Design And Modelling of Toroidal Inductors with Different Geometries for a Single-Phase Inverter Application

DOI
https://doi.org/10.18690/um.feri.4.2025.39

ISBN
978-961-286-986-1

Raymond Quinn, Joonas Vesa, Paavo Rasilo

Tampere University, Electrical Engineering Unit, Tampere, Finland
raymond.quinn@tuni.fi, joonas.vesa@tuni.fi, paavo.rasilo@tuni.fi

The prevalence of power electronic converters is increasing as part of the transition to renewable energy and electric transportation. One obstacle in improving the power density of converters is the size and mass of the electromagnetic components used in these devices. Fast and accurate design and modelling tools are required to optimise and reduce the footprint of electromagnetic components. This paper introduces a new approach based on the area-product method for rapidly designing inductors with different geometries. The behaviour of the designed inductors is simulated using a MATLAB Simulink model for laminated magnetic cores. The simulation results are presented and discussed.

Keywords:
area-product method,
inductor design,
loss models,
MATLAB Simulink,
power electronics

University of Maribor Press

I Introduction

Power electronic converters are an enabling technology of the transition to renewable energy and electric transportation. Converters utilise electromagnetic components such as inductors for purposes such as filtering. Despite the maturity of the field, electromagnetic components remain large and heavy compared to the other constituent parts of converters and remain an obstacle in improving their power density [1]. Volume and weight reduction of the electromagnetic components used in converters provides benefits such as reduced materials usage, lower cost, and better portability. To reduce the footprint of electromagnetic components, innovation in the design of ferromagnetic cores is needed which requires the development of fast and accurate design and modelling tools along with cost-effective rapid prototyping techniques for testing purposes. In this paper, a procedure for rapidly designing toroidal inductors with different core geometries is introduced. The procedure is based on the area-product method, but geometric parameters are able to be varied freely and the produced designs are not limited to standard core sizes. Once created, the behaviour of the designed inductors as L-filters in a single-phase inverter application is simulated using a MATLAB Simulink model for laminated magnetic cores based on that presented in [2]. The results can be used to determine optimal core geometries for different applications.

II Methods

A. Area-product method-based design

The area-product method is a well-established method for designing inductors which takes into account electrical, mechanical, and thermal requirements. It is described in detail in [3]. The area-product is the product of the core window area (W_a) and cross-sectional area (A_c). It is given by

$$A_\mathrm{p} = W_\mathrm{a} A_\mathrm{c} = \frac{L_\mathrm{ref} I_\mathrm{m}^2}{k_\mathrm{u} J_\mathrm{m} B_\mathrm{m}} \tag{1}$$

where L_ref is the required inductance, I_m the maximum current, J_m the maximum current density, and B_m the maximum flux density. k_u is the window utilisation factor and determines how much of the winding area is taken up by the copper winding.

Once the area-product has been calculated, the core which most closely matches the size determined by the area product calculation is selected from a catalogue. This often leads to a larger core than necessary being selected [4].

Growing accessibility to manufacturing techniques such as laser cutting and electric discharge machining allows for the rapid prototyping of cores, meaning cores which match exactly the calculated area-product can be quickly manufactured and studied. To this end, a modified area-product method was developed where hundreds of different cores, all with the same area-product, can be rapidly designed by varying the core height h and the ratio between the outer diameter d_o and inner diameter d_i of the toroidal core $k_\mathrm{d} = \frac{d_\mathrm{o}}{d_\mathrm{i}}$. Using this method, the inner diameter of the core is found from

$$d_\mathrm{i} = \left(\frac{8A_\mathrm{p}}{\pi h(k_\mathrm{d}-1)}\right)^{\frac{1}{3}}. \tag{2}$$

With this approach, 300 10.6 mH inductors were created using a MATLAB script and varying k_d between 1.4 and 2.6 for 12 different core heights between 12 mm and 80 mm. 25 designs were created for each core height. Figure 1 shows one half of the core of one of the designed inductors and the relevant geometric design parameters. Two halves are brought together, separated by an air gap, to create the whole inductor core.

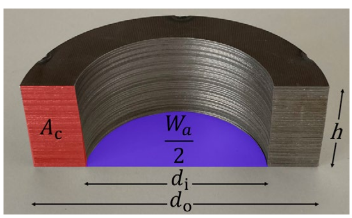

Figure 1: Example of inductor core geometric parameters

B. MATLAB Simulink inductor model

To simulate the behaviour of the designed cores, a time-domain MATLAB Simulink model for laminated cores was used [2]. The model combines eddy-current, hysteresis, and excess-loss models. Using the designed inductor geometries, equations for inductor voltage, flux linkage, magnetomotive force, and surface field strength in the core laminations are solved numerically for a given supply voltage waveform, and instantaneous power loss densities are obtained for each type of core loss. The total core losses are then found by multiplying the calculated instantaneous loss densities by the core volume and averaging over one period of the fundamental frequency. DC winding losses are also easily obtained from the model. The hysteresis curve supplied by the manufacturer for lamination material M330-35A was used to inform the model.

The inductor model was then combined with a simple single-phase inverter in Simulink with a 300 V DC input, 10.4 Ω load resistance, and switching frequency of 20 kHz. The RMS output current of the inverter was 5 A and an inductance value of 10.6 mH was selected to give a 5 % peak-to-peak current ripple at the output. Two periods of the fundamental frequency of 60 Hz were simulated and results for core losses, winding losses, current ripple, and inductance were obtained.

III Design and simulation results

Figure 2 shows the total weight of each of the designs made using the modified area-product method and their k_{d} values. Core heights increase for each set of 25 designs. Increasing the ratio between the outer and inner diameters initially reduces the weight of each design before increasing it. Similarly, weight decreases as the core height increases before beginning to increase. Many different variables can be studied in this way, including core weight, winding weight, air gap length, and volume. This can help in choosing an optimal design for a specific application.

Figure 3 shows results from the simulations which were carried out. For each set of core heights, increasing the ratio between the outer and inner diameters of the core increases the total losses. This is expected due to the increasing cross-sectional area of the cores. This trend was seen across the hysteresis, eddy-current, and excess losses which are also able to be separately studied. Winding losses showed the opposite relationship.

The inductor total losses were plotted against the price of materials for each individual inductor. It can be seen from Figure 4 that there are optimal inductors which have low losses and low costs. Attempting to reduce the losses past a certain point results in costs increasing.

IV Discussion and future work

The inductor design procedure presented in this paper allows for the rapid creation of hundreds of inductor designs for a single inductance value. Used in conjunction with the Simulink inductor model, data concerning each inductor's geometry, mass, and cost as well as power losses in power electronic applications can be easily studied, and optimal designs can be identified. The benefit of this kind of numerical inductor model is that it can model the behaviour of inductors much more quickly compared to analytical or finite element methods.

The next stage of the work is to validate the inductor model using empirical measurements taken from selected designs which will be manufactured from laminated sheets of the M330-35A material. Since the desire is to be able to produce rapid prototypes, initial tests have been carried out into which manufacturing methods are best for this purpose, with electric discharge machining showing the most promising results for cutting the core laminations. The veracity of the formulas used in calculating the effect of fringing flux as part of the area-product method are being studied using finite element analysis software. As one of the main goals of the work is to increase the power density of power electronic converters through optimisation of electromagnetic components, the inductor model will be used with the design techniques to study inductors operating in the saturation region as this offers a way of significantly reducing the sizes of the cores required.

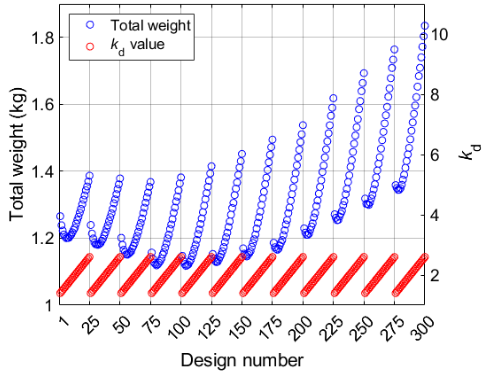

Figure 2: Total weight of each inductor design

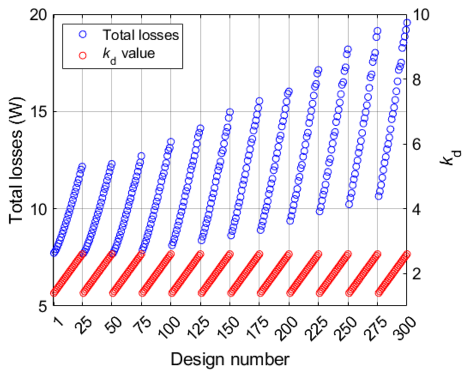

Figure 3: Total losses of each inductor design

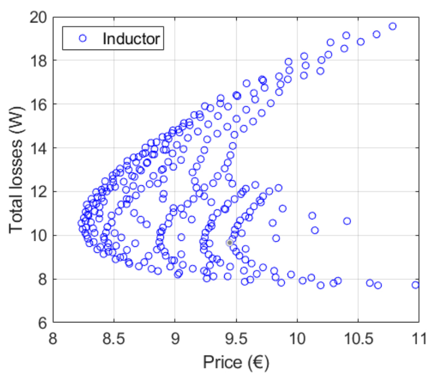

Figure 4: Losses versus price for each inductor design

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