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Impact of the fringing effect on temperature distribution in windings and physical properties of toroidal ferrite inductors with a dual air gap

Abstract

This paper examines the impact of the fringing field at an air gap on the temperature distribution, power loss and other properties of toroidal ferrite inductors with a dual air gap. An air gap constitutes a discontinuity in a magnetic path of an inductor, representing significantly greater reluctance to magnetic flux than that of a ferrite core. The magnetic flux does not cross the air gap in straight lines, but fringes out into the surrounding medium causing electromagnetic interactions with the copper winding enclosing the air gap. This phenomenon is a function of the air gap and the windings geometry as well as the operating frequency. The net effect of the fringing flux is to shorten the gap and to decrease the effective reluctance of the magnetic path. Consequently, coils wound on magnetic cores with a relatively large single air gap, thus with an exacerbated fringing effect, exhibit higher inductance than those with multiple, quasi-distributed or distributed air gaps of the same effective length as the discrete one. The presented research investigates the effects of splitting a discrete air gap on the electromagnetic and thermal properties of toroidal ferrite inductors.

Keywords: fringing effect, ferrite inductors, IR thermography, fringing-effect factor, power losses.

1. Introduction

The fringing effect is particularly germane to magnetic components, where conversion of power requires an air gap in the magnetic path of the component in order to handle magnetic flux. Air gaps are inherent to flyback transformers, single wound ferrite inductors, multi-wound ferrite inductors with no magnetic flux cancellation, PFC chokes and frequently LLC transformers where the ratio of primary inductance to resonance inductance is controlled by the size of the air gap [1]. The presence of an air gap prevents the core from reaching its saturation point, shedding its magnetic properties and becoming effectively an air core. Air gaps are also inserted into magnetic cores in order to have better control over changes in permeability due to temperature or excitation voltage. A relatively small gap, with a size of micrometres, will cause a so-called shearing of the B-H loop (see Fig. 3), significantly reducing and stabilizing effective permeability [2]. The fringing effect is especially evident for large gaps, as the magnetic flux, so far concentrated in the magnetic core, does not cross the air gap in straight lines but enters far into the neighbouring areas, crosses the coil, and induces voltage within it, which in turn causes eddy currents to occur. These eddy currents tend to counteract the useful current, thus reducing the effective area of the conductor, increasing its AC resistance (R_{AC}) as well as causing power loss, which in turn causes localized heating [3, 4]. This phenomenon manifests itself in the form of so-called hot spots (Fig.1) and can be readily analysed by the utilization of IR thermography [5, 6]. The fringing flux is a function of the size of the air gap, the cross-sectional area of the core, and the geometry of the windings, as well as the operating frequency. As it effectively shortens the gap, the total reluctance of the magnetic path is reduced, and the resulting inductance of a given magnetic component is larger than that determined without taking the fringing flux into consideration. The shortening of the gap may result in premature saturation of the core material if driven at a high level of magnetic flux density. There are a number of applicable methods for the reduction of the effects of the fringing field: spacing the windings away from the gap; replacing a portion of the core with a material of low permeability, thus forming a distributed air gap, ; constructing the windings with a so-called Litz wire; or splitting a discrete air gap into a number of smaller gaps. This paper examines the effects of splitting a single air gap into two separate gaps.

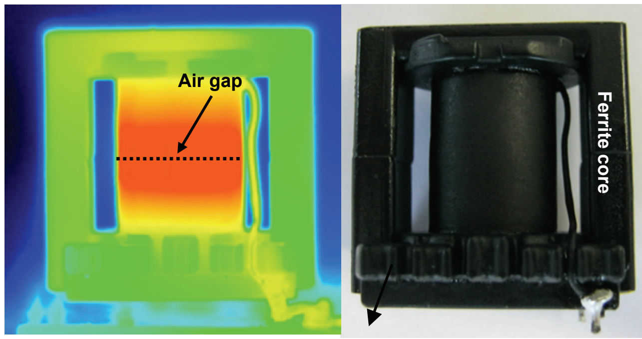

Fig. 1. Elevated temperature (hot spot) due to the fringing effect in windings around an air gap in a centre-gapped ferrite inductor

2. Measurement setup and analysis of a single gap toroidal inductor

A toroidal configuration of ferrite cores has the potential for particularly high AC conductor loss due to the lack of a coil former and the immediacy of the winding to the core and the air gap. The fringing flux penetrates the surrounding medium over a certain distance depending on the size of the gap and is at its strongest in the immediate vicinity of the gap. To demonstrate the impact of the fringing effect on temperature distribution in the winding, as well as power loss and inductance of toroidal ferrite inductors, the magnetic component in Fig.2 was constructed.

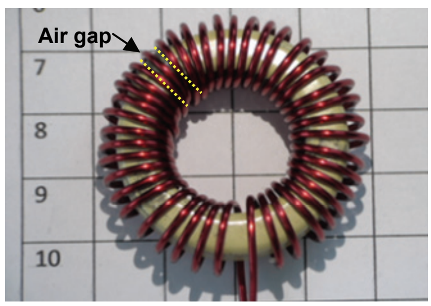

Fig. 2. Single gap toroidal ferrite inductor

The core, ferroxcube 3C90 TX36/23/10 [7], was gapped to 4.0 mm and combined with a 42-turn coil wound directly on the core to build an inductor of 100 μH. The inductance of a gapped ferrite inductor, if calculated without taking the fringing effect into consideration, may be expressed as:

$$L = \frac{N^2 \cdot \mu_0 \cdot A_e}{l_g + \frac{MPL}{\mu_m}}, \quad (1)$$

where: μ_0 – the permeability of free space = $4 \cdot \pi \cdot 10^{-7}$ H/m, N – number of turns = 42, A_e – core cross-sectional area = 0.0000649 m^2, l_g – length if the air gap = 0.004 m, *MPL* – magnetic path length = 0.0897 m, μ_m – the permeability of ferrite = 2300.

For ferrite cores the ratio of the magnetic path length to the permeability of material used, $\frac{MPL}{\mu_m}$, is frequently minute in comparison to the length of the gap l_g, and can be omitted in Eq.1, which now takes the following form:

$$L = \frac{N^2 \cdot \mu_0 \cdot A_e}{l_g}, \tag{2}$$

One can notice that if the figures were to be substituted into Eq.1, it would result in inductance of about 36 μH, a value considerably lower than the measured one. The fringing effect in this case has increased the value of inductance by a factor of F = 2.78. As mentioned above, the fringing-flux effect is a function of the inductor's geometry, and for simple cores the fringing-flux factor by which the inductance increases can be approximated by [8]:

$$F = 1 + \frac{l_g}{\sqrt{A_e}} \cdot \ln\left(\frac{2 \cdot G}{l_g}\right), \tag{3}$$

where: G – the length of the core window (winding width), equal to 0.0715 m.

The equation proves to be very effective as long as the coil covers the entire circumference of the toroidal core.

$$F = 1 + \frac{0.004}{\sqrt{0.0000649}} \cdot \ln\left(\frac{2 \cdot 0.0715}{0.004}\right) = 2.776$$

The maximum value of magnetic flux density B is directly proportional to the inductance value,

$$B_{max} = \frac{L \cdot I_{L max}}{N \cdot A_e}, \tag{4}$$

where $I_{L\max}$ is the peak value of the current flowing through the coil. The $B_{\max}$ has to be determined, as it cannot exceed the saturation flux density for the selected core material (Fig 3). Were the point of saturation to be reached, the core material would lose its ferromagnetic properties and technically the inductor would become an air core inductor. In case of gapped core magnetic components, Eq.4 changes its form to:

$$B_{max} = F \cdot \frac{L \cdot I_{L max}}{N \cdot A_e}, \tag{5}$$

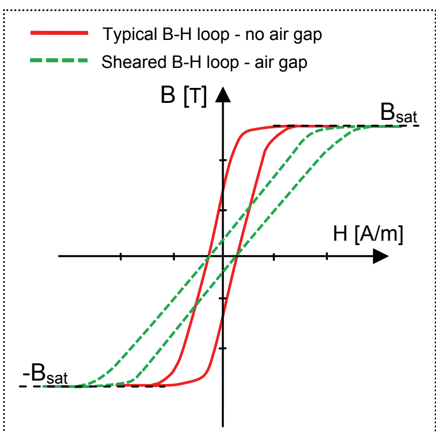

Fig. 3. Typical and sheared (an air gap) B-H loop for ferromagnetic material

The constructed toroidal choke was mounted prior to the measurements on the back of the 48 W DC-DC forward converter (Fig. 4), so as to eliminate the impact of any heat-radiating top-mounted components on temperature distribution in the coil. The component was sprayed with black matt paint to solve the problem of low copper emissivity. The forward converter was set to run at a frequency of about 63.4 kHz with a duty cycle of D = 17.5%.

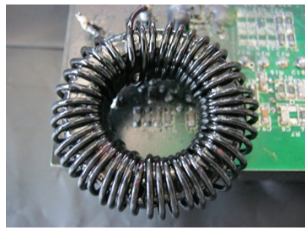

Fig. 4. Constructed inductor on the back of the 48 W forward converter

The output voltage was regulated at 12 V and the output current was set to 4 A. The current and voltage waveforms captured are presented in Fig.5.

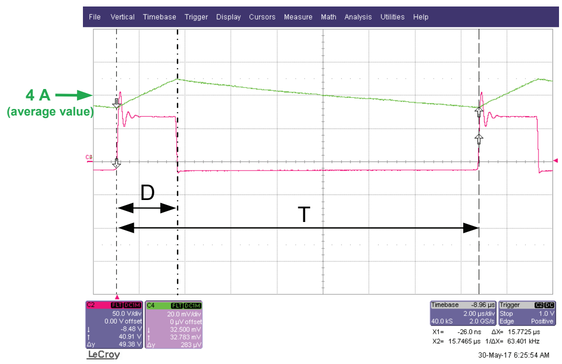

Fig. 5. Voltage (red) and current waveforms for 4.0 mm gap inductor

The converter was run until the temperature of the inductor settled at its maximum values, at which point the thermal image in Fig.6 was taken with an IR camera. The experiment was carried out at a constant ambient of 22 degrees centigrade. The impact of the fringing effect is clearly illustrated in Fig. 6 where the difference in maximum temperature between the section of the winding located directly over the gap and areas with no or a highly diminished fringing-flux component is about 20 degrees centigrade.

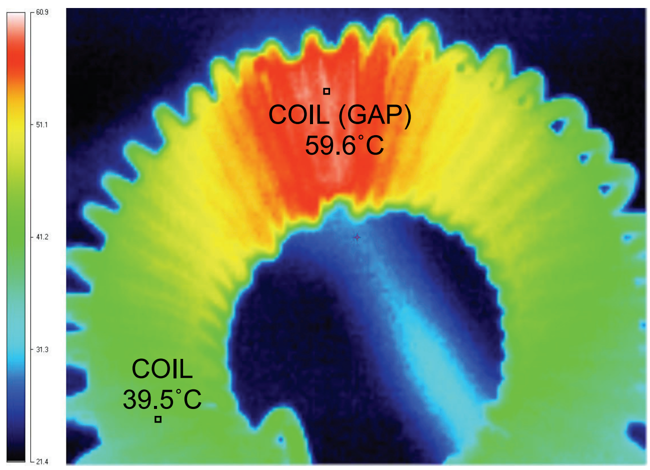

Fig. 6. Thermal image of the single gap toroidal ferrite inductor

The efficiency of energy conversion of the power supply as a whole was measured to be about 81.4%, a figure indicating potential improvements in this respect. Undoubtedly, increased AC winding loss due to the fringing field is a relevant factor reducing the converter's performance. One of the most elegant remedies is to use a low-permeability, high-quality (low-loss) core material to imitate a distributed gap. As such materials are often not readily obtainable, the introduction of an additional air gap into the magnetic path to decrease the length of individual gaps, and to lessen the fringing-effect loss, is frequently a feasible solution. In this experiment, the single gap core was substituted with a core comprising two discrete gaps suitably dimensioned to obtain the same value of inductance as the original inductor.

3. Toroidal inductor with a dual air gap

Initially, as intuitive reasoning would suggest, the core was double gapped to achieve an effective gap length of 4.0 mm. Since the fringing effect depends strongly on the size of the air gap, splitting the gap significantly altered the magnetic field configuration, reducing its “shortening” effect. Although the coil had the same geometry and consisted of an identical number of turns, its inductance was measured to be about 68.5 μH. One can conclude that the splitting of the air gap reduced the fringing-flux factor F to about 68.5% of its initial value for the single gap inductor. In order to keep the operating conditions of the forward converter unchanged, the length of the two discrete gaps was gradually decreased until the measured inductance reached 100 μH. The length of the individual gaps measured at this point was about 1.1 mm, with the result that the effective air gap was nearly halved. At this stage the captured current and voltage waveforms for the inductor were analogous to the ones illustrated in Fig.5.

Once more the converter was kept running until the toroidal choke reached the maximum steady temperature, at which point its thermal image was recorded (see Fig.7). As presented in the image, temperature distribution along the winding no longer exhibited a single hot spot located directly above the air gap, but instead its spread was nearly homogenous. Since individual turns of coils formed on toroidal cores are spaced much closer to one another as well as to the core/air gaps on the inside of the inductor, the fringing effect is more pronounced, and temperature is elevated on the inner side of the core. This can be observed in the thermal image. Although highly diminished, a certain discrepancy in temperature between the areas over the gaps and the remaining sections of the winding exists, and was measured to be about 4 degrees centigrade.

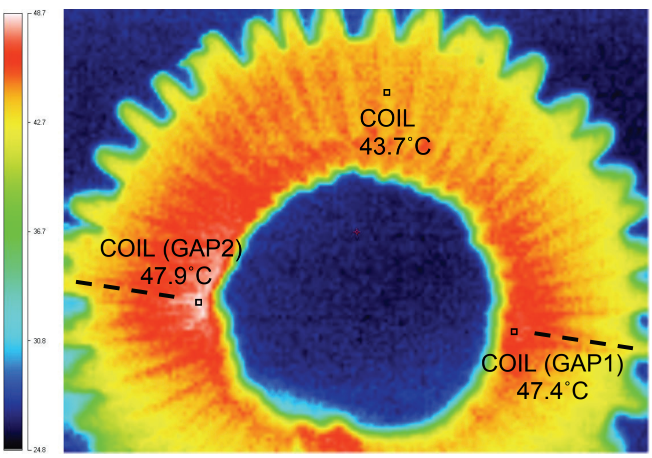

Fig. 7. Thermal image of the toroidal ferrite inductor with a dual air gap

As expected, the splitting of the air gap had an impact on the converter’s performance, increasing its efficiency to 81.6%, a value that corresponds to the decrease of about 0.148 W in total power dissipated in the 48 W converter.

Another key issue in the design of power supplies is electromagnetic interference (EMI), and gapped magnetics tend to have a high level of electromagnetic emissions [9]. Substituting a single gap with a multiple, quasi-distributed or distributed air gap frequently has a diminishing effect on EMI, bringing its level down to within compliance.

Ferrite cores such as E-cores, PQ cores or any other manufactured in halves, can be easily gapped to the required size by inserting spacers between the halves and creating a multiple air gap. It is often desirable not to centre-gap them as it increases the length of the gap, thus intensifying the fringing effect.

4. 3D FEM modelling of the fringing-flux factor in gapped toroidal inductors

The effect of the fringing flux on inductance in ferrite inductors with a multiple air gap can be ascertained by the utilization of finite element analysis (FEA). For this purpose, the COMSOL software was employed. For the cases illustrated in the previous paragraphs, the magnetic field distribution simulation was followed by the inductance estimation. Subsequently, the model was expanded to include a higher number of gaps in the magnetic path of the examined component in order to illustrate the change in the fringing-effect factor. The finite element method (FEM) model implemented was the 3D type (Fig.8) and the computations were based on the equations provided by the Magnetic Field interface in the AC/DC module of the program. The material properties were specified individually for the core, the winding and the air as the surrounding medium.

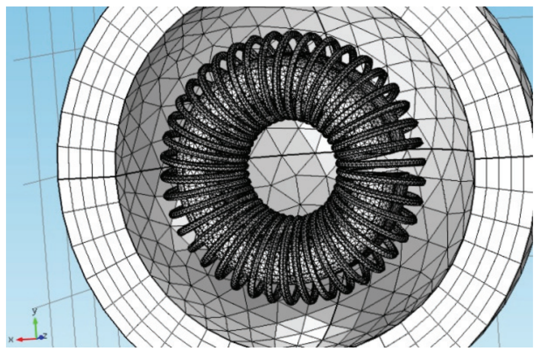

Fig. 8. FEM model of the analysed magnetic circuit

The evaluation of the magnetic flux distribution for stationary excitation of 1 A allowed us to calculate the inductance and the resistance of the modelled component. The values of the two parameters for the physical inductor with the single air gap and for the equivalent model were 100 μH, 0.0264 Ω and 106.18 μH, 0.0285 Ω, respectively. The discrepancy between the two physical properties for the real object and its FEM representation is in the range of a few per cent, which should be considered a satisfactory result.

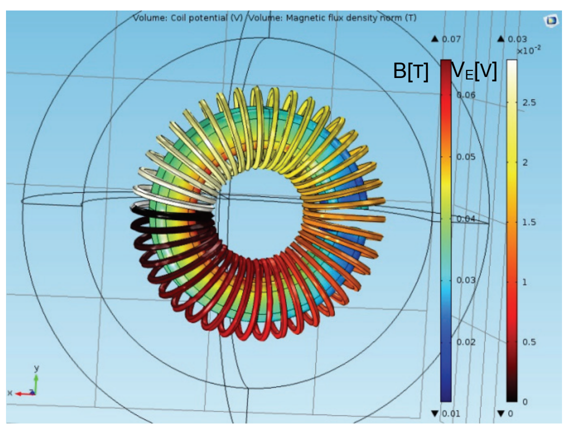

Fig. 9. Magnetic flux density and coil potential of the modelled single-gapped toroidal ferrite inductor

One can observe in Fig.9 that in the vicinity of the air gap the magnetic flux density in the magnetic domain is diminished. This is due to the fringing-effect phenomenon as the magnetic field lines are no longer entirely enclosed by the core, but tend to enter the surrounding medium. The principle of the continuity of the magnetic flux states that the magnetic flux present in the section of the core away from the gap is equal to the sum of the magnetic flux in the air gap and the fringing flux encompassing the gap.

Following the FEM analysis of the single-gapped choke, the modelled core featured two air gaps with an individual length of 2.0 mm. As predicted, the inductance of the component dropped significantly to a value of 67.16 μH, indicating that the created FEM representation quite closely depicted the physical object with the measured inductance of 68.5 μH. The estimated value of the fringing-flux factor F was about 1.87 for both the real and the modelled component.

The subsequent division of the initial air gap (see Fig.10) led to a gradual reduction of the fringing-flux factor and hence the component's inductance declined with the increasing number of gaps, as shown in Tab.1.

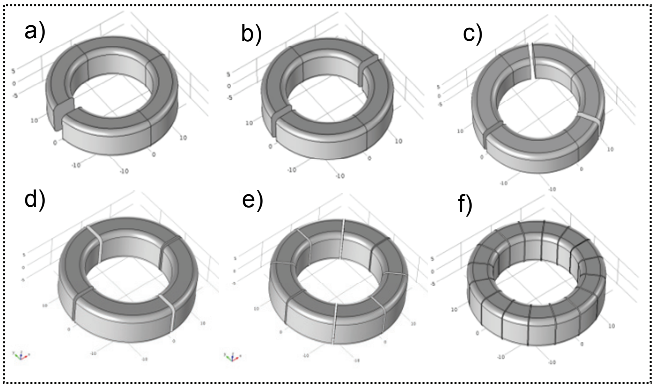

Fig. 10. Analysed ferrite cores with a multiple air gap: a) single gap, b) double gap, c) three gaps, d) four gaps, e) eight gaps, f) sixteen gaps with a total length of 4.0 mm

Tab. 1. The fringing-flux factor and inductance for the modelled toroidal inductors

Number of air gaps	Air gap effective length, mm	The fringing-flux factor F	Inductance, μH
1	4.0	2.776	106.18
2	4.0	1.866	67.16
3	4.0	1.526	54.94
4	4.0	1.288	46.39
8	4.0	1.096	39.46
16	4.0	≈ 1	35.13

In the ideal scenario, where the magnetic field lines at an air-gap occupy a section of space with the same cross-sectional area as a magnetic core, the fringing-flux factor tends to 1. This indicates that the fringing effect is not present or is highly diminished, and the value of the component's inductance should match that obtained with the use of Eq.1 or Eq.2. In the experiment carried out, if the discrete air gap were to be substituted with a quasi-distributed or a distributed gap, the value of the choke's inductance would be approaching 36 μH. This can also be determined from the FEM representation of the magnetic component where the computed inductance appears to be converging to a similar value for cores with a high number of gaps (see Tab.1).

5. Conclusions

Toroidal ferrite power inductors often find applications in highly compacted designs where a power supply with a low profile is necessary, due to packaging constraints. They can potentially replace planar inductors, displaying exceptionally high AC resistance as a result of the eddy current mechanism exacerbated by their small magnetic geometries and high-frequency operation. Ideally, due to the fringing-effect phenomenon and its impact on temperature distribution, as well as the maximum value of magnetic flux density, the choke should feature a distributed air gap. Since efficiency is frequently the best measure of a component's performance, the core used in the design should be manufactured from a low-loss material. As such materials are often not readily available, the transformation of a single air gap into a dual entity may become a practicable answer to the problem. From the thermals point of view, such an operation reduces the discrepancy in temperature between the section of the winding located directly over the air gap and other areas. This leads to reduction or elimination of hot spots, increases the efficiency of power conversion and frequently lessens electromagnetic emissions.

FEM analysis can be employed to determine the physical parameters of inductors with a multiple air gap that otherwise prove problematic to estimate due to the fringing-effect phenomenon. The numerical method showed that the fringing-effect factor, thus the fringing field, in the investigated inductor is strongly dependent on the length of the air gap, and for the multiple or quasi-distributed gap tends to 1.

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