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Research Article

A Comparative Simulations on the Electromagnetic and Mechanical Effects of the Various Inductor Core Forms for DC-DC Converter Circuits

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ABSTRACT

DC-DC power electronics converters are used in many applications such as electrical vehicles, energy storage systems, renewable energy sources. The inductors designed for a specific frequency and current level have significant impact on converter performance. In this study, an inductor is designed for a specific frequency and current value with some common core geometric structures called EE, block, pot and toroidal. Since inductors operate at high frequency values, the Kool-Mu which is a kind of powder core is selected. The Kool-Mu has distributed homogeneous air gaps and is used in inductor designs that saturation is not desired. Inductors are designed for EE core, toroidal core, pot core and block core structures. Electromagnetic modelling of these inductors designed for different core structures are carried out with finite element analysis (FEA), and inductance stability, core and winding losses, mechanical specifications and flux distributions have been reported comparatively. In addition, some suggestions are derived in core structure definitions for DC-DC converter inductor design.

Keywords: *High frequency inductor design, Core forms, DC-DC converters, FEA*

DA-DA Dönüştürücü Devreleri için Çeşitli İndüktör Nüve Şekillerinin Elektromanyetik ve Mekanik Etkileri Üzerine Karşılaştırmalı Bir Benzetim

ÖZET

Elektrikli araçlar, enerji depolama, yenilenebilir enerji kaynakları gibi birçok uygulama da DA-DA güç elektroniği dönüştürücüleri kullanılmaktadır. Bu devrelerde kullanılan farklı frekans ve akım değerleri için tasarlanmış indüktörlerin dönüştürücü performansı üzerinde önemli etkiye sahiptir. Bu çalışmada, yaygın olarak üretilen ve EE, blok, pot ve toroid olarak adlandırılan farklı geometrik yapılarla belirli bir akım ve endüktans değerinde bir indöktörün tasarımı gerçekleştirilmiştir. İndüktör yüksek frekans değerlerinde çalışacağından kayıpların az olması düşüncesiyle demir tozu alaşımı olan Kool-Mu tercih edilmiştir. Kool-Mu doyma etkisinin

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istenmediği indüktör yapılarında kullanılan ve dağıtılmış homojen boşluklar içeren bir malzemedir. İndüktörler, EE çekirdek, toroidal çekirdek, pot çekirdek ve blok çekirdek gibi farklı çekirdek yapıları ile tasarlanmıştır. Farklı nüve yapılarına göre tasarlanmış olan indüktörlerin elektromanyetik modellemesi sonlu elemanlar analizi (SEA) yazılımı ile yapılmış ve endüktans kararlılıkları, nüve ve sargı kayıpları, mekanik özellikleri ve akı dağılımları karşılaştırmalı olarak raporlanmıştır. Ayrıca, DA-DA dönüştürücü devrelerinin indüktör tasarım aşamasında çekirdek şeklinin belirlenmesi için önerilerde bulunulmuştur.

Anahtar Kelimeler: *Yüksek frekanslı indüktör tasarımı, Nüve şekilleri, DA-DA dönüştürücüler, SEA*

I. INTRODUCTION

The geometric form of the inductor core is especially determined at design stage depending on a few factors such as availability, cost and volume. However, the core form affects both electromagnetic and thermal behaviors of the inductors. The electromagnetic behavior of the inductor not only affects the efficiency of the converter circuits but also it substantially affects the performance of the power electronic circuit as well as mechanical factors such as power density and cooling methods.

In the past literature, a few studies regard of the core material selection were carried out and catalog specifications of the various available commercial products were compared [1-4]. Although the criteria such as efficiency, cost and volume were compared, any study were not found regard in the different geometric forms of the inductor core shape at the same technical properties. Especially, there are a few papers with the specific properties depending on the core material type, and propose ferrite and powder core (Kool-Mu) sizing. In addition, the electromagnetic behaviors of the designed C-core and the toroidal core transformers were compared by using the different core geometry with the ribbon metal alloy [5].

Air-gapped core structures of the high power inductors can be designed with the ribbon core materials like amorphous, nanocrystalline and non-oriented silicon steel. [6]. Though ribbon metal alloys are more preferred at the medium frequency high power applications such as LCL filter inductors, the ferrite and the powder core materials are used in DC-DC converter circuits [7-8]. In order to achieve high power density, the cross sectional area of the inductor core can be increased by using additional core for the high power applications.

Thanks to the electromagnetic modeling with finite element analysis (FEA), electromagnetic behavior of the various core structures can be easily determined, thus the electromagnetic modeling software like ANSYS- Electronics allows a quick design scope of the magnetic components. In traditional design comprehension, electromagnetic and thermal effects cannot be exactly determined before the inductor prototype, and generally it is revised according to the experimental results after the prototype. Recently, the FEA software contributes very important to the inductor designing thanks to the more improved computer hardware technologies, and it allows to co-simulate the electromagnetic and the thermal performances of the inductors at design stage [6-8].

In this paper, three-dimensional (3D) electromagnetic modeling of the four various core geometric forms of the inductors have been carried out with the ANSYS-Electronics for the DC-DC buck converter. These design parameters of the inductor include as the 20% inductor current ripple, 1 mH inductance value, 20 kHz switching frequency and 5 kW rated power. The parameters such as flux distributions, power losses and inductance roll-off values have been compared and reported according to the co-simulation results in the power electronic software (ANSYS-Simplorer). In addition, mechanical properties such as volume and weight of the designed inductor core forms have been comparatively presented.

II. Inductor Design Stage For Dc-Dc Converters

In the power electronic circuit design, the performances of the magnetic components such as transformer and inductor should be considered as the important factors. In this context, the allowed inductor current ripple (ΔI_L) affects core flux magnitude (B_m) for inductor design of the DC-DC converters. The core flux density can reach to the saturation flux value (B_s) of the core material due to the high frequency flux ripple added on the DC bias flux density (B_{dc}), which inductance value of the magnetic component decreases and the continuous conduction mode of the power converter can be missed because the critical inductance value cannot be provided [9-10]. As seen in Fig.1, with the high frequency flux ripple that added on the DC bias flux density, the peak-to-peak flux density (B_{pk}) of the inductor core can be given in Eq.1

$$B_{pk} = B_{DC} + \frac{B_m}{2} \tag{1}$$

The relation of the inductance value determined according to the inductor technical properties in the DC-DC buck converter circuit and allowed inductor current ripple can be defined as given in Eq.2 [9-10]:

$$\Delta I_L = \frac{(V_s - V_o)DT}{L} \tag{2}$$

where V_s is the input voltage, V_o is output voltage, D is the duty ratio, and T is the switching period of the power converter circuit. In addition, L represents inductance value of the magnetic component. In order to not exceed maximum current density (J_{max}), maximum inductor current can be easily defined as given in Eq.3 in the core sizing stage [9-10]:

$$I_{L\max} = I_o + \frac{\Delta I}{2} \tag{3}$$

here, I_o is inductor dc current value. Thus, energy stored (W) in the inductor can be given with the Eq.4.

$$W = \frac{1}{2} L I_{L\max}^{2} \tag{4}$$

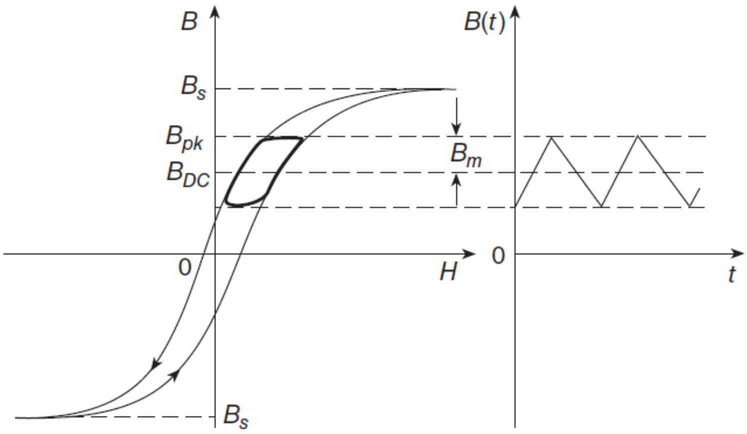

Figure 1. *Flux waveform of the inductor in dc-dc converters [9].*

As product of the core cross-sectional area (A_c) and core window area (W_a), the basic core mechanical parameter (A_p) is defined according to the stored energy in the inductors in Eq.5 [9-10]:

$$A_p = A_c \times W_a = \frac{2W10^4}{K_u J_{\max} B_{pk}} \tag{5}$$

here, K_u is relating parameter of a certain filling ratio in the core window limit as window utilization factor. This factor can have different values depending on the conductor shape like round, foil or Litz, and thus it affects core sizing. Although, the core cross-sectional area is determined to meet the desired design value from the product catalog of the composite core materials, especially core window area is determined according to the conductor shape and the number of turns of the winding at the design stage. Thus, these core mechanical parameters can be arranged compatible each other.

III. SIMULATION STUDIES

In this paper, 3D electromagnetic modeling of the equivalent inductors has been carried out with four different core forms according to the technical properties as given in Table I, and they have been co-simulated in the power electronic circuit given in Fig.2.

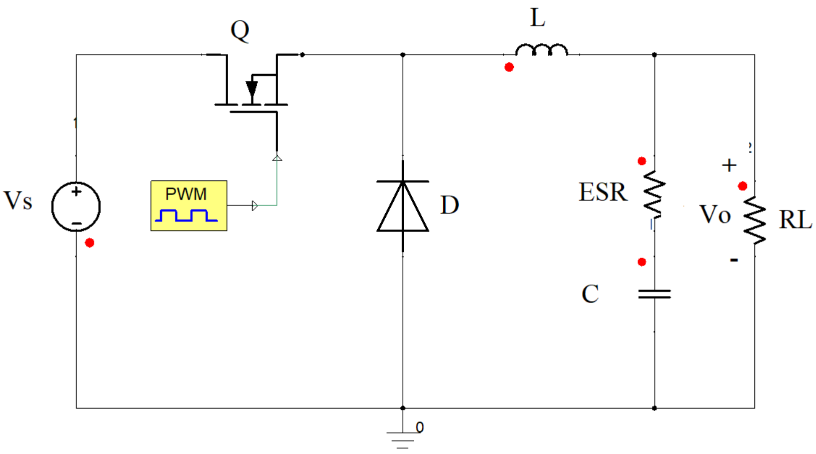

Figure 2. *Power electronic circuit in ANSYS-Simplorer [8].*

Table 1. *Technical Properties of the DC-DC Buck Converter*

Parameters	**Value**
Power Density	5 kW
Input Voltage	400 V
Output Voltage	200 V
Inductance Value	1 mH
Inductor DC Current	25 A
Inductor Current Ripple (ΔIL)	5 A
Switching Frequency	20 kHz
Window Utilization Factor	0.4 (for stranded modeling)
Current Density	2.5 A/mm^2
Conductor Type	Stranded
Conductor Material	Copper
Core Material	Powder (KoolMu 26µ)
Core Forms	EE, block core, pot core and toroid

In order to obtain same inductance values and energy stored with the determined core geometric forms, two pieces of EE cores, four pieces of toroidal cores, and ten pieces of block cores have been combined. Thus, they have been designed as 3D electromagnetic modeling with the FEA software as seen in Fig.3. The mechanical parameters (A_c and W_a) of the designed inductors in different core geometric forms have been given in Table II for the powder core material (Kool-Mu 26µ) [11-12].

Table 2. *Technical specs of the core forms*

Core Forms	**Code**	A_c	W_a	**Number of Core Pieces**	V_c	W_t
EE core	EE8020	3.89 cm^2	11 cm^2	2	144.2 cm^3	0.7 kg
Toroidal core	77908	2.27 cm^2	18 cm^2	4	208.3 cm^3	1 kg
Pot core	P6656	7.2 cm^2	14 cm^2	1	88.2 cm^3	0.42 kg
Block core	B6030	4.5 cm^2	18 cm^2	10	270 cm^3	1.3 kg

Here, two pieces of EE8020 core has been used in EE core structure; four pieces of 77908 toroidal core has been used in toroidal core structures; and ten pieces of B6030 block core has been used in core structures. A P6656 pot core has been used in pot core inductor design [11-12].

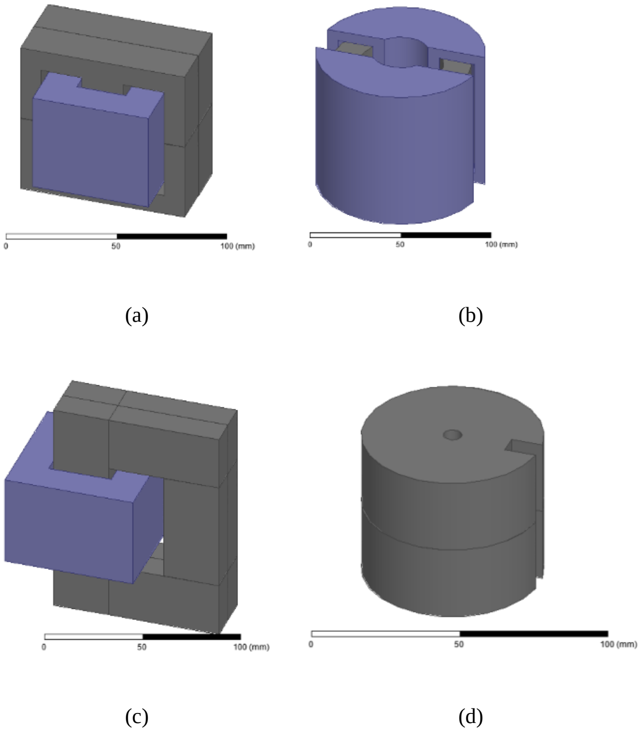

Figure 3. *FEA imagines of the core forms, a) EE core, b) toroidal core, c) block core, d) pot core*

Inductor current waveform is given in Fig.4. Here, the current ripple value is approximately 20%, and the ripple frequency is 20 kHz and equals to the switching frequency. Inductor core flux distributions have been given in Fig.5 for 0.4 T the peak value. The saturation flux density of the inductor designed using Kool-Mu 26µ core material is 1.05 T. Since it has a distributed gapped specification, the air-gapped core design is not required in this study.

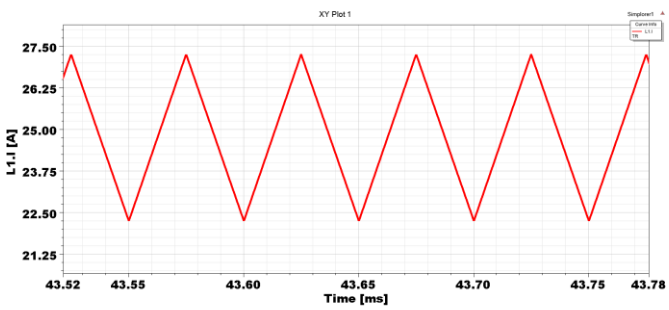

Figure 4. *Inductor current waveform*

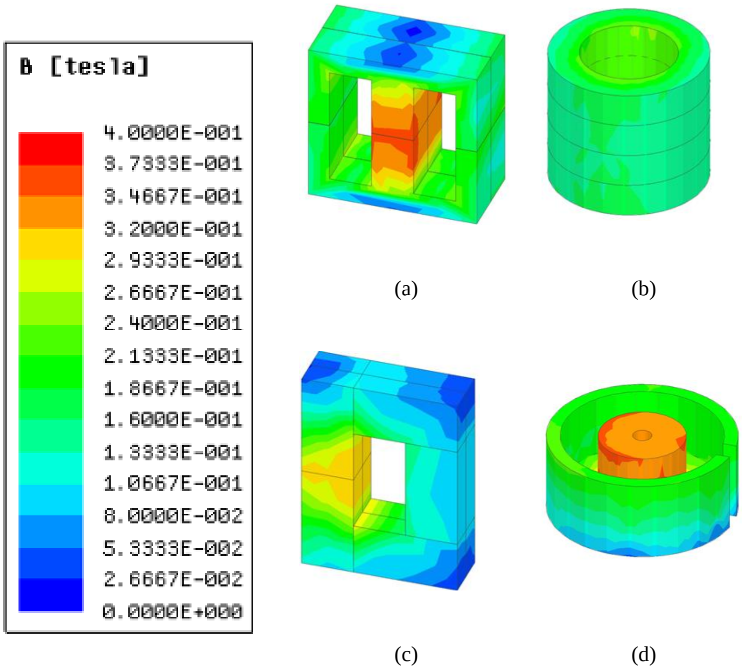

Figure 5. *Flux distributions of the inductor cores for maximum 0.4 T a) EE core, b) toroidal core, c) block core, d) pot core*

A. The flux density comparison

When the flux distributions are examined, it is seen that the flux density is close to the limit of about 0.4 T in the inner parts of the pot core. Similarly, in the EE core structure, the flux density in the center leg exceeded the 0.4 T limit. In the toroid core structure, it is clearly visible that the flux distribution has a homogeneous structure. In the design of block core inductor, the flux density in the core leg is about 0.35 T, but the distribution is not homogeneous. If the windings were equally divided and distributed to both core legs, there would be a more homogeneous flux distribution.

B. Roll-off inductance value comparison

The collapse of the inductance values is an important detail that must be taken into account in the design stage to ensure that the critical inductance value can be achieved. Therefore, the parametric inductance variations of the inductors were determined depend on DC current magnitude with the FEA parametric solver. Thus, the obtained parametric inductance graphs have given in Fig.6.

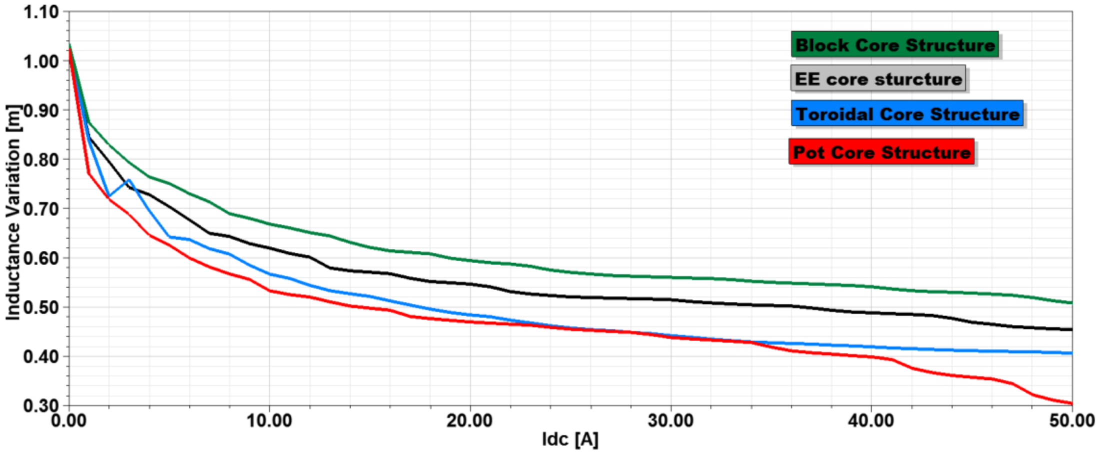

Figure 6. *The parametric inductance variation of the inductors*

The roll-off values of four designed inductors have been determined. It is clear that, it is 58% for the block core structure, 44% for the toroidal core and the pot core structures and 52% for the EE core structure. Thus, it is seen that in terms of the roll-off values (inductance stability), the most suitable design is the block core structure.

C. Power losses comparison

When different core geometries are used, the core and the winding losses that occur in designed inductors have been obtained with the FEA electromagnetic modeling, and they are given in Table 3.

Table 3. *Loss Comparison of the Inductors*

Core Geometry	Core Losses	Winding Losses	Total Losses
EE core	12.2 W	12.5 W	24.7 W
Toroidal core	14.7 W	12.2 W	26.9 W
Pot core	11.5 W	15.3 W	26.8 W
Block core	8.5 W	10.2 W	18.7 W

According to this table, the design with the block core structure provides lowest power losses for both the core losses and the winding losses and resultant the total losses. The highest power loss occurs in the pot core and the toroidal core. Thus, unique designs can be obtained with the block core structures that can better accommodate the availability, power losses and winding utility in the design of large power inductors. In addition, the most unfavorable design when using natural cooling according to the cooling conditions is the inductor with pot core. In the pot core inductors, the windings are located inside the core, and according to the flux distribution, the temperature rise is the much higher in the inner part of the core. Thus, the hotspots that occur both in the core and in the windings are not in contact with the outer surface of the inductor. This is also the case with toroid core structure, but the windings are in contact with the outer surface air convection, and cooling the toroidal inductors is easier than pot core inductors.

D. Design availability comparison

The hardest design in terms of design availability is toroidal core inductors because of the difficulties encountered with the placement of the windings in inductor. In this core structure, designing the carcass to accommodate the windings in the case where the toroid core pieces are placed over the top can cause both time and cost increases. In the pot core structure, the windings are placed in a cylindrical roller which is already available. This is valid for the EE core. However, when more than one EE core is used for large powers as in this study, it is necessary to prepare the carcass for the windings. Design availability in the block core structure depend on the size and number of blocks. Increasing the number of block core units according to the desired power level, increase the core cross sectional area and the window area. Thus, the problems of fitting the windings are also removed and the placement of windings is easier.

IV. CONCLUSION

In this study, designs with four different core geometric forms (the EE core, the toroidal core, the pot core and the block core) were compared for equivalent inductors. Both electromagnetic and mechanical aspects of the core geometry have been investigated in these comparisons. Thus, it is seen that the block core structure is the most suitable design considering the roll-off inductance value, design simplicity, power losses and flux distribution. This structure also suitable to design inductors for high power applications. With the block core units, the original core structures can be designed in desired core section area and window area dimensions. This makes easier to install the windings and to meet the cooling requirements in high power applications.

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