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Magnetic Components Precise Modeling for Power Converters

A. Hilal, M.A. Raulet, C. Martin, F. Sixdenier

University of Lyon, University Lyon 1, CNRS UMR5005 AMPERE, Villeurbanne, F69622, France

In power electronics applications, magnetic components are often subjected to non-sinusoidal waveforms, variable frequencies and DC bias conditions. These operating conditions generate different losses compared to sinusoidal losses provided by manufacturers. Since virtual prototyping is used to predict and improve system's behavior before realization, losses and behavior prediction of components is required. Circuit simulators and their compatible components models are required. This work is summarized by proposing non-linear dynamic model of magnetic components for use in circuit simulators. It includes the material's nonlinear hysteresis behavior with accurate winding and core modeling. The magnetic component model is implemented in circuit simulation software "Simplorer" using VHDL-AMS modeling language. Waveforms and losses of a powder core inductor in a buck converter application are simulated and compared to measured ones.

Index Terms—Dynamic magnetic modeling, DC-DC converters, power losses, simulation, powder core.

I. INTRODUCTION

Power consumption and efficiency have always been of great concern in the development of power electronics systems. The increasing demand of low power, high efficiency devices [1] forced designers to precisely analysis losses in each component constituting the system. In the design and analysis of systems in general, specifically power converters, virtual prototyping assure time, failure rate and cost reduction [2]. Individual components models exist and are associated together to form a complete converter model. Passive components especially magnetic ones play a key role in power converters [3], thus behavior and loss analysis of these components is essential [4].

In this context our work takes place by proposing a non-linear dynamic model of magnetic components for use in circuit simulators. It includes the material nonlinear hysteresis and dynamic behaviors with accurate modeling of winding and core losses. The full model is described using VHDL-AMS modeling language and implemented in the circuit simulator "Simplorer". It is then tested for a powder core inductor in a buck converter. The model is validated for different ripple currents, different loads and a wide frequency range (10-100 kHz).

II. MAGNETIC MODEL CONCEPT

Inductors are components found in most power applications and converters. For each point of load application a specific design of these components is required. Considering a buck converter circuit Fig.1, the magnetic component model would replace the inductor. In the interest of precision and in order to be adaptable for different types of magnetic materials, the inductor model must adopt a structural modeling approach. As a consequence the model consists of 3 major blocks: a winding allowing the coupling between electrical and magnetic domains using Ampere's and Faraday's laws, a static model to describe the static hysteresis behavior of the magnetic material, and a dynamic model to add classical and excess losses in the core. VHDL-AMS language is chosen to describe each block behavior due to its multi-domain

modeling feature and since it is supported by several circuit simulators. Considering the middle operating frequency range, parasitic effects are negligible and not taken into account in the model.

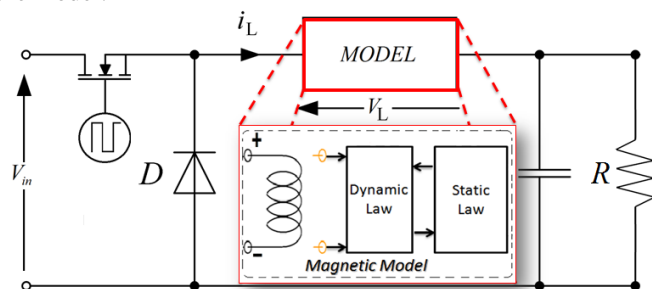


Fig. 1. Buck converter with the magnetic component structure.

Different static and dynamic models can be used to describe the behavior of magnetic material. The choice of the model depends on 3 main criteria: the material characteristics, the application and simulation factors like ease of implementation, accuracy and speed of simulation. The static and dynamic models chosen and their parameters identification are discussed in the following sections.

III. MAGNETIC MATERIAL CHARACTERIZATION

The behavior of magnetic components depends mostly on magnetic properties and geometry of core material used. Each material has its specific hysteresis and dynamic behaviors. Hence material characterization is mandatory to predict the appropriate static and dynamic models and their parameters.

Static measurements are performed on a test transformer consisting of primary and secondary coils wound on a toroid powder core. A sinusoidal current is applied to the primary winding, to create a magnetic field H and the flux density is calculated from the secondary voltage measured.

To describe the static behavior of the material, a mathematical model based on a piecewise polynomial function of order n is used. This model is reversible and limited to materials with low coercive field [5]. The parameters of the static model are identified from the static measurements using basic mathematical fitting.

Dynamic measurements are performed on the same test transformer under a sinusoidal 30 kHz applied flux density for different induction levels. The aim of these measurements is to study the dynamic losses arising in the material due to relatively high frequency applied flux density and extract the model parameters.

The dynamic model is based on the principle of separation of losses into static and dynamic contributions, as well as Bertotti's theory [6] assuming that the dynamic loss is the sum of both classical and excess losses. The total magnetic field is the sum of static field due to hysteresis and dynamic fields due to eddy currents and wall motion effects.

IV. BUCK CONVERTER APPLICATION

In many power applications, magnetic materials are excited with non-sinusoidal waveforms. This provokes different losses compared to those provided by manufactures based on sinusoidal excitation [7]. DC bias has also a significant effect on losses [8]. In order to investigate magnetic components behavior in power applications, a 40 W buck converter is realized. The circuit design allows variable voltage, frequency and load. Inductor used in the circuit is the same powder core previously characterized with 30 turns copper wire.

To measure precisely magnetic losses, a small shunt is added in series with the inductor and 10 secondary turns are wound to the same core. The shunt allows precise current measurements, while open secondary side allows voltage measurement excluding coil losses. Knowing the primary current and secondary voltage, iron losses are calculated using (3)

$$P = \frac{1}{T} \int_0^T \frac{N_1}{N_2} v_2(t) \cdot i_1(t) \cdot dt \quad (3)$$

A circuit identical to the buck circuit used for measurements is simulated in Simplorer. The model replaced the inductor including both static and dynamic models plus core dimensions. Winding resistance and number of turns are inserted to the winding block in the model. Measured and simulated waveforms are in good agreement, Fig. 8 and Fig. 9.

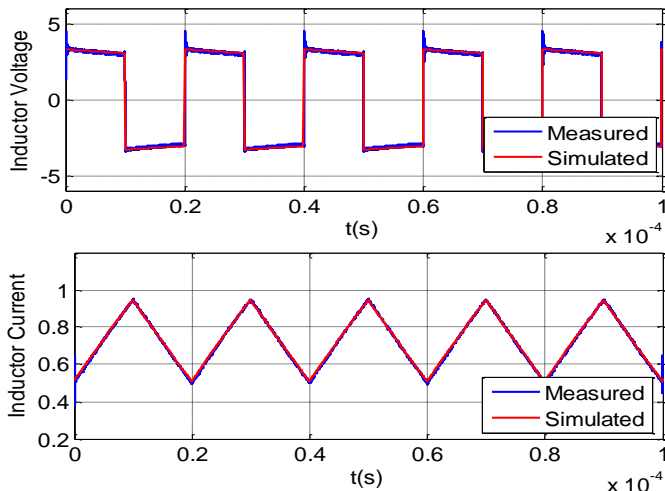


Fig. 9. Measured and simulated inductor voltage and current at $f=50$ kHz.

Furthermore simulated iron losses for different induction levels are compared to measured ones in the 40 to 100 kHz frequency range. Results are shown in Fig. 10. We note that the losses are predicted using a single dynamic parameter “ α ” identified from sinusoidal measurements. Experiments confirm model's loss prediction accuracy with a maximum error of 3%.

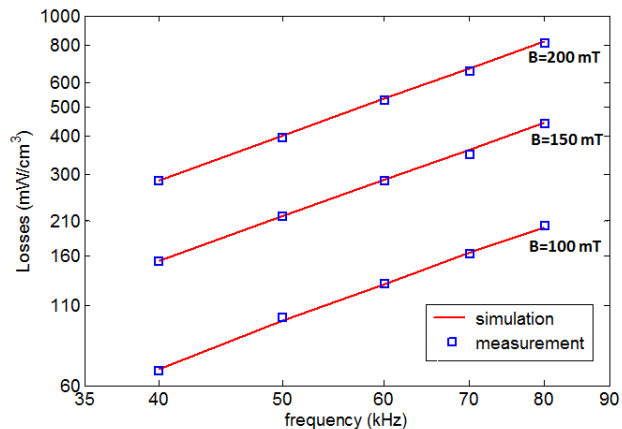


Fig. 10. Measured and simulated core losses.

V. CONCLUSION AND PERSPECTIVES

In this paper the behavior of a power inductor in a widely used power converter topology is studied. Development of a magnetic component model for use in circuit simulation is presented. Simulations of a buck converter including the proposed model are compared to measurements. The magnetic component model allows precise prediction of core and winding losses. Simulated inductor current and voltage correspond to measured ones. Model's parameters are extracted from magnetic material characterization under sinusoidal excitation. Results are in good agreement for different induction levels and a wide frequency range.

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