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Analysis of High Frequency Effects in the Inductors and Transformers Windings for Switching Converters Application.

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Abstract

Power electronics switching converters widely utilize high-frequency magnetic components; inductors and transformers. The efficiency and power density of such converters depend on the design technology of the windings to minimize the high-frequency losses. This paper presents an analytical investigation of the skin and proximity effects in the windings, it simulates the AC resistance as a function of the layer thickness. More particularly, the theoretical analysis and simulation of copper foil and Litz windings for high frequency applications are reviewed and discussed. Also, the performance is compared on the basis of the AC resistance factor and leakage inductance. The magnetic components are optimally designed with low AC resistance and leakage inductance to yield higher efficiency and high density switching converters.

I. Introduction

It is significant to investigate and characterize power electronic circuits which are widely used in modern electric power systems. Nonetheless, inductors and transformers are considered crucial elements in such circuits and systems. Inductors are dynamic storage devices and usually used to store electric energy for various operating modes in converters' circuits. Also, inductors act as filters for switched current waveforms. In snubber circuits, inductors limit the rate of change of current and provide transient current limiting. However, transformers are energy transfer devices which step up and down voltages and currents, in addition transformers provide electrical isolation between electrical circuits. Also, they provide impedance matching to yield maximum power transfer between circuits, and they can also sense voltages and currents [1]. General definitions and essential concepts are discussed and reviewed in the introduction.

The electric transformer is built of two or more mutually coupled windings placed on an appropriate magnetic core. The transformer size is inversely proportional to its operating frequency. When the primary winding is supplied by an alternative voltage source, a changing magnetic flux field is produced according to Faraday's law of electromagnetic induction. Normally there is no air gap in the magnetic core to obtain high flux which depends on the core reluctance. A small air gap may be produced during the manufacturing process, it obtains an advantage of controlling the inrush current magnitude. The magnetic flux is coupled to the secondary winding in the transformer, and so the induced output voltage is obtained. The design of the transformer core usually considers reducing the eddy current loss by using iron laminations. For high frequency transformers the core is made of ferrites or ferromagnetic alloys. The practical transformer model considers the following factors: magnetizing

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current, core loss, winding resistance, and magnetic leakage flux. Moreover, winding capacitance may be significant for power electronics applications at high frequencies resonance conditions [1].

Operating at higher frequency allows to design small size inductors and transformers. However, losses have to be minimized, and heat dissipation should be considered as well. It's known that high-frequency operation for power electronics applications results in increased AC loss in windings because of skin and proximity effects [1]. The range of operating frequency for recent power supplies is 50 to 500 kHz and so skin and proximity effects must be considered. Proximity effect is caused by eddy currents induced in a wire due to the alternating magnetic field of other conductors in the vicinity. However, eddy currents cause a distortion of the current density as shown in Fig. 1. Then to minimize the eddy currents in the magnet wires, the ratio of the AC resistance to the DC resistance should be decreased.

The traditional role of the transformer considers sinusoidal voltage excitation while in power electronics applications the analysis is expanded to include frequencies well above typical mains frequencies, in addition to non-sinusoidal excitation waveforms which have to be considered. In high frequency operation, it is significant to minimize losses due to the leakage inductance, so the magnetic leakage can be neglected when the transformer is appropriately designed.

Foil is used for magnet wire to obtain the main advantage of fill factor, which is mainly designed in high current, high frequency DC to DC converters. One of the main reasons for operating in high frequency is reducing the size because the power transformer is the largest component in the system. High frequency transformer design procedure consider size, weight, cost, efficiency, rated power, frequency, and temperature rise. However, operating transformers at high frequencies requires utilizing smaller wires to mitigate the skin effect. More parallel strands of wire or Litz wires are used to yield the required wire size for higher current density. The use of small wire has a large effect on the fill factor. Designing transformers and inductors with foil is a very laborious task for several advanced applications [2].

The impact of proximity effect is at the minimum level for a transformer with a single layer secondary, therefore transformers would be designed with a minimum of layers. The design with a minimum of layers can be produced by selecting a core with a long narrow window the same way as picking a core for a minimum of leakage inductance. High-frequency transformers with multiple layers have more issues with proximity effect. The eddy current losses caused by the proximity effect rise exponentially with layers number. A core with a long winding length to a winding height ratio, can be used to reduce the number of layers to a minimum [2-4].

The conversion circuit in power electronics uses transformers which are usually the heaviest and bulkiest component in the circuit. So, the design of such transformers has an important influence on the overall system weight, power conversion efficiency, and cost. Because of the interdependence and interaction of these parameters, judicious trade-offs are necessary to achieve design optimization. Therefore, several constraints have to be considered in the design of different transformers. One of these constraints is the output power, P_0 (operating voltage multiplied by maximum current demand) in that the secondary winding must be capable of delivering to the load within specified regulation limits. Another constraint relates to minimum efficiency of operation, which is dependent upon the maximum power allowed loss in the transformer. Still another constraint defines the maximum permissible temperature rise for the transformer when it is used in a specified temperature environment [5-8].

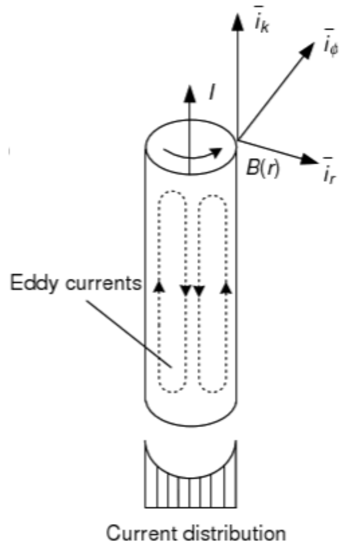

Figure 1. Eddy currents in a round conductor [1].

Transformer efficiency, regulation, and temperature rise are all interrelated. Not all of the input power to the transformer is delivered to the load. The difference between input power and output power is converted into heat. This power loss can be broken down into two components: core loss, P_{fe}, and copper loss, P_{cu}. The core loss is a fixed loss, but the copper loss is a variable loss that is related to the load current. The copper loss increases by the square of the current which is termed a quadratic loss. Maximum efficiency is achieved when the fixed loss is equal to the quadratic loss at rated load [9, 10].

II. Skin and Proximity Effects.

For direct current and at low frequencies; the current carried by a conductor is distributed uniformly across the conductor, while at higher frequencies the concentration of current is near the wire surface. Since the ratio of effective alternating current resistance to direct current is greater than unity, we need to consider skin effect at high frequency. So conductor size has to be carefully evaluated when designing any winding for power electronics switching converters. The skin depth (ϵ or δ) is defined as the distance below the surface, where the current density has fallen to 37 percent of its value at the surface [2].

$$\epsilon = \frac{6.62}{\sqrt{f}} K \ , \ cm \tag{1}$$

where, f is the frequency in hertz, and K is a factor equal to 1 for copper.
When selecting the wire for high frequency, it has to be selected where the relationship between the AC resistance and the DC resistance is 1. Using multistrands of wire is recommended instead of just one large strand wire for the winding which operate at high frequency. Next equations describe how to choose the proper wire size in order to minimize the skin effect for a specified frequency [2].

Skin effect problems in inductors are like those in transformers. The skin effect depends on the value of AC current in the inductor. The high frequency inductor current has two components: the DC current, and the AC current. The DC current travels in the center of the conductor, while the AC travels on the surface of the conductor [2]. A good approximation of the AC and DC resistances of a round conductor of radius r_0 is given in equation 2 [1], and the resistance ratio is shown in Fig. 2.

$$R_{ac} = R_{dc}\left[1 + \frac{\left({}^{r_0}/_{\delta}\right)^4}{48+0.8\left({}^{r_0}/_{\delta}\right)^4}\right] \quad (2)$$

where, δ *is the skin depth.*

In the winding of an inductor or a transformer, the distribution of current in a layer can be affected by the other layer's current distribution. The proximity effect factor has been explained and derived in the references from the principles based on foil layers and by extending the window full height. The concept of porosity which considers the window length and copper equivalent area is also explained. The ratio of AC resistance to DC resistance for proximity effect with sinusoidal excitation is given by equation 3, which is the proximity effect factor (K_p).

$$K_p = \frac{R_{ac}}{R_{dc}} = \varDelta\left[\frac{\sinh 2\varDelta + \sin 2\varDelta}{\cosh 2\varDelta - \cos 2\varDelta} + \frac{2(p^2-1)}{3}\frac{\sinh \varDelta - \sin \varDelta}{\cosh \varDelta + \cos \varDelta}\right] \quad (3)$$

where, $\varDelta = d/\delta_0$, d is layer thickness, and δ_0 is skin depth at fundamental frequency.

From this equation it is clear that as the layers number increases, the AC resistance increases too for a given layer thickness and frequency. The AC to DC resistance ratio due to proximity effect for different number of layers with sinusoidal excitation is presented by Fig.3. As the number of layers increases the resistances ratio clearly increases for the given layer thickness and frequency.

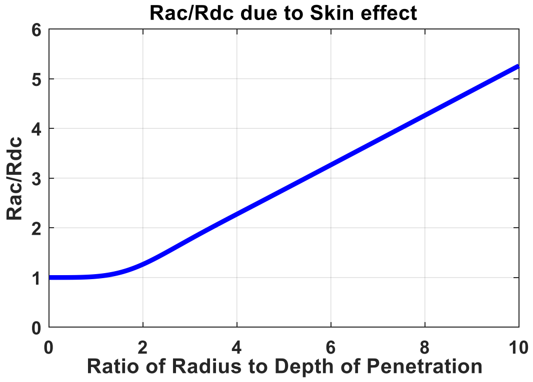

Figure 2. R_{ac}/R_{dc} due to skin effect.

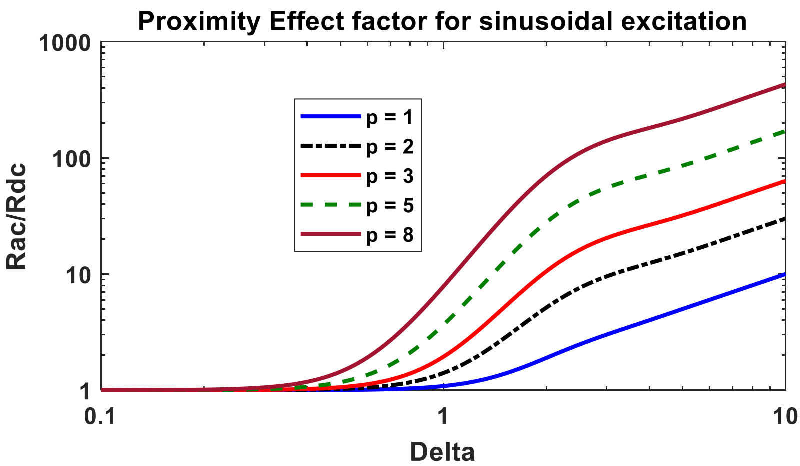

Figure 3. Proximity effect for different number of layers.

III. Interleaving the windings to reduce losses.

The electric field intensity and the magnetic field intensity magnitude affect the current density in the layers, and by interleaving the windings in a transformer (alternating the primary and secondary layers) the current density distribution is improved. Therefore, the proximity effect loss is significantly reduced [1]. The primary and secondary layers of the transformer are interleaved to improve the copper loss, as the magnetomotive force (MMF) shape is adjusted. Also, partial interleaving yields partial improvement in reducing proximity effect [3].

Then power electronic applications proximity effect has to be considered for the non-sinusoidal waveforms. The ratio of effective resistance to DC resistance $R_{\text{eff}}/R_{\text{dc}}$ in a copper foil of thickness d carrying the pulsed current waveform shown in Fig. 4 is calculated.

The Fourier series of $i(t)$ is:

$$\begin{aligned} i(t) &= I_{\text{dc}} + \hat{I}_1 \sin \omega t + \hat{I}_2 \sin 2\omega t + \ldots \\ &= \frac{I_o D}{2} + \sum_{n=1}^{\infty} I_o \operatorname{sinc}^2\left(\frac{n\pi D}{2}\right) \cos(n\,\omega\,t) \end{aligned} \tag{4}$$

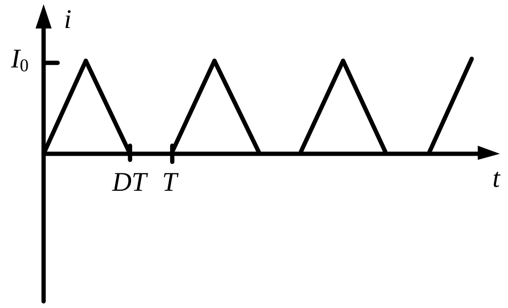

Figure 4. Triangular current waveform.

The rms value of the current is $I_{\text{rms}} = I_o \sqrt{\dfrac{D}{3}}$.

The proximity effect factor due to $i(t)$ is found from equation 5.

$$\frac{R_{\text{eff}}}{R_{\text{dc}}} = \frac{I_{\text{dc}}^2 + \sum_{n=1}^{\infty} k_{p_n} I_n^2}{I_{\text{rms}}{}^2} = \frac{\left(\dfrac{I_o D}{2}\right)^2 + \sum_{n=1}^{\infty} k_{p_n} \left[\dfrac{I_o \operatorname{sinc}^2\left(\dfrac{n\pi D}{2}\right)}{\sqrt{2}}\right]^2}{\left[I_o \sqrt{\dfrac{D}{3}}\right]^2} = \frac{\left(\dfrac{D}{2}\right)^2 + \sum_{n=1}^{\infty} k_{p_n} \left[\dfrac{\operatorname{sinc}^2\left(\dfrac{n\pi D}{2}\right)}{\sqrt{2}}\right]^2}{\sqrt{\dfrac{D}{3}}} \tag{5}$$

k_{p_n} is the proximity effect factor due to the n^{th} harmonic found from equation 3, while the ratio $R_{\text{eff}}/R_{\delta}$ is found from equation 6.

$$\frac{R_{\text{eff}}}{R_{\delta}}=\frac{\frac{R_{eff}}{R_{dc}}}{\Delta}=\frac{\left(\frac{D}{2}\right)^{2}+\sum_{n=1}^{\infty}k_{p_n}\left[\frac{\text{sinc}^{2}\left(\frac{n\pi D}{2}\right)}{\sqrt{2}}\right]^{2}}{\Delta\sqrt{\frac{D}{3}}} \tag{6}$$

The AC resistance of multilayer transformer windings with arbitrary current waveforms was discussed and optimized in [11]. A new formula for the optimum foil or layer thickness without the need for Fourier coefficients and calculations at harmonic frequencies has been presented and analyzed. Leakage inductance in transformer multilayer windings has to be considered in high frequency recent applications. An advanced technology of planar Litz structure is explained in [12] to reduce the high-frequency losses in planar windings. The planar Litz type conductor is constructed by weaving many narrow strands along the length of the conductor in such a way that each strand can be subjected to every point of the winding cross sectional areas. So, the current distribution on conductors can be uniform. The finite-element modeling (FEM) showed that the planar Litz structure is effective in reducing AC resistance in the appropriate operating frequency range by reducing the skin and proximity effects. The measured results in the experimental prototypes showed that the reduction of AC resistance by using Litz winding instead of solid conductor could be as high as 30%. Therefore, the planar Litz structure is very promising for applications with planar magnetic component designs and yields lower AC resistance than a solid conductor over a specific frequency range [12].

Planar inductors with embedded PCB windings suffer higher winding loss due to the accumulation of magnetomotive force (MMF) and the skin effect compared to conventional Litz wire-based designs. One approach to reduce winding loss is to interleave windings of different phases in a form of coupled inductor. Reference [13] proposed a winding interleaving approach which extends the lower limit of coupling coefficient to zero while still maintaining the benefits of winding interleaving. Furthermore, balance technique is integrated with PCB winding-based inductors for common-mode (CM) noise suppression. A 2.2 kW GaN-device based totem-pole power-factor correction (PFC) converter is demonstrated. The proposed PCB-based inductor structure achieved a peak efficiency of 99% [13].

To summarize the future research direction, more significant relevant references are cited; the comparative analysis of copper foil and Litz wound transformers for high frequency applications including the skin and proximity effects due to eddy currents are analyzed. The design and selection of foil and Litz windings for a high frequency transformer is discussed, and the designed transformers are compared on the basis of their AC resistance factor and leakage inductance. A method to reduce the AC resistance factor and leakage inductance for the two winding techniques is also proposed in [14]. Further research studies about magnetics which form an integral part of power electronics based energy conversion systems for power conditioning are pointed out in [15]. The challenge lies in designing high frequency magnetics with minimal loss. Therefore, the maximum temperature at higher power densities does not affect the insulation, conductors or the core of the magnetic component [15].

48V power architecture has attracted more interest in data centers as it offers more efficient architecture on the implementation of the DC-DC stage of the power supply system. Approximately a 99% efficient 400 V-48 V LLC converter with a very high power density and low profile fully integrated on PCB is presented in [16]. A matrix of four resonant inductors is also designed to reduce the proximity effect between inductor windings and reduce inductor PCB winding loss. The converter integrates a matrix of four transformers and resonant inductors on a 6-layer PCB and single-core for easier manufacturability and lower cost [16].

Foil windings are preferable in high-current high-power inductors to realize compact designs and to reduce DC-current losses. At high frequency, however, proximity effect will cause a very significant increase in AC resistance in multi-layer windings, and lead to high AC winding losses. An inner auxiliary winding, which is connected in parallel with an outer main winding is used in [17]. The auxiliary winding is optimally designed with low AC resistance and leakage inductance to carry the ac current while the outer winding is designed for the large DC current. Detailed analysis and design of a 350 A, 10 kW inductor with the proposed technique are presented with discussions. Experimental results of a prototype 350 A inductor, used in a 10 kW fuel cell DC-DC converter, are also presented to demonstrate the validity of the proposed technique and its superior performance [17].

IV. Simulation and Discussion.

In order to improve the efficiency of the switching converters which includes reducing the losses of the inductors and transformers when operating at high frequency, the effective resistance should be minimized for any layer thickness. The optimum thickness for the resistances ratio is illustrated by Fig. 5. As it can be noticed, for any number of layer the minimum resistance is shown for a specific optimum layer thickness. The expression is plotted in Fig. 6 which shows the locus of the minimum AC resistance for different number of layers (*p*) from 1 to 8. For each value of *p* in Fig. 6, there is an optimum value of Δ where the AC resistance of the winding is minimum. These optimum points lie on the line marked minima. The simulation work was performed using MATLAB m-file scripts, and the illustrated results in this paper have not been presented in the previous researches.

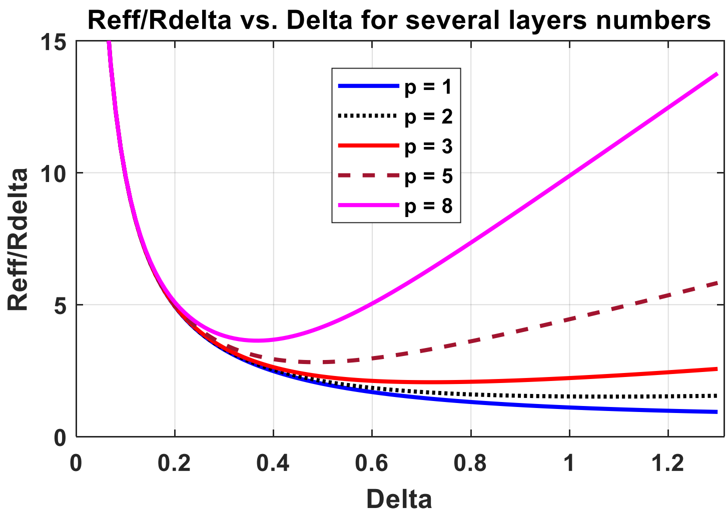

Figure 5. The effective resistance versus the layer thickness for different number of layers.

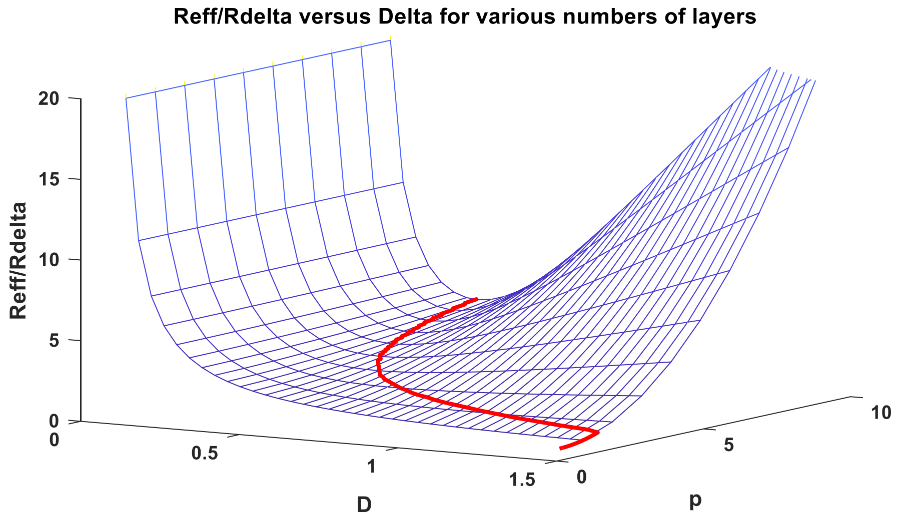

Figure 6. Plot of R_{eff}/R_{δ} versus Δ for various numbers of layers.

Inductors and transformers are essential components in switching converters, which are commonly used in power electronics to convert electrical energy efficiently. At high frequencies, these components can experience significant high-frequency losses, which affect the overall efficiency and power density of the converter. The efficiency and power density of these converters are heavily influenced by the design of the windings in inductors and transformers. Proper winding design helps minimize the high-frequency losses, leading to more efficient power conversion.

The paper presents an analytical investigation of skin and proximity effects, simulating how the AC resistance of windings varies as a function of layer thickness. Layer thickness plays a key role in minimizing losses due to these high-frequency effects. The results discuss an analytical investigation into the design of magnetic components (inductors and transformers) used in power electronics switching converters which operate at high frequencies. Also, the paper reviews and compares the performance of copper foil windings and Litz wire windings for high-frequency applications.

Copper foil windings are made of flat copper strips and are often used in high-frequency transformers and inductors to reduce skin effect. However, Litz wire consists of many thin, insulated strands of wire twisted together, which helps reduce both the skin and proximity effects, making it highly effective for high-frequency use.

The paper investigates how skin and proximity effects influence the performance of high-frequency windings in power electronics converters. By analyzing and simulating copper foil and Litz wire windings, the performance in terms of AC resistance and leakage inductance were compared. The goal is to design magnetic components that minimize these losses, leading to more efficient and higher-density switching converters for power electronics applications.The findings could help in designing switching converters with better performance, making them more efficient and compact, which is crucial in many power electronics applications like renewable energy systems, electric vehicles, and smart grid networks.

V. Conclusion

Modern power electronics switching converters are deployed in many recent significant applications for improved efficiency, density, and reliability. Skin and proximity effects in the windings are significantly increased when compared with the operation at 50/60 Hz; therefore, the wire has to be carefully selected. High frequency effects on the windings of inductors and transformers in power electronics converters are investigated, and analyzed in this paper. The AC to DC resistances ratio due to proximity effect for different number of layers is investigated. Also, the minimum resistance for any number of layers is described. Essential equations to minimize the AC resistance factor and leakage inductance for the magnetic components are reviewed and simulated.

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تحليل تأثيرات الترددات العالية للملفات والمحولات المستخدمة في تطبيقات مبدلات القدرة الكهربائية.

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الكلمات المفتاحية: الترددات العالية، الملفات، تأثيرات القشرة والتقارب، المفاقيد.

الملخص

تستخدم مبدلات إلكترونيات القدرة المكونات المغناطيسية عالية التردد (المحاثات والمحولات) على نطاق واسع. وتعتمد كفاءة وكثافة الطاقة لهذه المبدلات على تكنولوجيا تصميم اللفات لتقليل خسائر التردد العالي. يقدم هذا البحث دراسة تحليلية لتأثيرات القشرة والقرب في اللفات، حيث يحاكي مقاومة التيار المتردد كدالة لسمك الطبقة. وبشكل أكثر تحديدًا، تمت مراجعة ومناقشة التحليل النظري ومحاكاة رقائق النحاس ولفائف ليتز للتطبيقات عالية التردد. أيضًا، تمت مقارنة الأداء على أساس عامل مقاومة التيار المتردد ومحاثة التسرب. كما تم تصميم المكونات المغناطيسية على النحو الأمثل لتكون قيمة كلا من مقاومة التيار المتردد ومحاثة التسرب منخفضتين للحصول على مبدلات قدرة ذات كفاءة أعلى وبكثافة عالية.