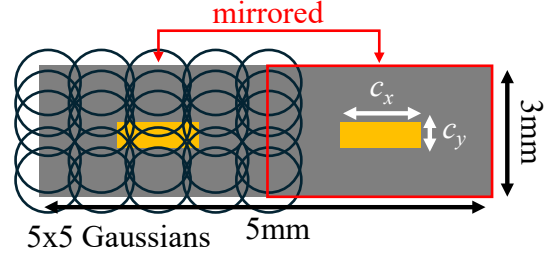


Fig. 3. Gaussian distribution and coil parameters, where 25 Gaussian functions are arranged and coil structures are determined by c_x and c_y .

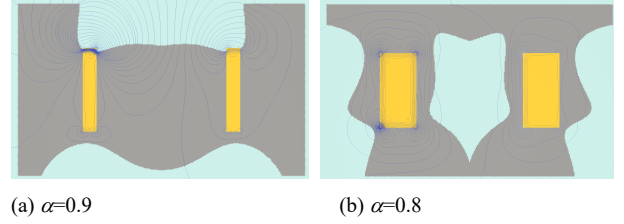


Fig. 4. Optimized topology by CMA-ES.

	L (nH)	M (nH)	R_{dc} (m Ω)	η	V/V_0
$\alpha=0.9$	35.4	-6.0	0.30	92.3%	0.77
$\alpha=0.8$	25.1	-7.4	0.18	91.9%	0.69

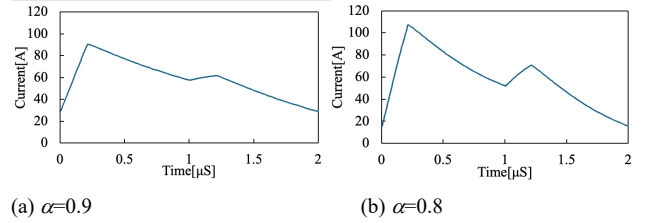


Fig. 5. Current waveform in optimized coupled inductor with a 12 V_{in} , 1.2 V_{out} buck converter.

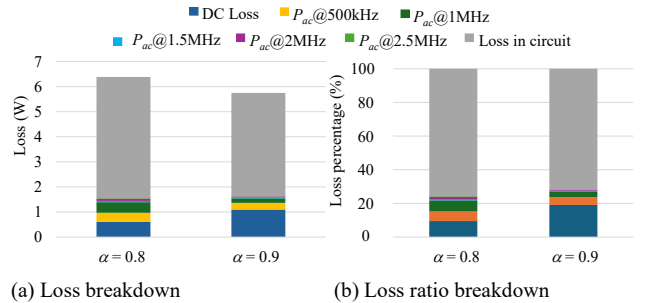


Fig. 6. Loss breakdown for the optimized coupled inductor with a 12 V_{in} , 1.2 V_{out} buck converter.

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