Università degli Studi di Salerno

Dottorato di Ricerca in Informatica e Ingegneria dell'Informazione
Ciclo 31 – a.a 2017/2018

Tesi di Dottorato / Ph.D. Thesis

Methods and Algorithms for Behavioral Modeling of Ferrite Power Inductors

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Abstract

Information technology allows solving numerous problems regarding all the aspects of everyday life, including technical activities related to the design of devices and systems. In the electronic field, different types of softwares are widely used to support designers in solving the problems of electronic circuit design, at device level and system level. Power electronics is one of the most important modern technologies, since power supply systems are used to feed any electric and electronic device and system in manifold applications (e.g. computers, automotive, aerospace, consumer electronics, *etc*). Switching power supply design is mostly driven by high efficiency and high reliability requirements. The strong non linearity of switching power supplies and the difficulty of application of advanced design methodologies often push designers to adopt a conservative approach, based on simplified robust and reliable methods. This mostly result in sub-optimal design solutions characterized by components oversizing. This dissertation discusses innovative applications of enhanced numerical techniques and intelligent algorithms to power supplies optimization and design. The impact of innovative modeling and computing techniques in the discovery of novel advanced solutions outperforming the traditional conservative designs is emphasized.

Power electronics is ever moving towards higher efficiency and higher power density. Magnetic components — inductors and transformers — occupy a significant amount of space in today's Switch-Mode Power Supplies (SMPSs), and furthermore, considerable losses occur in these components. In order to achieve a higher level of miniaturization, reduction in the size of these components is crucial. Ferrite Power Inductors (FPIs) are usually the first choice for high-efficiency designs of SMPS, thanks to their resulting low losses. However, FPIs suffer of a pretty sharp inductance drop when their current exceeds a certain threshold, occurring due to the saturation of their magnetic

core. In SMPS design, it is commonly considered a good practice to select FPIs operating in the region of *weak saturation* (within about 20% inductance drop). This limitation is due to the lack of methods for quick prediction of real impact of FPIs saturation in SPMS applications. The consequence of the adoption of such conventional design approach is that inductors are often oversized.

In recent years, inductors saturation has been the subject of several scientific investigations. Some authors have verified that smaller volume inductors working in moderate saturation help achieving more compact SMPSs with an acceptable amount of power losses. To effectively and safely exploit the benefits offered by the use of FPIs in moderate and controlled saturation, appropriate saturation models and power loss models are needed. As regards the saturation models, recently several inductor manufacturers have started providing more complete information about the inductance *vs* current (L *vs* i_L) curves of their magnetic parts, at different operating temperatures. To accurately describe such curves, an *arctangent-based* behavioral model has been recently proposed, which can be used in combination with a developed numerical algorithm to reliably reconstruct the inductor current wave-shape under SMPS conditions, including saturation. Such model and numerical algorithm have been verified only for positive inductor currents in Continuous Conduction Mode (CCM). However, certain applications may involve High Current Ripple (HCR) inductor operation, which represents the new trend in power converters using wide band-gap devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) transistors. HCR operation can result in the occurrence of negative inductor currents in synchronous-rectification converter topologies, and Discontinuous Conduction Mode (DCM) in diode-rectification topologies. Hence the existing arctangent-based saturation model needs to be extended and the relative numerical algorithm adapted also to cases involving negative inductor currents and DCM operation, in order to develop a generalized saturation behavioral model for FPIs. However, to obtain realistic reconstructions of the inductor current waveforms in saturation, reliable L *vs* i_L data are needed. The datasheet L *vs* i_L curves are typically characterized by high uncertainty levels (e.g., ±20%), due to manufacturing tolerances on components. Moreover, such curves are measured under small-signal sinusoidal voltage test conditions, thus making the manufacturers' data not sufficiently reliable for a realistic determination of the peak-to-peak inductor current ripple in large-signal square-wave voltage conditions imposed by the SMPS operation. Therefore, the systematic procedures are needed for identification of the temperature-dependent L *vs* i_L curves in real SMPS conditions.

As regards the power loss models, FPIs total power losses are determined by winding losses and magnetic core losses. However, the core and winding losses cannot be easily measured as separate contributions in SMPS applications. FPIs total power losses can be alternatively evaluated as the sum of a DC term and an AC term. Since the DC losses can be easily estimated from the DC winding resistance and the DC current flowing through the winding, the major challenge still remains how to determine a compact behavioral model for the AC losses of FPIs, given as a function of the main operating conditions directly imposed to the inductor by the SMPS.

The saturation models and power loss models of FPIs need to be coherent between them. As discussed above, the saturation L *vs* i_L curves depend on the inductor temperature, which, in its turn, is dependent on the ambient temperature and inductor total power losses, through the device thermal resistance. Thus the temperature is not a real *input* to the inductor model, but rather an *output*, representing the response of the device to given ambient temperature and total power losses. Hence the inductor total power losses should be used as an input to the saturation model, instead of temperature. Once the saturation and power loss behavioral models of FPIs are identified, they can be adopted at system-level simulation of the converter, so as to discover and exploit the benefits offered by the use of FPIs in saturation.

Considering the above issues, the aim of this dissertation is to provide organic and systematic answers to the problems of the high-power-density SMPS design exploiting the use of FPIs operating in saturation. In particular, the specific objectives of this dissertation are:

a) development of numerical techniques and intelligent algorithms for generation and discovery of behavioral models for saturation and power losses of FPIs used in SMPS applications;

b) development of enhanced numerical algorithms, using the above models, able to reliably predict the FPIs behavior under given SMPS conditions;

c) development of enhanced numerical algorithms able to identify feasible inductor solutions, possibly operating in saturation, allowing to reduce the inductor size and increase the converter power density.

The dissertation is organized as follow:

In Chapter 1, a generalized *arctangent*-based behavioral model accurately fitting the L *vs* i_L curve of FPIs is presented. Such model can be used in combination with the proposed numerical algorithm to reliably predict the inductor current wave-shape in whatever operating condition, including saturation.

In Chapter 2, the Evolutionary Algorithm-based approach for the identification of the temperature-dependent L *vs* i_L curves of FPIs is discussed, based on the use of experimental inductor current waveforms and temperatures in real SMPS conditions. Then, an alternative approach is presented, based on the local and global approximations of the inductor saturation characteristic, obtained under small-amplitude and large-amplitude current ripple conditions, respectively.

In Chapter 3, a non-linear modeling of ferrite inductors with a stepped air-gap is discussed. The arctangent-based L *vs* i_L model, proposed in Chapter 1 for fixed air-gap FPIs, is extended to a *double-arctangent model.* Such model accurately describes the saturation characteristic of stepped air-gap inductors and allows to reliably predict their current wave-shapes in saturation.

In Chapter 4, the Sustainable Saturation Operation (SSO) of FPIs is discussed, which is verified if the inductor current ripple, power losses and temperature rise are acceptable and reliable for both the device and the SMPS, despite the inductance drop determined by the core saturation. An algorithm is presented which identifies SSO-compliant FPIs with minimum size and volume, thus allowing to increase the SMPS power density, while preserving the overall converter efficiency.

In Chapter 5, behavioral modeling of the FPIs total power losses is presented, followed by the modeling of the sole *AC* loss contribution. Both approaches are based on the use of a Genetic Programming algorithm, which identifies the power loss model structure and the relevant parameters, starting from a set of experimental power loss data measured on a wide range of SMPS operating conditions.

In Chapter 6, a novel *power-loss-dependent* saturation model is presented, which provides the inductance as a function of inductor current, parameterized with respect to the component total power losses.