

A NEW STRATEGY OF MAGNETIC DESIGN FOR DC-DC CONVERTER APPLICATIONS

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ABSTRACT

This study presents an innovative method for the selection and design of magnetic cores for DC-DC converters. In contrast to conventional approaches that rely on the Area Product (A_p) and involve extensive trial and error, our proposed methodology employs two main key parameters: the Core to Copper Loss Ratio (γ) and the Window Utilization Factor (k_w) during the inductor design process. Loss models for the inductor are developed based on these variables, taking into account the influence of DC bias, a critical factor in high magnetic field strength applications. To reduce magnetic loss, we utilize the PSO algorithm. The simulation results confirm the effectiveness and rationality of our magnetic models and optimization approach. Therefore, our method offers an efficient and practical alternative to the traditional trial-and-error method for magnetic core selection and design in DC-DC converters.

Keywords: *magnetic design, Inductor design, DC-DC converters, optimization algorithms.*

1. INTRODUCTION

Numerous magnetic design methods have been proposed in the literature, typically involving core and conductor selection, loss assessment, and other parameter estimations [1]–[3]. However, these methods often rely solely on the Area-Product (A_p) parameter for core selection, necessitating repetitive

trial-and-error processes. While some approaches attempted to relate A_p to total magnetic component loss and design the inductor with the assistance of 3D-graphical method [4], [5], they still required trial and error during designing the inductor. Therefore, this paper proposes a new approach to inductor design for a DC-DC converters. In this

paper, the winding loss (P_{cu}) and ferrite loss (P_{core}) are formulated in terms of A_p [5]. To enhance accuracy, the effect of DC bias is also addressed in modeling the inductor loss. The PSO algorithm is used for optimizing total loss of the inductor while addressing constraints. And simulation results are used to confirm the reliability of the proposed inductor loss models.

2. MAGNETIC CIRCUIT ANALYSIS

2.1 Inductance Analysis

The inductance value can be calculated by the following equation (1):

$$L_0 = \frac{V_o \cdot D}{f_{sw} \Delta I} \quad (1)$$

Where:

V_{in} is the input voltage of the DC-DC converters,

D is duty cycle,

ΔI is the current ripple of the inductor,

f_{sw} is the switching frequency.

While the inductance value is conventionally considered constant during operation [1]– [5]. However, the presence of DC bias has been identified as a significant factor that alters the inductance value, leading to shifts in its frequency response and elevated core losses [6]. Therefore, in this study, the inductance value is reevaluated based on the circuit's operating conditions, as described by the following equation (2).

$$L_b = L_0 \cdot k_b \quad (2)$$

Where:

L_b is recalculated inductance value; k_b is the DC bias gain which depends on the magnetic core material.

In this paper, the magnetic core of Micrometal manufacture is used to illustrate the design process. From [7], k_b can be expressed by the Equation (3):

$$k_b = \frac{1}{\frac{1}{a_1 + b_1 B_{ac}^{c_1}} + \frac{1}{d_1 B_{ac}^e} + \frac{1}{f_{sw}}} \quad (3)$$

where a_1 , b_1 , c_1 , d_1 and e is the material coefficients; B_{ac} is AC flux density of magnetic core.

2.2. Core Parameters Formulation

The design of an inductor typically begins with selecting a core. The first step in this design process is to reformulate A_p in [1]– [3] related to magnetic mechanical, electromagnetic, and power dissipation parameters. This relationship is described in [4] with considering the effect of DC bias as following equation (4):

$$A_p = \left[\frac{\sqrt{1 + \gamma K_i L_b I_{max}}}{B_m K_t \sqrt{k_u \Delta T}} \right]^{\frac{8}{7}} \quad (4)$$

Where:

$\gamma = \frac{P_{fe}}{P_{cu}}$ is core to copper loss ratio,

K_i is root-mean-square to maximum inductor current ratio,

L_b is the inductance value calculated in 2,

K_t is a dimensional constant,

ΔT is the temperature rise of the inductor.

The key characteristics and physical measurements of the core, including W_a , A_c , core volume (V_c), the mean length turn (MLT), the magnetic path length of the core (l_e), winding volume (V_w) and total surface area (A_t), can be determined based on the value of A_p using dimensional analysis, as explained in the references [4]. In order to simplify the number of unknown factors, [5] introduced a ratio of W_a to A_c , which can be expressed by the following equation (5):

$$x = \frac{W_a}{A_c} \quad (5)$$

Therefore, the values of W_a , A_c , V_c , and l_e that correspond to each A_p value can be calculated by using the equations described in (6):

Where:

k_c depends on geometry and the manufacture; $k_c = 5.6$ with vertical core and $k_c = 3.3$ with toroidal core typically [4].

Then the current density (J) within the winding needs to meet the maximum allowable temperature and can be

expressed in terms of k_u , γ , ΔT and A_p as the following equation (7):

$$\begin{cases} W_a = \sqrt{A_p \times x} \\ A_c = \sqrt{\frac{A_p}{x}} \\ V_c = k_c \times A_p^{\frac{3}{4}} \\ l_e = \frac{V_c}{A_c} \end{cases} \quad (6)$$

$$J = K_t \frac{\sqrt{\Delta T}}{\sqrt{k_u(1+\gamma)} \sqrt[3]{A_p}} \quad (7)$$

2.3. Loss Formulation

Inductor loss includes ferrite loss on the magnetic core and copper loss dissipating on windings as follows by equation (8):

$$\Delta P_{ind} = P_{fe} + P_{cu} \quad (8)$$

From [7] the core loss can be estimated by the following equation (9):

$$P_{fe} = V_c \left(\frac{f_{sw}}{\frac{a_2}{B_{ac}^3} + \frac{b_2}{B_{ac}^{2.3}} + \frac{c_2}{B_{ac}^{1.65}}} + d_2 \cdot B_{ac}^2 \cdot f_{sw}^2 \right) \quad (9)$$

where a_2, b_2, c_2, d_2 are core loss coefficients

Substituting (6) to (9), P_{fe} can be calculated in terms of A_p , by following equation (10):

$$P_{fe} = k_c \times A_p^{\frac{3}{4}} \cdot \left(\frac{f_{sw}}{\frac{a_2}{B_{ac}^3} + \frac{b_2}{B_{ac}^{2.3}} + \frac{c_2}{B_{ac}^{1.65}}} \right) + d_2 \cdot B_{ac}^2 \cdot f_{sw}^2 \quad (10)$$

Apply approximation methods, [5] reports a calculation of the copper loss in terms of A_p , k_u and J as following equation (11):

$$P_{cu} = k_\omega \cdot A_p^{\frac{3}{4}} \times \rho_\omega \times k_u \times J^2 \quad (11)$$

where ρ_ω is the resistivity of copper winding; $\rho_\omega = 1.68 \times 10^{-8}$, k_ω depends on types of cores, $k_\omega = 8$ with toroidal core.

3. DESIGN METHOD

3.1. Objective Function

The primary purpose of this study is to design a lowest-loss inductor. Therefore, the objective function is to minimize the inductor loss. The equation (12) derives the objective function equation from this study:

$$f(\gamma, k_u, x) = \Delta P_{ind} \rightarrow \min \quad (12)$$

3.2. Design Constraints

Minimization of f must meet the predetermined constraints as described in (13) contain constraints that must be appropriate in this inductor design:

$$\left\{ \begin{array}{l} c_1(\gamma, k_u, x) = J - J_{max} \leq 0 \\ c_2(\gamma, k_u, x) = J_{min} - J \leq 0 \\ c_3(\gamma, k_u, x) = L - L_0(1 + 5\%) \leq 0 \\ c_4(\gamma, k_u, x) = L_0(1 - 5\%) - L \leq 0 \\ c_5(\gamma, k_u, x) = 70\% \times L - L_b \leq 0 \\ c_6(\gamma, k_u, x) = k_u - k_{u,max} \leq 0 \\ c_7(\gamma, k_u, x) = k_{u,min} - k_u \leq 0 \\ c_8(\gamma, k_u, x) = \gamma_{min} - \gamma \leq 0 \\ c_9(\gamma, k_u, x) = \gamma - \gamma_{max} \leq 0 \\ c_{10}(\gamma, k_u, x) = x_{min} - x \leq 0 \\ c_{11}(\gamma, k_u, x) = x - x_{max} \leq 0 \end{array} \right. \quad (13)$$

Table I is a type of optimized design variables along with its lower and upper bounds.

Table I. Lower and upper bounds for genetic algorithm

Parameter	Symbol	Lower Bound	Upper Bound
Current density	J	1 A/mm ²	9 A/mm ²
Window utilization factor	k_u	0.05	1
Core to copper loss ratio	γ	0.5	5
Wa to Ac ratio	x	2	6

4. CASE STUDY, RESULTS AND SIMULATION

4.1. Case Study

This design is applied to the boost DC-DC converter, with the specifications shown in Table II. The constraints are used based on Equation

(13), and the lower bounds and upper bounds of each optimized design variables are presented in Table I.

Table II. *Specification parameters*

Parameter	Symbol	Value	Unit
Rated Power	P_{rate}	550	W
Input Voltage	V_{in}	45	V
Switching Frequency	f_{sw}	30	kHz
Inductance Value	L	120	μH
Peak Flux Density	B_m	500	mT
Temperature rise	ΔT	40	$^{\circ}\text{C}$

4.2. Results and Simulation

The results of the design process are displayed in Fig. 1 and Fig.2. In Fig. 1, the x-axis represents the number of iterations completed by the PSO algorithm, and the y-axis illustrates the fitness of the best individual within each iteration's population. These relationships are further explained in Fig.2, which provides a three-dimensional plot showing the interplay between the total loss and the variables of the fitness function. Notably, the cost values of the individuals in each iteration are progressively approaching the global optimal point, signifying the effective convergence of the PSO algorithm toward the optimal solution. The optimal fitness value, which corresponds to the

minimum inductor loss, is achieved at 3.380 W for a particular set of parameters (γ, k_u, x) with values of (0.537, 0.251, 4.01). Table III shows other important parameters. The core MS157075-2 of Micrometal manufacture and AWG 12 wire are selected to match the above parameters.

Table III. *Calculated core parameters*

Parameter	Symbol	Value	Unit
Core to copper loss ratio	γ	0.537	
Window utilizing factor	k_u	0.251	
Wa to Ac ratio	x	4.01	
Window area product	A_p	4.263	cm^4
Inductance at initial	L_0	127.94	μH
Inductance at peak current	L_b	90.15	μH
Number of turns	N	35	Turns
Total loss	P_{tot}	3.380	W
Core loss	P_{fe}	1.202	W
Copper loss	P_{cu}	2.178	W

To validate the designed inductors, a finite-element analysis (FEA) was conducted using the ANSYS Maxwell version 18.0 and the results of simulation

are depicted in Fig.3. In addition, the comparison between the calculated and simulated values is shown in Table IV.

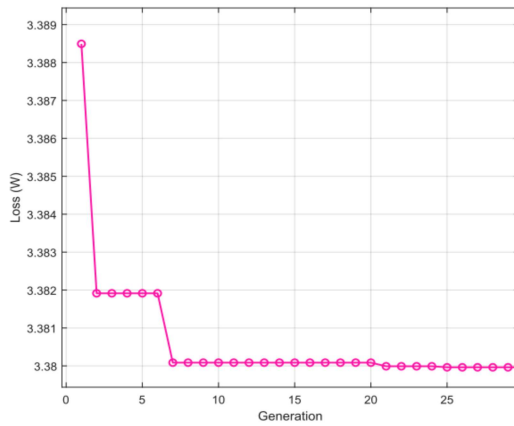


Fig.1. The objective function value

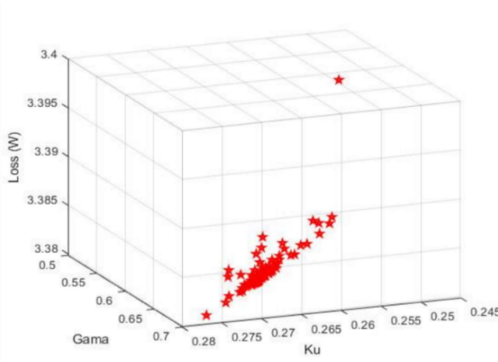


Fig.2. Optimization of positioning

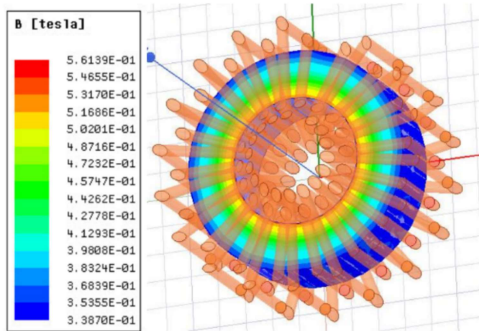


Fig.3. Simulation results with ANSYS Maxwell

Table IV. Calculation and simulation parameters

Parameter	Symbol	Value	Unit
Inductance at initial	L_0	127.94 μH	128.32 μH
Inductance at peak current	L_b	90.15 μH	93.20 μH
Core loss	P_{fe}	1.202 W	1.26 W
Copper loss	P_{cu}	2.178 W	2.19 W
Peak flux density	B_m	500 mT	562 mT

CONCLUSION

This study introduces an innovative methodology for designing and selecting magnetic cores for DC power optimizers. Unlike the traditional approach relying on the Area Product and involving trial-and-error, the proposed method uses key parameters (Core to DC Copper Loss Ratio and Window Utilization Factor) to initiate the inductor design process. Considering the significant impact of DC bias, the inductor's loss models are formulated using these variables. The Particle Swarm Optimization algorithm is then applied to minimize magnetic loss. Simulation results validate the rationality and high effectiveness of this approach, offering a more efficient way to design and select magnetic cores for DC power optimizers compared to traditional trial-and-error methods.

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