A Novel Concept to Optimize Core Loss in Planar Magnetic Based on an Unbalanced-Flux- Approach

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Keywords

« unbalanced-flux », « balanced-flux », « core loss », « magnetic power factor », « safe operating area».

Abstract

This paper presents a new method to design planar magnetics. Unlike existing magnetics which have a balanced-flux distribution, the proposed method is based on the principle of unbalanced-flux distribution. The Steinmetz model, derived for this design principle, shows that the unbalanced-flux method reduces the core loss by more than 50%. The core loss reduction brings several benefits to planar magnetics such as: high magnetic power factor, better thermal performance and larger safe operating area (SOA). The proposed method is experimentally evaluated and compared with the balanced-flux method. The obtained results confirmed the advantages of the unbalanced-flux method found from the theoretical study. The core loss is decreased by more than 50%, the magnetic power factor is increased by 73% and the SOA is much larger.

Introduction

In recent years, the use of planar magnetics in switching mode power supplies (SMPS) has witnessed a sharp increase thanks to their advantages compared to high profile magnetics. These advantages are centered on two main features: higher thermal performance and lower manufacturing cost in mass production [1]. The emerging of the Wide-band-Gap devises and the natural soft switching of the resonant converters such as LLC and CLLC converters enable to push the switching frequency up to MHz range, which becomes as an indispensable solution to increase the power density and the efficiency of planar magnetics. Certainly, the magnetic components is still considered as the main obstacle to achieve high power density and efficiency for SMPS. To address the matter, several techniques such as matrix transformers, integrated magnetics, fractional turn, flux cancellation, interleaved windings, single and multiphase circuits have been tested at MHz switching frequency. Numerous studies that have been carried out argued that the power density and the efficiency has improved because of increasing the switching frequency to MHz range [2-5]. Undoubtedly, the overall power density and efficiency of the converter has increased. Nevertheless, despite this improvement, the existing works lacks the scientific evidences which prove that the choice of the MHz is what contributes to the increase of the power density and the efficiency of planar magnetics from one side, and that this achievement is not possible at few hundreds frequency range from another side. To briefly assess the MHz solution, we can consider the 1kW-380/12 V LLC converter, which is widely assessed in academic and industrial research. The volume of the realized magnetics in this circuit varies between 11 and 14 cm^3 (Tab. I). According to [6], the same power could be carried out with an ETD39 (13 cm^3) core at 300 kHz in a full-bridge and halfbridge converters. With the assumption that the transformer design for LLC and full-bridge converters is principally the same, several questions prop up to the surface about the efficacy of the MHz switching frequency. The evidence lies in the fact that the increase in the power density and the efficiency was achieved thanks to GaN features (low volume, high efficiency) and not to the magnetic devices. This can be understood by calculating the magnetics-to-converter volume ratio (MCVR) for both kinds of design: the few 100s kHz design and the MHz design. The common estimated MCVR for the few 100s kHz design varies from 30% to 50%, but, it ranges between 50% and 75% for the MHz design (see Tab. I, Fig. 1 and Fig. 2) [2-5].

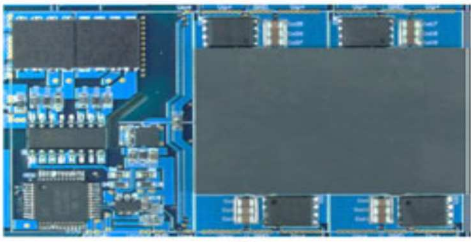

Fig. 1. Planar magnetics size for 1 kW-380/12V LLC converter [2].

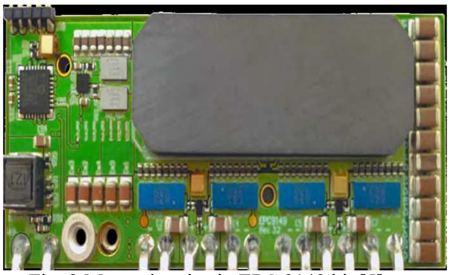

Fig. 2.Magnetics size in EPC 9149 kit [5].

TABLE. I KEY DATA OF SOME BUILT LLC CONVERTERS AT 1 MHZ

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References	[2]	[3]	[4]
Converter power [W]	800	1000	1000
Frequency [MHz]	1	1	1
Magnetics box volume [cm^3]	11	12.44	14.2
Converter Power density [W/cm^3]	54.9	37.6	-
Magnetics density [W/cm^3]	72.72	80.38	70.4
MCVR	0.75	0.47	-

To sum up, increasing the switching frequency is generally beneficial to reduce the core volume, but at the same time, it leads to decrease the efficiency and the power capability as it will be shown in section II. The power capability can be characterized by the magnetic power factor (*MPF*), defined by $MPF = f\, B_m{}^2$. The *MPF* characterizes the maximum power capability of a magnetic core under thermal constraint for a given f and B_m. plotting the MPF of a given core in the (B, f) space with consideration of the thermal and saturation constraints determines its safe operating area (SOA).

The designer needs to have the necessary knowledge about the frequency effect on the core loss and the MPF of the magnetic core in order to optimize his design.

One fundamental principle of the existing magnetics is they have a balanced-flux distribution within the full core length. From our perspectives, this is the main obstacle that limits to improve the magnetics performance, which may ultimately lead to increase the core loss. Definitely, core loss is a detrimental factor to the efficiency and the power density of the magnetic components.

Unlike the balanced-flux approach and the existing design methods, a new method based on the principle of unbalanced-flux distribution is developed. The suggested method helps to reduce significantly the core loss, which in turns increases the power density, the efficiency, the MPF and the thermal performance of the magnetic core.

This paper is structured as follows: section II analyzes the limitations of the MHz approach and presents a new tool to optimize the (f, B) operating region of a given magnetic core. The unbalanced-flux method is developed in section III. The experimental part and the verification with the theoretical results is presented in section IV. Finally, the paper’s major contributions are dealt with in the conclusion.

Principle and analysis of the Unbalanced-flux approach

The principle of the unbalanced-flux design is to generate unequal magnetic flux density between both: the central and the outer parts of the magnetic core. The central part is the central leg around which, the coil is wound to generate the required magnetic flux density. The outer part includes all remaining sections to close the magnetic path. In the balanced-flux design, the magnetic flux density has an approximate uniform density within the full core. One single condition for such design is that the cross section of the outer part is half the one of the central part (Fig. 3). This condition is not applied in the unbalanced-flux method. An example of the unbalanced-flux approach, where the outer and the central cross section are equal, is shown in Fig. 4.

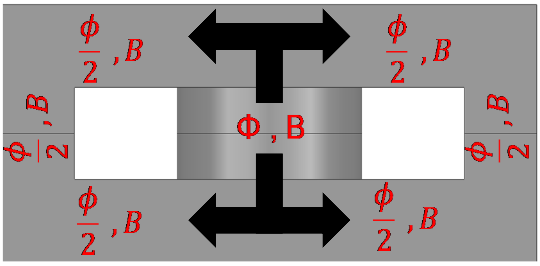


Fig. 3. Φ and B within central and outer parts for a balanced-flux design (A_o=A_c/2).

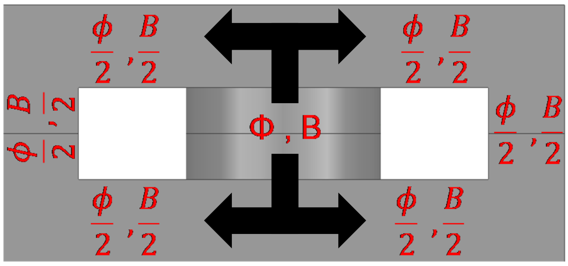


Fig. 4. Φ and B within central and outer parts for unbalanced-flux design, case (A_o=A_c).

One important characteristic of planar magnetics that has a significant influence on the proposed method, is the volume ratio between the outer-part volume and the total volume. This ratio is denoted as δ and expressed as follows:

$$\delta = \frac{V_{co}}{V_{c\_b}} \tag{1}$$

Where V_{c_b} and V_{co} are the total core volume and the outer-part volume respectively of a balanced-flux-based magnetic core. δ depends on the core dimensions. The expression of δ for a typical ETD shape planar core as function of the core dimensions is given by (2) and its variation with respect to the ratio between the window-width and the window-height is shown in Fig. 5. Typical planar cores usually have f/h higher than 2 and Fig.5 clearly shows that δ is higher than 80%.

$$\delta = \frac{V_{co}}{V_{c\_b}} = \frac{h+2f+d}{2\left[h+f+\frac{d}{2}\right]} \tag{2}$$

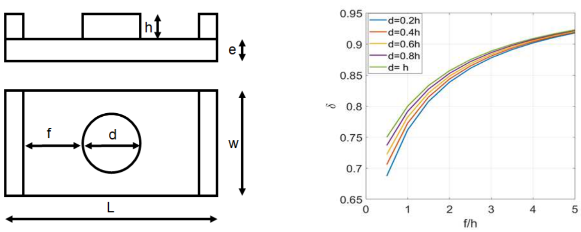


Fig. 5. Core dimensions and variation of δ with respect of f/h and for different d/h.

The Steinmetz equation is a common model to calculate the core loss [7-8].

$$P_{c\_b} = k\, f^{\alpha} {B_m}^{\beta}\, V_{c\_b} \tag{3}$$

B_m is the peak magnetic flux density, (k, α, β) are the Steinmetz parameters. This model could not be applied to the unbalanced-flux design method because the magnetic flux density is not uniform. Thus, it is required to use the superposition technique through which the core loss is calculated for each part and then sum up all the loss terms [9]. Consequently, the total core loss can be expressed as follows:

$$P_{c\_unb} = P_{cc} + P_{co} = k\, f^{\alpha} B_m{}^{\beta}\, \delta\, V_{c\_b} + k\, f^{\alpha} B_{mo}{}^{\beta}\, V_{o\_unb} \tag{4}$$

where P_{c_unb}, P_{cc}, P_{co} are the core loss of: the full core, the central part and the outer part respectively.

The relationship between the magnetic flux density and the cross section of the central and outer parts is given as follows:

$$\emptyset_{mo} = \frac{1}{2}\emptyset_{mc} \tag{5}$$

$$\frac{B_{mo}}{B_m} = \frac{1}{2}\frac{A_c}{A_o} \tag{6}$$

In the unbalanced-flux design, the volume of the outer part increases by a factor of $\left(\frac{2A_o}{A_c}\right)$ compared to the balanced-flux design. Using (1), V_{o_unb} can be written by the following equation:

$$V_{o\_unb} = \delta \left(\frac{2A_o}{A_c}\right) V_{c\_b} \tag{7}$$

Substituting (1), (6) and (7) in (4), we get the core loss of the unbalanced-flux design:

$$P_{c\_unb} = k\, f^{\alpha} B_m{}^{\beta} \left[\left(\left(\frac{A_c}{2\,A_o}\right)^{\beta-1} - 1 \right) \delta + 1 \right] V_{c\_b} \tag{8}$$

The core loss ratio (R_L) between the unbalanced and the balanced flux designs:

$$R_L = \frac{P_{c\_unb}}{P_{c\_b}} = \left(\left(\frac{A_c}{2\,A_o}\right)^{\beta-1} - 1 \right) \delta + 1 \tag{9}$$

Fig.6 shows the evolution of R_L with respect to A_c/A_o for different cases of β. As it can be seen, the core loss can be substantially decreased by reducing A_c/A_o. Obviously, the case ($A_c/A_o = 2$) corresponds to the balanced-flux design where R_L is unit. For $A_c=A_o$, the core loss can be reduced by about 50%. R_L can reach up to 30% for A_c/A_o equals to 0.5. It can also be seen that magnetic materials with high β achieve high R_L. This means, if we consider two balanced-flux magnetic cores (core (X) and core (Y)) of two different materials having respectively β_1 and β_2, where β_1 is bigger than β_2 and let's suppose core (1) has higher core loss. Then, core (1) could have lower loss than core (2) in the unbalanced-flux design as shown in equation (10).

$$R_{Lx} = \frac{P_{c\_unb}(A)}{P_{c\_unb}(B)} = C_b\, \frac{\left(\left(\frac{A_c}{2\,A_o}\right)^{\beta_1-1} - 1 \right) \delta + 1}{\left(\left(\frac{A_c}{2\,A_o}\right)^{\beta_2-1} - 1 \right) \delta + 1} \tag{10}$$

Where $C_b = \frac{P_{c\_b}(A)}{P_{c\_b}(B)}$.

Fig.7 shows the loss ratio R_{Lx} (10) between core (X) and core (Y) for the case (β_1=2.3 and β_2=2) in the unbalanced-flux design. As an example, for C_b=1.1, core (Y) starts to have lower core loss than core (X) in the unbalanced-flux design when A_c/A_o is lower than 1.3.

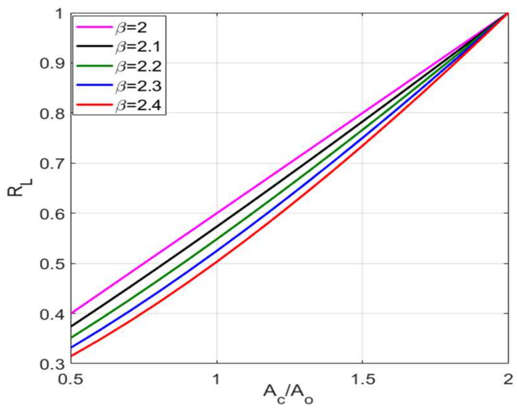


Fig. 6. Variation of R_L with respect to Ac/Ao for different β, δ=0.8.

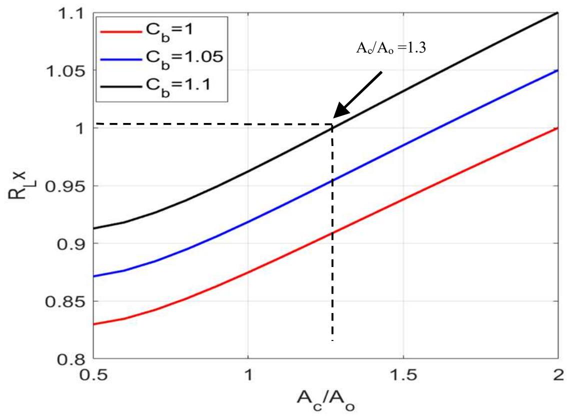


Fig. 7. Variation of R_{Lx} with respect to Ac/Ao for different C_b, δ=0.8, β_1=2.3 and β_2=2.

One disadvantage of the unbalanced flux design is the increase of the core volume. The volume-increase-factor (R_V) is expressed by (11) and its variation as function of A_c/A_o is depicted in Fig.8. For instance, it is about 80% for equal A_c and A_o.

$$R_V = \frac{V_{c\_unb}}{V_{c\_b}} = \left(\left(\frac{2A_o}{A_c}\right) - 1\right) \delta + 1 \tag{11}$$

While the increase in the volume is detrimental to the power density, it is advantageous to the core loss density which is beneficial to the thermal performance. It is written as follow:

$$P_{c\_u} = \frac{P_{c\_unb}}{V_{c\_unb}} = k\, f^{\alpha}\, B_m{}^{\beta}\, \frac{\left[\left(\left(\frac{A_C}{2\,A_O}\right)^{\beta-1} - 1\right)\delta + 1\right]}{\left(\left(\frac{2A_O}{A_C}\right) - 1\right)\delta + 1} \tag{12}$$

The core loss density ratio between the balanced and the unbalanced flux designs (R_{cu}) is given by:

$$R_{cu} = \frac{P_{c\_u}(unbalanced)}{P_{c\_u}(balanced)} = \frac{\left[\left(\left(\frac{A_C}{2\,A_r}\right)^{\beta-1} - 1\right)\delta + 1\right]}{\left(\left(\frac{2A_r}{A_C}\right) - 1\right)\delta + 1} \tag{13}$$

Despite the increase in the core volume, the core loss density has significantly decreased as given by (13) and Fig. 9. As an example, R_{cu} decreases by about 70% for A_c/A_o equals to 1. The core loss density reduction has a huge effect on improving the thermal performance of the magnetic core. Eventually, it enables to extend the (SOA) in comparison to the balanced flux design.

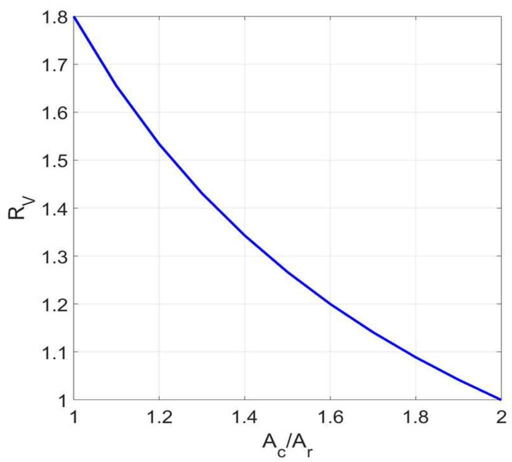


Fig. 8. Variation of R_V with respect to Ac/Ao, δ=0.8.

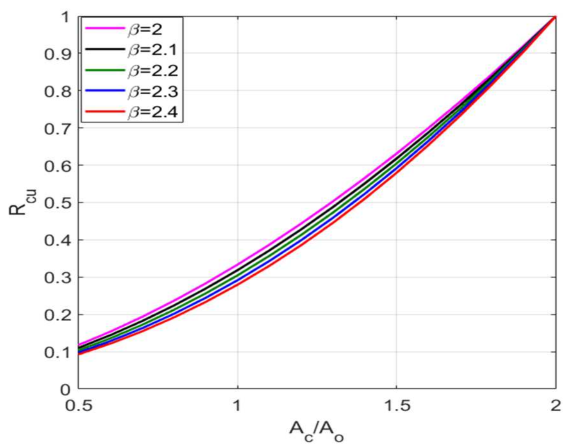


Fig. 9.Variation of R_{cu} R_{cu} with respect to Ac/Ao for different β, δ=0.8.

The proposed method enables to significantly reduce the core loss in comparison to the balanced-flux design. The reduction factor depends of the ratio between the cross section of the central and the outer parts. It is about 50% when both cross sections are designed equally. The loss reduction also depends on β. magnetic materials with high β have more capability to reduce the core loss. Despite the volume increase in the proposed design, the core loss density has significantly decreased. It brings several important advantages such as high power capability, better thermal performance and wider SOA. These advantages will be experimentally evaluated in the following section.

Experimental verification and discussion

In this section, the evaluation of the proposed method is established. To verify the proposed magnetics design, two unbalanced-flux magnetic cores are built (core2 and core3) and their performances are compared to a balanced-flux magnetic core (core1) (Fig. 10). The details of the tested cores dimensions are given in Tab. II and its magnetic material is DMR96 [9]. To achieve a reasonable comparison of the proposed method, we have designed core2 with nearly equal volume to core1 while core3 has twice the volume of core1. The shape of Core1 was chosen in a way it has better thermal performance compared to core2 and core3 as explained in the following remarks:

•Core1 and core 2 have approximately same volume, however core1 has larger base surface and slightly lower height.

•Core3 is a two integrated transformers. It has double the core volume to core1 but its base surface is only 1.7 time the base surface of core1.

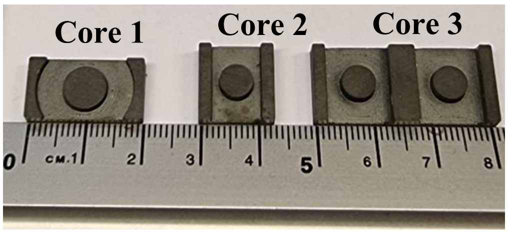


Fig. 10. Photo of the tested cores.

TABLE. II GEOMETRY CHARACTERISTICS OF THE TESTED MAGNETIC CORES

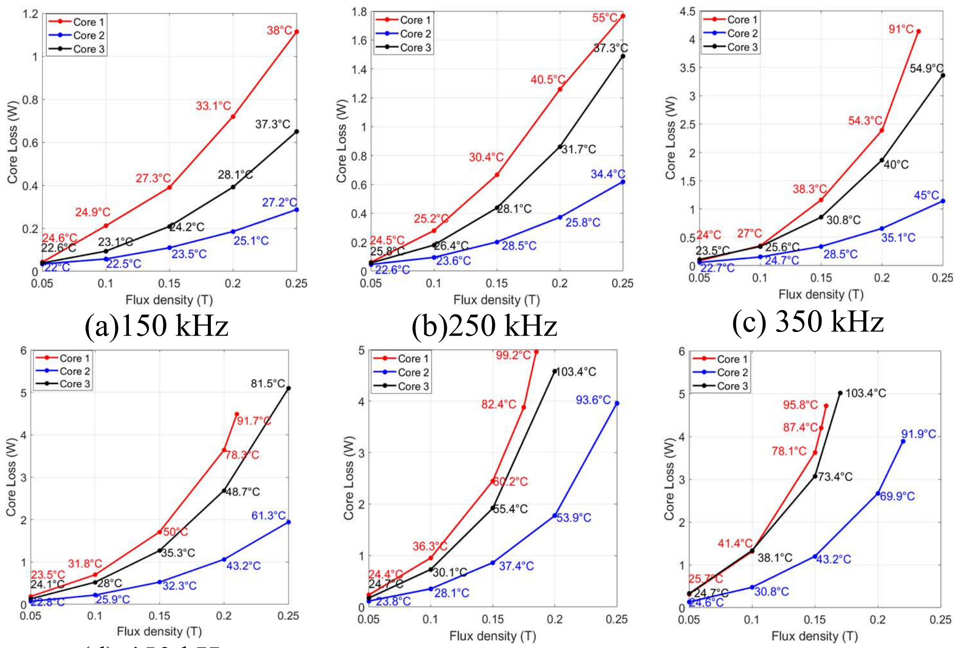
	Core 1		Core 2	Core 3
Flux	balanced		unbalanced	
Volume(mm^3)	1284		1114	2254
A_c (mm^2)	47.8		28.3	2*28.3
A_o (mm^2)	24.75		28.3	2*28.3
δ	0.9		0.97	0.97
Base area (mm^2)	226.5		192.7	384

The comparison criteria of this study are: core loss, temperature rise, the MPF and the SOA. For each core, we have applied the same magnetic flux density at a specific frequency and we measure its core loss and temperature using a fast calorimetric measurement technique. This measurement technique was used to measure switching devices and magnetic core loss and the reader is referred to [10-12] for more details about its principle. In the following, we discuss the comparison results:

Core loss and temperature evaluation

•***Core1 VS Core2***: though core2 has nearly same volume as core1, its core loss is much smaller as shown in Fig.11. It can also be noticed that core2 has also much lower temperature. Fig.12 (a) shows that the core loss density of the balanced flux design is 2 to 3.5 times the core loss density of the unbalanced-flux design over the flux density range [0.1-0.25] T.

Concerning the thermal behavior, it is clear that the core2 has achieved much better thermal performance than core1. For instance, in case (f) for B=0.15 T, the registered temperature for core2 is 43.2°C, however it peaks at 78.2°C for core1 (Fig.11). It should be clearly noticed that the main reason, for the low temperature registered for core2, is the low core loss and certainly is not because of having lower thermal resistance. This can be synthesized by comparing the temperature of both cores at equal core loss. For instance, we can take the case (0.15T, 650 kHz) for core2 and the case (0.1T, 650 kHz) for core1, in which both cores have approximately the same core loss and nearly same temperature.



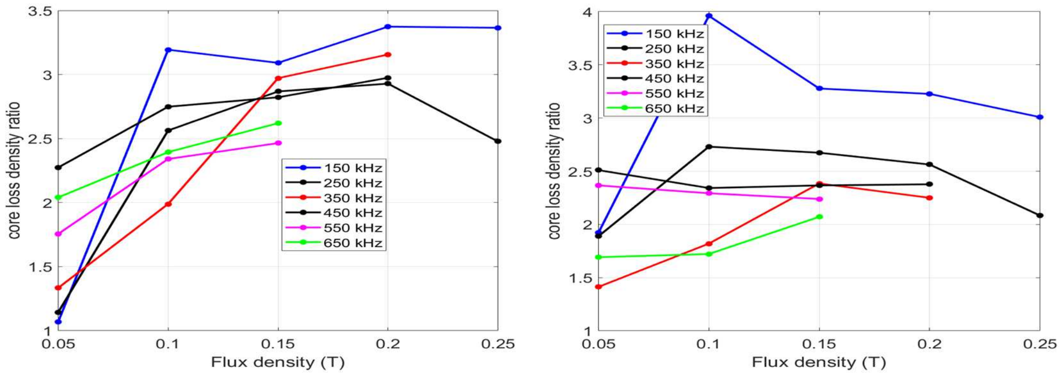
(a)150 kHz (b)250 kHz (c) 350 kHz

(d) 450 kHz (d) 550 kHz (d) 650 kHz

Fig. 11. Measured core loss and temperature of the tested cores.

•***Core1 VS Core3***: in general, core3 has achieved lower core loss and lower temperature rise despite its volume is twice the volume of core1. Fig.12 (b) shows that the core loss density ratio between the balanced and the unbalanced flux designs varies between 2 and 3.5 times in the interval [0.1-0.25] T. Three exceptions are registered for 0.1T at 650, 150 and 350 kHz, which could be due to some measurement errors. It can also be seen that core has achieved lower temperature than core1 at same core loss. As an example, at (0.1 T, 650 kHz), the core loss are same, but the temperature for core1 and core3 are 41.4 °C and 38.1 °C respectively. This means that core3 has lower effective thermal resistance than core1 despite that core1 has a higher outer surface-to-volume ratio.

In the previous comparison cases, the registered core loss density ratio, at 0.05 T, is smaller than 2. This is due to the core loss behavior at low temperature and low flux density. We can also notice that the loss density ratio depends on B and f. This aspect is very important and will be furtherly investigated in future works.



(a) Core1/Core2 (b) Core1/Core3

Fig. 12. Core loss density ratio between balanced and unbalanced flux designs

MPF and SOA evaluation

The core loss for core 1, core2 and core3 are measured over the frequency range [0.15-0.65] MHz and the corresponding MPF and SOA are given in Fig.13 and Fig.14. The obtained results show that the unbalanced-flux method enables to increase significantly the MPF. The MPF_{max} of core2 and core3 peaked at 34.4 MHz.B^2 and 28.1 MHz.B^2 respectively compared to 19.8 MHz.B^2 for core1. This means that core2 has 73% more power capability than core1 despite it has lower base surface and slightly lower volume. Additionally, despite the previous advantages accounted for core1, core2 has achieved much better performance such as, lower core loss, higher MPF and larger SOA. Fig.13 shows the limits of the SOA for core2 and core1. Similarly, Fig.14 shows the SOA for core3 to core1. As it can be seen, the SOA has been considerably increased which gives the designer more freedom to select the suitable combination of (B, f) in order to meet with the design requirements. Higher MPF and larger SOA definitely enable to reduce the number of turns which in turns can bring down the winding loss.

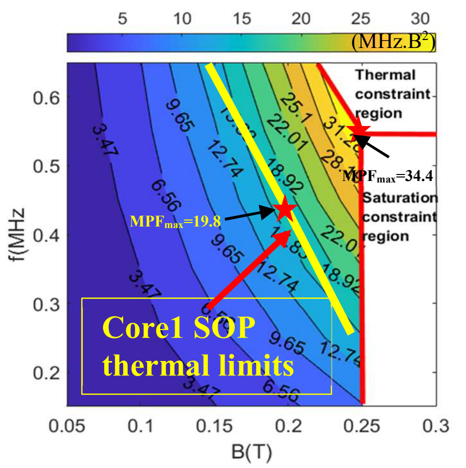


Fig. 13. MPF and SOA for core2 vs core1.

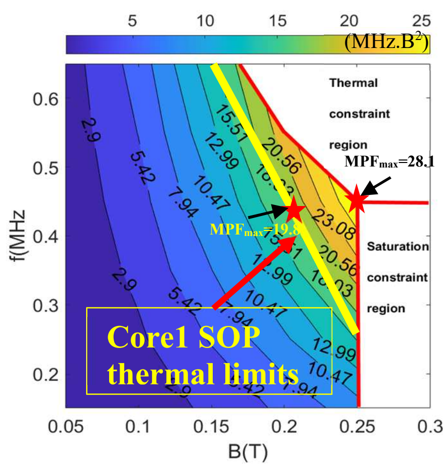


Fig. 14. MPF and SOA for core3 vs core1.

Conclusion

This paper has introduced a new design method based on the principle of the unbalanced-flux distribution in order to improve the power density and the efficiency of planar magnetics. Although these objectives are not dealt with in this work, the benefits offered by the proposed method such as low core loss, better thermal performance, high magnetic power factor (MPF) and larger safe operating area can only help to boost the efficiency and the power density. The theoretical and the experimental results, performed on the tested cores, have shown that core loss can be minimized by more than 50%, which in turn helps to improve the MPF by 73% and to enlarge significantly the SOP and the thermal performance. This study has opened a new direction in the design of magnetic components, however, more results and investigations need to be addressed. It will concern the optimization approach, the thermal modeling and more importantly its applications on the SMPS and how it affects the efficiency and the power density compared to the literature.

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