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Closed-loop model: An optimization of integrated thin-film magnetic devices

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ABSTRACT

A generic analytical model has been developed to fully describe the flux closure through magnetic inductors. The model was applied to multiple device topologies including solenoidal single return path and dual return path inductors as well as spiral magnetic inductors for a variety of permeabilities and dimensions. The calculated inductance values from the analytical model were compared with simulated results for each of the analyzed device topologies and found to agree within 0.1 nH for the range of typical thin-film magnetic permeabilities ($\sim 10^2$ to 10^3). Furthermore, the model can be used to evaluate behavior in other integrated or discrete magnetic devices with either non-isotropic or isotropic permeability and used to produce more efficient device designs in the future.

1. Introduction

Thin film magnetic materials are being increasingly integrated into electronics to boost transduction in inductors [1–5], transformers [6,7], micro-electromechanical systems [8–10], and sensors [11,12]. Apart from cost effectiveness, the main obstacle standing in the way of proliferation of magnetic integration is the difficulty of understanding and predictably modeling thin-film magnetic behavior. As magnetic devices decrease in size and go from discrete components to integrated forms, the behavior changes dramatically and typical textbook expressions fail to capture it. Various analytical models have been put forth to help predict the behavior of specific device topologies [4,13,14]. However a more comprehensive model is required to describe a broader range of topologies and explain the change in magnetic flux behavior as devices transition from discrete to integrated forms.

When magnetic materials are converted from bulk to thin film forms for integrated devices, the reluctance of the magnetic core changes, resulting in a different spatial distribution of the flux closure. The main reasons for this change are that compared to bulk magnets, thin-film magnetic materials (1) have lower permeabilities, (2) suffer from larger demagnetization effects, and (3) are often patterned into rectilinear structures with sharp edges that have increased local demagnetization fields. Taking into account all these factors, this paper presents a rather concise and accurate model for magnetic closed-loop devices by considering all the possible paths in which the flux can close. The model is compared against simulations of both integrated and discrete inductors in order to demonstrate its versatility. Additionally, since the model takes into account the different flux paths contributing to the total inductance, a comparison is made in order to identify, as a function of both permeability and design dimensions, which flux path has the greatest contribution to the inductance. Equipped with this information, integrated thin-film magnetic devices can be optimized to maximize both flux flow through the magnetic film and enhancement due to it.

2. Analytical model

The analytical model is based on an analysis of the total reluctance of the design, considering all the possible ways in which the flux can close. The analysis is similar in methodology to several previous works [13–15]. While some assumptions had to be made about the device structure and demagnetization factors to simplify analysis, the model was kept as general as possible in order to apply broadly to a wide range of magnetic devices. Assumptions related to structure and demagnetization are explicitly stated as they arise in the derivation below. Closure in the model is assumed to be directly related to isotropic permeability in the magnetic

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core, which is difficult to achieve experimentally, but has been demonstrated to a certain degree in [16,17]. Later, the model is generalized for cases of non-isotropic permeability as well. Two solenoid inductor structures with isotropic permeability are described initially, while more topologies and non-isotropic permeability cases will be considered in the discussion section of this paper. The two isotropic inductor structures, illustrated in Fig. 1, are the single return path (SRP) and dual return path (DRP) topologies, which are defined by whether they have one or two sections of magnetic material in which the flux can return. The DRP topology has the advantage that flux generated anywhere in the solenoidal region can close through the nearest magnetic return path, and thereby have a shorter overall flux path and lower reluctance than the SRP topology.

Ampere's law explains that the total magnetomotive force, V_{mmf}, is given by the integral of the magnetic field around a closed loop. This same magnetomotive force can then be understood to be a sum of the drops across each of the different sections of the path.

$$\oint H \cdot dl = V_{mmf} \tag{1}$$

$$\sum_{i=1}^{n} V_{mmf_i} = V_{mmf} \tag{2}$$

The reluctance of each section of the flux path can therefore be evaluated separately and related back to the equivalent magnetic circuit model to compute the total reluctance and, finally, the total inductance.

For instance, for the SRP design, the circuit model represented in Fig. 2 begins with a flux-forming region where the coil perfectly surrounds the magnetic core. (Although the magnetic potential is not instantaneously created, the model locates it specifically at the beginning of the coil and evaluates the potential drop across this region to be V_{mmf_1}.) The flux then branches off. In one case, the flux can flow entirely through the magnetic curvature and, in another case, the flux can take a shortcut directly across the gap to reach the magnetic core on the other side. After this section, the flux recombines and returns through the magnetic core straight leg section, then once again splits up to follow either the magnetic curvature or cut across the gap one final time. In parallel with all of this is a reluctance path that describes the flux returning entirely through air.

For each of these sections, an expression for the magnetic field, and subsequently, the flux density and flux are evaluated as a function of permeability and dimensions. The reluctance is the ratio of the magnetomotive force to the flux flowing through the section, $\mathcal{R} = V_{mmf}/\Phi$. The total reluctance of the structure is then evaluated according to the series and parallel circuit models of Fig. 2. Finally, the inductance is equal to the ratio of the square of the number of turns to the total reluctance:

$$L = \frac{N^2}{\mathcal{R}} \tag{3}$$

The reluctance of the flux-forming region is given as

$$\mathcal{R}_{nominal} = \frac{l_m}{\mu_0 \mu_r w_m t_m} \tag{4}$$

where l_m, w_m, and t_m are the length, width, and thickness of the magnetic core, respectively, and μ_0 and μ_r are the free-space and relative permeabilities.

In order to define the flux through the curved core region, the model must account for the variation in the flux density as a function of position. Assuming uniform isotropic permeability, the flux will attempt to travel along the shortest possible path around the curvature, hugging the inner edge of the core, in order to see the smallest reluctance possible, as seen in Fig. 3. Therefore, best designs minimize the radius of curvature. In addition, since the flux is more concentrated in the inner region of the core, it follows that an effective closure width, w_{eff} can be defined beyond which increasing the width dimension of the closure region of the device will result in minimal increase in inductance since very little flux flows near the outer radius of the core. Evaluating this effective width would help in designing area-efficient closed-loop inductors.

To calculate the flux through the curved region, an integral must be evaluated as a function of radius s drawn from the inner edge of the core. The flux density at a given radius, in expressed as:

$$H_{curve} = \frac{V_{mmf_2}}{l_g + \pi s} \tag{5}$$

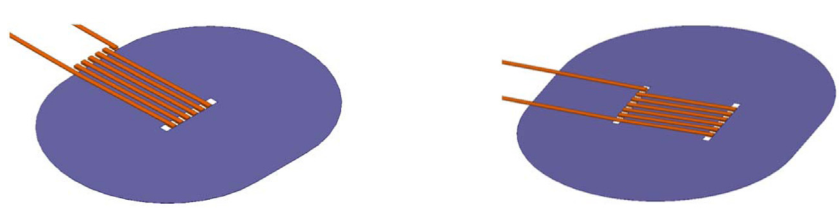
$$B_{curve} = \mu_0 \mu_r H_{curve} = \frac{\mu_0 \mu_r V_{mmf_2}}{l_g + \pi s} \tag{6}$$

This expression is then integrated from the inner radius ($s = 0$) to the outer radius based on the width of the core in the closure region ($s = w_m$).

$$\Phi_{curve} = \int_0^{w_m} B_{curve} t_m ds = \frac{\mu_0 \mu_r V_{mmf_2} t_m}{\pi} ln \left| \frac{l_g + \pi w_m}{l_g} \right| \tag{7}$$

$$\mathcal{R}_{curve} = \frac{V_{mmf_2}}{\Phi_{curve}} = \frac{\pi}{\mu_0 \mu_r V_{mmf_2} t_m} \left(ln \left| \frac{l_g + \pi w_m}{l_g} \right| \right)^{-1} \tag{8}$$

An expression for the amount of flux that cuts across the gap can be determined once approximate dimensions for the area of the flux region are defined. As the flux crosses the gap, the length of the path is assumed to be the gap length, l_g, while the width can be approximated as half the length of the magnetic core in the flux-forming region, i.e. $l_m/2$, allowing for the flux to cut back across the gap in the other half. (Although this implies the flux travels only an infinitesimal length between these two sections, to first order, this approximation appears to give good results.) The thickness of the flux cross-section area is assumed to be the thickness of the core, t_m. Note that the magnetic field in this case is that in air and the permeability is that of free space, μ_0. In order to relate these two values to the magnetic field and flux inside the magnet, demagnetization effects must be taken into account to give an effective



(a) Single Return Path (b) Dual Return Path

Fig. 1. The two closed-loop magnetic solenoid inductor topologies used for optimizing the analytical model, including either (a) only one section or (b) two sections through which the flux can return in the magnetic core.