Rafal KASIKOWSKI [1,2]
[1] Aim-TTi, Huntingdon, Cambridgeshire, United Kingdom
[2] INSTITUTE OF ELECTRONICS, LODZ UNIVERSITY OF TECHNOLOGY, 90-924 Łódź, Wólczańska 211/215 St.

Reduction of Fringing-Effect in Inductors by Quasi-Distributed-Gap Method

Abstract

The fringing-field phenomenon can have a significant impact on the key performance parameters of magnetic components with an air gap. The fringing magnetic flux at the air gap has an effect on a component's inductance, power loss and temperature distribution in copper windings. The induced excess eddy currents in the windings due to the fringing effect cause localized heating and reduce the overall efficiency of power conversion. This effect can be analysed by infra-red thermography to demonstrate the potential hazards of designing magnetic components with an air gap. Design engineers are frequently forced to design around the problem by employing a number of available techniques. The quasi-distributed-gap technique combats the issue at the origin as it essentially constrains the fringing magnetic flux at the downsized air gaps to their immediate vicinity. The selection of the length of the individual air gaps as well as their placement is not straightforward, as the phenomenon is a function of the air gap length and geometry. The resulting inductance of the component has to be the same or at least comparable to the original value in order to maintain the operating conditions of the application which the component is part of. This paper examines the effects of splitting a discrete air gap on the electromagnetic and thermal properties of inductors and presents a method to aid the design of quasi-distributed-gap inductors based on finite-element simulations as well as measurements. An analytic expression, which closely approximates the required length of quasi-distributed gaps, is developed.

Keywords: fringing effect, inductors, fringing-effect factor, quasi-distributed air gap, IR thermography.

1. Introduction

Air gaps in magnetics circuits are inherent to applications where conversion of power would drive magnetic flux density near or beyond the saturation point of a given magnetic material. A discontinuity in the magnetic path represents a drastic change in its reluctance to magnetic flux. At the point of crossing the air gap, the magnetic flux so far enclosed within the magnetic core tends to leak into the surrounding medium causing electromagnetic interactions with copper windings. The fringing flux at the gap effectively shortens the gap and decreases the overall reluctance of the magnetic path. As a consequence, coils wound on magnetic cores with a relatively large air gap tend to yield inductance larger than that determined without taking the fringing flux into consideration. This increase in inductance is often represented by the so-called fringing-effect factor F – a ratio of the measured inductance to the inductance predicted by calculations not accounting for the fringing effect. The fringing-flux phenomenon poses further adverse effects on the performance of magnetic components. The shortening of the gap may result in premature saturation of the core material as the maximum operating flux density is increased by the factor of F [1] and the induced eddy currents in the windings bring about extra power loss that manifests itself in the form of hot spots, as shown in Fig. 1 [2].

A number of methods have been developed to counteract the negative impact of the fringing field, such as spacing the windings away from the gap or using a so-called LITZ wire, which mitigates the increase in winding AC-resistance due to eddy currents. The quasi-distributed-gap technique appears to offer the most effective solution, although there is a somewhat limited number of publications on the design of a quasi-distributed gap in inductors [3]. What is more, even fewer research papers touch the issue of splitting a single air gap into a number of individual gaps while maintaining the same inductance of the component and hence the same operating conditions, which is a concern of key importance in many power electronics applications. An adequate solution can be arrived at by the use of trial and error, but this is not an effective approach in practical design. Herein, the thermographic analysis of splitting an air gap is presented and simplified design rules for a practical range of gap lengths are given.

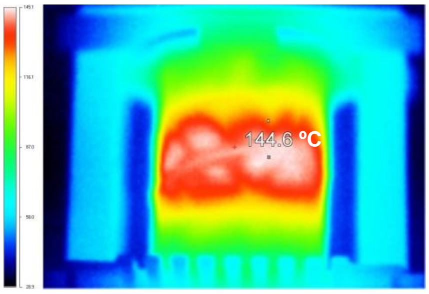

Fig. 1. Elevated temperature (hot spot) in windings due to the fringing effect

2. Single gap inductor vs quasi-distributed-gap inductor

Gapped magnetic components in switch-mode power converters are frequently designed to operate under a substantial AC-current ripple. If these operating conditions are combined with a relatively large single air gap, the fringing effect becomes particularly evident. Ferrite output inductors in forward-topology converters (Fig. 1) or chokes used in PFC (power factor correction) modules (Fig. 2) are only some of the examples where both factors coincide. These magnetic components, due to the fringing phenomenon, exhibit impaired efficiency of power conversion and the materials used for their construction are often exposed to highly elevated temperature in the vicinity of the air gap. It is not unheard of that the insulation on a poorly designed component was undergoing accelerated aging or, what is worse, became deformed or melted. The latter may pose a safety hazard. Frequently, magnetic components are a source of excessive electro-magnetic interference and require shielding to bring the emissions down to within compliance. Copper shields, due to their thickness and a relatively large cross-sectional area, are especially susceptible to the fringing effect and tend to develop considerable eddy currents (Fig. 2).

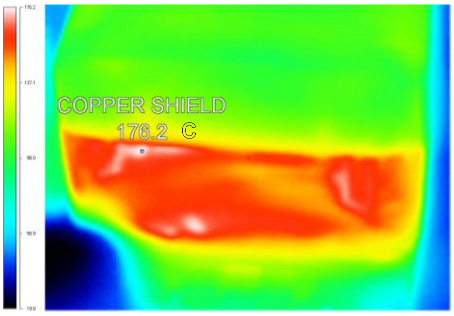

Fig. 2. Thermal image of PFC choke with copper shield affected by fringing flux

The quasi-distributed-gap technique under such circumstances appears to be one of the most appropriate approaches to diminish the adverse effects of the fringing flux (Fig. 3). An intuitive rule of thumb might suggest that substituting the discrete gap with a number of individual gaps of the same total length would yield the required result, but due to the reduction in the fringing magnetic field, the inductor having a plurality of discrete gaps displays lower inductance and hence altered physical properties. The decrease in inductance forces higher currents through the component. This leads to extra power loss, may negatively impact the electro-magnetic emissions of the component and changes the operating conditions of the converters. Ideally, the inductance, thus the inductor current, should be the same or comparable to the original values.

The multiple-gap inductor constructed under this constraint will have improved performance from the efficiency and thermal point of view.

Fig. 3. Thermal image of quasi-distributed-gap PFC choke with copper shield around windings

3. Simulation parameters and analysis

There is no well-established method to implement a quasi-distributed gap in the magnetic path of inductors that would produce the same inductance as the discrete gap. It is possible to run finite-element simulations and tune the lengths of individual gaps to give the wanted result, but this approach is not necessarily more efficient than the trial and error method mentioned above. Preferably, the designers should be able to calculate or estimate the measurements for a quasi-distributed gap without the need for time-consuming finite-element analysis. With the aim of determining an analytical expression to aid the design, a 3-D type FEM model of a single-coil inductor was developed based on a ferroxcube 3C90 ETD39/20/13 core, and a series of simulations was carried out (Fig. 4). Simultaneously, a physical inductor was built to verify the results of the computations.

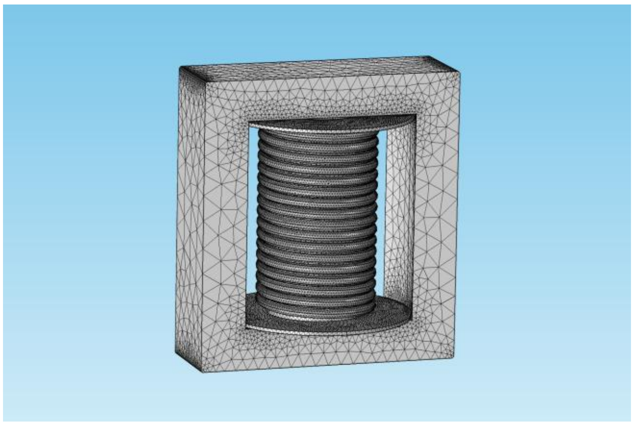

Fig. 4. FEM model of analysed magnetic circuit

For the practical range of gap lengths used in switch-mode power converters, replacing a single gap with just 3 discrete gaps leads to a substantial reduction of the impact of the fringing effect on temperature distribution and power losses in the windings. Figures 5 and 6 illustrate the air-gap configurations implemented and the corresponding thermal images taken at the thermal steady-state of the examined inductor.

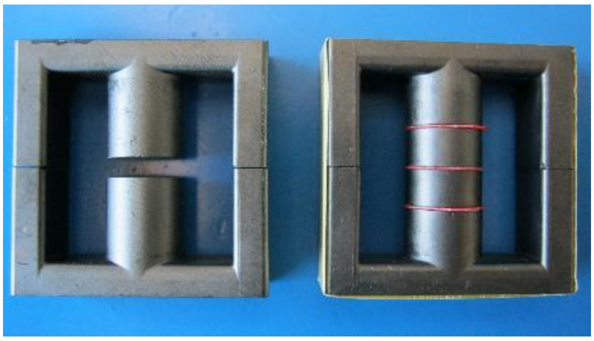

Fig. 5. Two air-gap configurations: left) single gap, right) quasi-distributed air gap

As shown in Fig. 6, temperature distribution does not undergo significant changes along the middle column due to a considerable attenuation of the fringing effect. The entire difference in power dissipation between the two chokes shown can be attributed to the near-elimination of the fringing effect, as the current through the component remained unchanged.

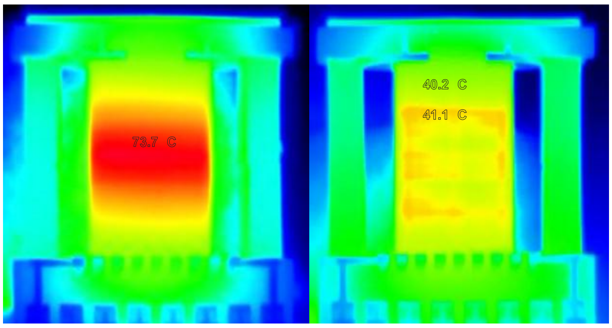

Fig. 6. Thermal images for: left) single-gap inductor, right) quasi-distributed-gap inductor

The air gap configurations of Fig. 5 can constitute a convenient starting point for finite-element simulations. The choice of the location and distances between individual gaps in a multiple-gap inductor is not obvious, for, as shown in Fig.8, their placement significantly impacts the value of the inductance. To simplify the problem, the central gap was positioned in the middle of the core column as it seemed to be a logical approach for magnetic cores coming in pairs, and the outer gaps were gradually moved away from the centre (Fig. 7) so that the resulting inductance L was a function of the distance between the gaps d. The length of each of the gaps lg was fixed.

Fig. 7. FEM modelling of inductance as function of distance between individual gaps

The biggest value of inductance L was found, as expected, for the distance d between the gaps equal to 0, effectively forming a single discrete air gap in the middle of the column. As the gap pitch gets larger, L significantly decreases, eventually reaching its minimum at about the point where the gaps are spread evenly over the entire length of the column.

This indicates that the impact of the fringing magnetic field on the total reluctance of the core, thus the fringing factor *F*, is the weakest. As the outer gaps approach the ends of the core column, *L* gradually increases again but only by a fraction of its maximum value registered for the single gap.

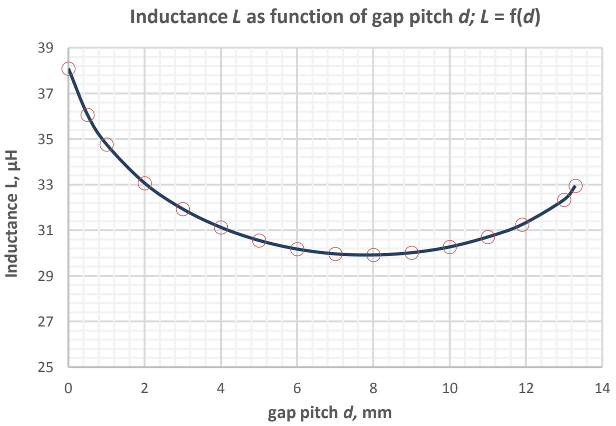

Fig. 8. Inductance *L* as function of gap pitch *d* for 3C90 ETD39/20/13 core

For the example shown in Fig. 8, the choice of the gap pitch became obvious as *L* is the smallest at the distance between gaps referring to their uniform distribution along the column, but it is still larger than the value that would be calculated without including the fringing-flux contribution. Having selected the pitch, the length of the gap became a variable in the subsequently run simulations. A functional range of gap lengths incorporated in power supplies usually falls within 0.1 mm to 4 mm, where the latter should be considered relatively large. Figure 9 illustrates how the total length of quasi-distributed gap Lg changes in respect to the length of the discrete gap G to obtain the same value of L.

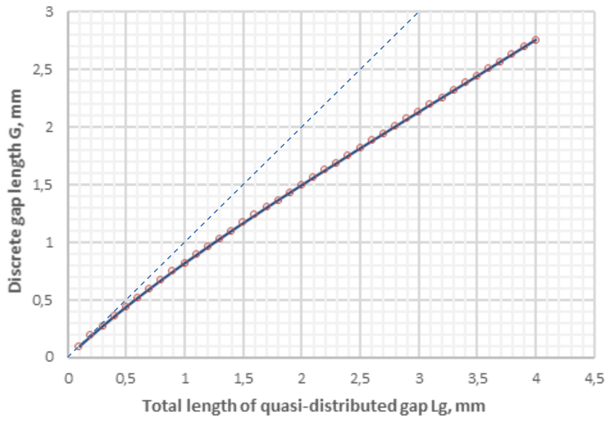

Fig. 9. Discrete gap lengths and corresponding quasi-distributed-gap lengths that result in the same *L* if incorporated in ETD39/20/13 core of magnetic components

Looking at the plot above one can find a required total quasi-distributed-gap length for any corresponding discrete gap length that yields identical inductance if introduced in the core of an inductor, or, in fact, of any magnetic component if constructed using an ETD39/20/13 core or similar. For the gaps of relatively short lengths, within the range of 0.1 mm to 0.5 mm, the relation is nearly linear, whereas for larger gaps the curve angles gradually away from the centre. This shows that the quasi-distributed-gap technique is particularly effective in coils wound on magnetic cores with a relatively large single air gap, thus with an exacerbated fringing effect.

4. Formulation of analytical expression for quasi-distributed gap

To facilitate the design of quasi-distributed gaps for ETD-type cores, without the need for implementation of complex numerical analysis, an empirical expression to describe a quasi-distributed-gap length, as a function of the spatial dimensions of the core and the physical properties of a given magnetic component, is required. The expression for inductance of a gapped core in (1) assumes that there is no fringing magnetic flux in the vicinity of the air-gap.

$$L = \frac{N^2 \cdot \mu_0 \cdot A_c}{G + \frac{MPL}{\mu_m}}, \qquad (1)$$

where: μ_0 – the permeability of free space, N – number of turns, A_c – core cross-sectional area, G – length of the discrete air gap, MPL – magnetic path length, μ_m – the permeability of magnetic material.

In general designation, Eq.1 takes the following form:

$$L = \frac{N^2}{R_c + R_G}, \qquad (2)$$

where: R_c and R_G are reluctance of core material and reluctance of an air gap, respectively.

$$R_c = \frac{MPL}{\mu_0 \cdot \mu_m \cdot A_c}, \qquad (3)$$

$$R_G = \frac{G}{\mu_0 \cdot A_G}, \qquad (4)$$

where: A_G – cross-sectional area of an air gap.

Eq.1 assumes that the cross-sectional area of both the core and the air gap are the same, $A_G = A_c$, which is, as we know, not the case in practice where the magnetic field lines while crossing the air gap are no longer constrained by the core but fringe out into the neighbouring areas. In order to obtain the actual value of the reluctance of the air gap, hence inductance of the component, the cross-sectional area of the gap has to be increased. There are a number of views concerning the extent to which the special dimensions of the gap should increase [1,5]. One of the most elegant approaches, and the one yielding satisfactory results, is to represent the cross-sectional area as a function of the air-gap length G. According to [6], the effective cross-section area of the gap that accounts for the fringing effect can be obtained by adding the air-gap length to each of the linear dimensions in the cross-section. In here, as the examined core has a round central column, it is proposed that the radius should be increased by G.

$$R_G = \frac{G}{\mu_0 \cdot \pi \cdot (r+G)^2}, \qquad (5)$$

where: r – radius of the central column.

For the quasi-distributed-gap configuration in Fig. 5, Eq.1 is expressed now as:

$$L = \frac{N^2}{\frac{MPL}{\mu_0 \cdot \mu_m \cdot A_c} + \frac{3 \cdot g}{\mu_0 \cdot \pi \cdot (r+g)^2}}, \qquad (6)$$

where: g – length of one of the gaps in the quasi-distributed air gap.

In order to arrive at the sought analytical expression, the above equation should be solved for g. The remaining coefficients can be either found in the available literature or read from the published core data. A series of mathematical transformations leads to a formulation of the following expression:

$$g = \frac{1-2\cdot A\cdot r-\sqrt{1-4\cdot A\cdot r}}{2\cdot A}, \qquad (7)$$

where:

$$A = \frac{\left(N^2-L\cdot R_c\right)\cdot \mu_0\cdot \pi}{3\cdot L}, \qquad (8)$$

It has to be borne in mind that the value of MPL in Eq.3, if read from the core datasheet, shows the magnetic path length of an ungapped core, and, therefore, before substituting it into the expression, it should be decreased by the length of the single gap which is being replaced by the quasi-distributed gap.

$$R_c = \frac{MPL-G}{\mu_0\cdot \mu_m\cdot A_c}, \qquad (9)$$

Fig. 10 compares the total length of the quasi-distributed gap Lg computed by the above expressions (Eq.7 and Eq.8) to the results of the simulations.

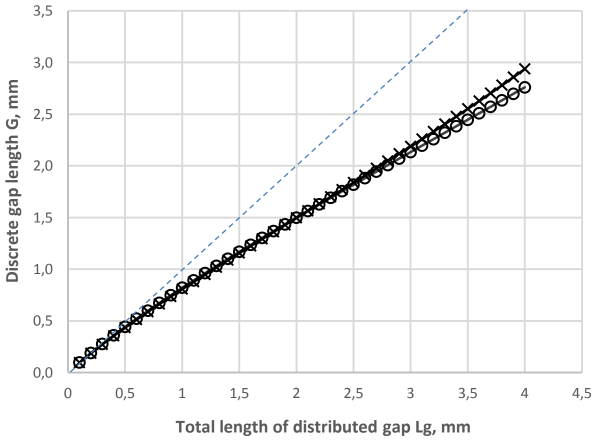

Fig. 10. Discrete gap lengths and corresponding total quasi-distributed-gap lengths (o – simulation, x – computation) that result in the same *L* if incorporated into ETD39/20/13 core of magnetic components

One can see that the expression approximates the simulations very closely for relatively short gaps and it is still quite accurate for larger gaps, which should be considered a satisfactory result.

5. Conclusions

Splitting a discrete air gap in a magnetic component into a number of individual gaps, thus forming a quasi-distributed air gap, alters the magnetic field around the gap. Adequately selected, the number of gaps and their lengths will prevent the fringing flux from entering windings, thus bringing about a significant reduction in power loss and maximum temperature of the windings. It was shown herein that deciding on as few as three gaps may in practice constrain the phenomenon to the immediate vicinity of the gaps. The FEM simulations carried out allowed the construction of an approximate analytical formula that determines the size of the quasi-distributed gap, which replaces a discrete gap without a change in the inductance of the magnetic component built on an ETD-type core. It is believed that a similar technique can be extended to different core shapes by linking the length of the gap to the linear dimensions in the cross-section of the core.

6. References

[1] Colonel Wm., McLyman T.: Transformer and Inductor Design Handbook, Fourth Edition, CRC Press, 2011, ISBN 9781439836880.

[2] Kasikowski R., Wiecek B.: Ascertainment of fringing-effect losses in ferrite inductors with an air gap by thermal compact modelling and thermographic measurements, in: Applied Thermal Engineering 124 (2017) 1447–1456.

[3] Yang Rachel S., Hanson Alex J., Reese Bradley A., Sullivan Charles R., Perreault David J.: A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications, in: IEEE Transactions on Power Electronics 2019.

[4] Ferroxcube Data Handbook: Soft Ferrites and Accessories, 2013, p.541.

[5] Ekekwe N., Ndubah J.E., White K., Ben O.: Practical process in high frequency distribution transformer design. Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Technology Conference, 2003. Proceedings.

[6] Hurley W. G., Wölfle W. H.: Transformers and inductors for power electronics: theory, design and applications. John Wiley and Sons, 2013.

Received: 12.12.2018 *Paper reviewed* *Accepted: 04.02.2019*

Rafal KASIKOWSKI, MSc

Received the MSc degree in electrical engineering from the Technical University of Częstochowa in 2002 and the MSc degree in energy engineering from the University of East Anglia, United Kingdom, in 2013. Since 2012 he has worked as a power supply design engineer. His current research interests include optimization of power magnetic components in switch-mode power supplies, thermal analysis and modelling of power converters.

e-mail: Rafal.Kasikowski@tti.co.uk