Optimum Air Gap Selection in Powder Core Inductors

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Luigi Solimene, *Student Member, IEEE*, Davide Cittanti, *Student Member, IEEE*, Fabio Mandrile, *Member, IEEE*, Carlo Stefano Ragusa, *Senior Member, IEEE*, and Radu Bojoi, *Fellow, IEEE*
Politecnico di Torino, Department of Energy "Galileo Ferraris", Turin, Italy, luigi.solimene@polito.it

The requirements of magnetics for power electronics are high power density and low power losses, driven by the need for more compact and more efficient power converters. Metal powder materials are a common choice for high power and high frequency inductors subject to a magnetic field bias applied because of the high saturation flux density and their "distributed" air gap property that allows adopting these materials in un-gapped core configurations. Nevertheless, in certain conditions, a concentrated air gap could maximize the overall inductance factor for a given winding configuration (i.e. the number of turns). Therefore, this paper proposes a straightforward procedure to maximize the inductance factor of metal powder magnetic cores by selecting the optimum air gap length for a specified design operating point. The proposed methodology is theoretically described and then experimentally validated on an XFlux 60 core from Magnetics®.

***Index Terms*—power inductors, magnetic powder materials, powder cores, magnetic cores, air gap, soft saturation, optimization**

I. Introduction

THE SPREAD of power electronics converters is nowadays growing exponentially in several applications. Numerous innovations in the field of semiconductor devices have led to high power density converters, with the ever higher switching frequency, up to the MHz range. Passive components such as inductors and capacitors, some of the bulkiest devices in a converter, represent an obstacle to maximizing the power density. In particular, focusing on inductors operating with a magnetic field bias, the principal limit to reducing the component size is the saturation of the magnetic material [1]. Ferrite cores are widely adopted for these applications, but they are generally operated in a gapped configuration due to the low saturation flux density and the sharp differential permeability profile. Metal powder cores represent a solution to improve power density in applications with a magnetic field bias. These cores are manufactured from magnetic alloy grains bound together with an insulating material, thus producing a distributed air gap that allows an effective permeability value comparable to gapped ferrite cores, with a smoother dependence on the DC bias field applied [2]. Typically, these cores can be adopted in a wide range of current values with no need for a concentrated air gap. Furthermore, compared to ferrite cores, the differential permeability profile of a metal powder core exhibits a gradual saturation, with a predictable behavior even at high values of applied magnetic fields. However, for high current applications, a small concentrated air gap helps to maximize the inductance factor provided by a given metal powder core [3]. The optimal length of the air gap is a function of the magnetomotive force imposed by the application. Figure 1 shows the differential inductance profiles of a powder core inductor for different air gap lengths. As the applied current increases, solutions with a larger air gap can gradually provide a higher inductance value than solutions without an air gap. A maximum inductance profile can be determined and related to an optimum air gap profile as a function of the applied current. According to the required current operating point, adopting this optimum air gap length provides a zero-cost solution to obtain a non-negligible inductance gain with respect to the un-gapped condition. This solution does not imply specific manufacturing or operational drawbacks if the air gap length is kept within limited values. Therefore, this paper aims to define and validate an analytical methodology for estimating the optimal air gap length for powder core inductors according to the design specifications, requiring only the data available from the manufacturer's datasheet. The proposed method does not require a high computational effort, as the solution of a non-linear equivalent magnetic circuit through an iterative method of rapid convergence is sufficient.

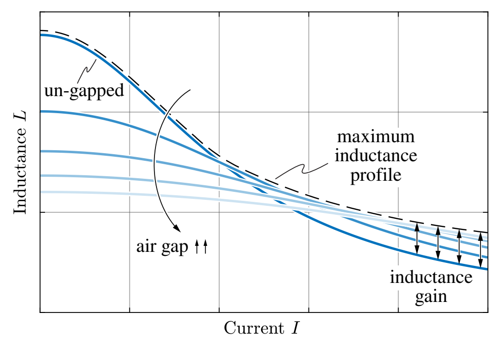

Fig. 1. Qualitative overview of the differential inductance L profiles of a metal powder core as a function of the DC-bias current I, for different air gap values.

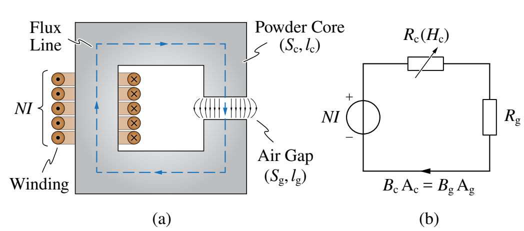

Fig. 2. (a) Considered core and winding dimensions. (b) Equivalent reluctance model of the core.

(a) (b) (c)

Fig. 3. (a) Optimum air gap profile for the tested inductor. The prediction of the proposed model is compared with experimental measurements. (b) Measured inductance factor obtained by adopting the predicted optimum air gap profile compared to the un-gapped configuration. (c) Inductance factor gain obtained adopting the predicted optimum gap selection, with respect to the un-gapped configuration.

II. Optimum air gap length computation

Considering a core with an air gap, as the one represented in Figure 2, the computation of the operating magnetic field in the magnetic material, caused by the operating current of the application, is determined through the Ampere's law, as

$$H_{\mathrm{c}}(NI, l_{\mathrm{g}}) = \frac{NI - H_{\mathrm{g}} l_{\mathrm{g}}}{l_{\mathrm{c}}}. \tag{1}$$

The inductance per square turn of a magnetic core, also defined as inductance factor A_{L}, can be expressed as:

$$A_{\mathrm{L}} = \frac{1}{\mathcal{R}_{\mathrm{tot}}}, \tag{2}$$

where the total reluctance of the core can be described as

$$\mathcal{R}_{\mathrm{tot}}(H_{\mathrm{c}}) = \frac{l_{\mathrm{c}}}{\mu_0 \mu_{\mathrm{c}}(H_{\mathrm{c}}) S_{\mathrm{c}}} + \frac{l_{\mathrm{g}}}{\mu_0 S_{\mathrm{g}}}. \tag{3}$$

The estimation of the inductance factor for a given core requires the computation of the operating magnetic field in the magnetic material, which is a function of the applied magnetomotive force and the air gap length. The effect of the air gap length on the inductance factor can be exploited to maximize its value. An optimum air gap profile as a function of the applied magnetomotive force can be identified to maximize the inductance factor of the core. The problem can be formalized as

$$\max(A_{\mathrm{L}}(NI, l_{\mathrm{g}})) = \min(\mathcal{R}_{\mathrm{tot}}(NI, l_{\mathrm{g}})). \tag{4}$$

In other words, it corresponds to determining the air gap thickness for each applied magnetomotive force that minimizes the total reluctance of the magnetic circuit. The complexity of the proposed approach, which only requires data provided by the core manufacturer's catalogs (core geometry, material magnetization curve), derives from the non-linearity introduced by the magnetic characteristic of the core material. For this reason, (4) cannot be solved analytically. Therefore, an iterative method called the polarization fixed point method is here adopted to perform the analysis.

III. Results

The 6527 E core in XFlux 60 (Magnetics®) is tested to validate the proposed methodology. As represented in Figure 3a, starting from a magnetomotive force of approximately 1300 At, the model suggests introducing an air gap, and its optimum value is almost linear as the magnetomotive force increases. Thus, for the experimental measurements, the component has been tested with an air gap thickness varying from 0 to 1 mm, with a step of 0.25 mm. Considering only these discrete steps, the model predicts the magnetomotive force value ranges suitable for each gap value to maximize the inductance factor. Figure 3a represents the comparison of the optimum gap selection, as a function of the magnetomotive force, between the experimental measurement and the prediction. Assuming to switch from an air gap configuration to the next one, as predicted by the model, the measured inductance factor profile represented in Figure 3b is obtained. The increase of the inductance factor given by the predicted optimum gap values, with respect to the un-gapped configuration, depicted in Figure 3c, clearly shows the benefit received by adopting the proposed methodology. The results highlight that the optimum air gap profile estimation is consistent with the experimental data, and the adoption of the suggested length allows increasing the inductance factor of a metal powder core at high magnetomotive force values.

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