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Switching Power Supplies with Ferrite Inductors in Sustainable Saturation Operation

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ABSTRACT

This paper investigates the Sustainable Saturation Operation (SSO) of Ferrite Core Power Inductors (FCPIs) in Switch Mode Power Supplies (SMPSs). A ferrite inductor is considered in SSO if its 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 discussed, which identifies SSO-compliant FCPIs with minimum size and volume, given the SMPS specifications about the allowed power losses, temperature rise and peak-to-peak current ripple of the inductor. The experimental results relevant to a 465 kHz/3.3 V/1.5 A buck converter show that SSO-compliant inductors allow to increase the SMPS power density, while preserving the overall converter efficiency. Despite the proposed low power application, the findings relevant to the utilization of power inductors in partial saturation have general conceptual valence and similar investigations can be prospectively re-assessed for few kW output power DC/DC converters.

1. Introduction

Magnetic components occupy a significant amount of space in Switch Mode Power Supplies (SMPSs) with inductive energy transfer. The minimization of inductors and transformers is crucial in order to obtain higher-power-density SMPSs, for both discrete and integrated solutions. Ferrite Core Power Inductors (FCPIs) are usually the first choice for high-efficiency designs of SMPSs, because they are characterized by low losses [1] and no thermal aging [2]. For each FCPI, the manufacturer typically provides the levels of current $I_{10\%}$, $I_{20\%}$ and $I_{30\%}$, causing 10%, 20% and 30% drop of the inductance with respect to its nominal (zero current) value L_{nom}. These parameters are normally used by power designers to select FCPIs. For a given desired inductance value, the size of the core needed to design the inductor is larger if higher $I_{10\%}$ and $I_{20\%}$ values are required [3]. In fact, the conventional design approach consists in ensuring that, even in the worst case conditions, the peak current flowing through the inductor does not exceed the $I_{10\%}$ or the $I_{20\%}$ value, keeping the maximum inductor peak-to-peak current ripple $\Delta i_{Lpp,\max}$ close to 40% [4]. This limitation is partially motivated by the assumption that an inductor operating with higher saturation may be subjected to higher core losses due to the higher peak-to-peak current ripple. As possible second reason, it looks difficult to predict the peak-to-peak current ripple when the inductor operates in the region where the inductance sharply rolls off. The consequence of the adoption of conventional design approaches is that inductors are often oversized [5].

In recent years, inductors saturation has been subject of several investigations [5–9]. In [5] a 3.3 × 3.3 × 1.0 mm^3 (10.9 mm^3) ferrite core with 1 μH nominal inductance and rated for 1.6 A can properly operate in SMPS also past its saturation point up to 2.1 A. Similarly, saturated inductors can reduce PCB area and space by at least 50% over competing alternatives, while increasing total peak power conduction losses by no more than 3%. In [6] a modeling procedure for the simulation of a POT type FCPI has been proposed, allowing to reproduce both the magnetic flux *versus* current curve and the corresponding inductance *versus* current curve in the entire working range, from the linear to the saturation region. In [7] a nonlinear model has been developed to adjust the inductance curve of a nonlinear saturable inductor with respect to a desired shape, showing that a highly efficient construction with low stray fields and maximum package density can be achieved. In [8] a numerical method to analyze the effects of saturation of FCPIs in SMPS applications is discussed. Given the voltage applied to the FCPI in the charge and discharge intervals of a SMPS, such modeling technique allows to reliably predict the magnitude of the inductor current ripple for whatever amount of saturation. An enhancement of [8] is presented in [9]. The resulting generalized numerical method presented in [9]

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Nomenclature

V_{in}	input voltage [V]	Δi_{Lpp}	inductor current ripple [A]
V_{out}	output voltage [V]	$I_{L,rms}$	inductor rms current [A]
I_{out}	output current [A]	DCR	inductor dc resistance [Ω]
T_s	switching period [s]	T_a	ambient temperature [°C]
f_s	switching frequency [Hz]	P_{Fe}	core losses [W]
D	converter main switch duty-cycle	P_{Cu}	winding losses [W]
I_{pk}	inductor peak current value [A]	R_{th}	inductor thermal resistance [°C/W]
I_{vl}	inductor valley current value [A]	A_e	equivalent cross-sectional area [m^2]
L_{nom}	nominal inductance of the inductor [H]	l_e	equivalent magnetic path length [m]
L_{sat}	inductance value in deep saturation [H]	B_{pk}	ac peak magnetic flux density [T]

allows to achieve a reliable prediction of the current ripple for different converter topologies (buck, boost and buck-boost) and in whatever operating conditions (continuous and discontinuous conduction modes), including high-current-ripple-based applications. Since such recent studies have definitely highlighted that FCPIs operating in moderate saturation can reduce the size, weight and cost of SMPSs, if compared to the conventional design approach, manufacturers are now providing more data and detailed inductance *vs* current curves for FCPIs [10–13].

Military and civil aircrafts, space stations and satellites are all increasing the electrical power demand, due to the increase of communications, surveillance and monitoring systems and mostly to the partial or complete replacement of pneumatic, mechanical and hydraulic equipments by electrical systems [14]. Enhanced power electronics is needed to handle such growing demand of electric power in More Electric Aircraft (MEA) power systems. In this context, new high voltage DC (±270VDC, 10 kW load) and AC (230VAC, 10 kW load) architectures and enhanced hybridization of power sources with storage devices are the main trends [15]. More integrated power systems also represent remarkable challenges [16]. In this scenario, the weight and volume reduction of power electronic equipments is worthy of major attention. New approaches ensuring power electronic solutions with higher power density deserve to be explored, both in traditional military and space systems, and in new challenging applications, like unmanned aircrafts and micro/nano-satellites, where the weight reduction issues are even more important.

Magnetic components, transformers and inductors, represent an important issue limiting the integration of power converters for MEA power systems. In recent years, different DC/DC isolated converters for MEA applications have been proposed and prototypized, for example with 4.5 kW maximum power and 94% nominal efficiency [17], or 12 kW maximum power and 1 kW/kg power density [18]. The exploitation of magnetic component saturation in high voltage architectures can potentially benefit the achievement of high-power-density and high-power-efficiency MEA power systems. In fact, the design of SMPSs with power inductors working in Sustainable Saturation Operation (SSO) is a viable approach to increase the power density, thanks to a strong reduction of inductors volume. The design of enhanced converters for MEA applications, including SSO-compliant magnetics, is a challenging goal. However, to the best of Authors' knowledge, no useful guiding principle on SSO of magnetic components have been ever provided in literature. Therefore, the goal of this paper is to provide guidelines to validate the SSO of FCPIs in the design of SMPSs with high power density. The discussion is herein referred to non-isolated DC/DC converters topologies, with output power levels lower than 100 W. This choice has allowed and made easier a comprehensive and wide experimental campaign, conducted both at device and at system level, whose results are presented in this paper. Nevertheless, the considered low power application is only a reference example, and the findings relevant to the utilization of power inductors in partial saturation discussed in this paper have a more general conceptual valence. Indeed, the same investigation can be prospectively re-assessed for a few kW output power DC/DC converter with similar results.

In Section 2, a FCPIs modeling in SMPSs and a related analysis algorithm for their SSOs evaluation are presented. Such algorithm allows to identify SSO-compliant FCPIs with minimum size and volume, given the SMPS specifications about the allowed power losses, temperature rise and peak-to-peak current ripple of the inductor. Reference case studies are discussed in Section 3, where optimal design solutions, including SSO-compliant FCPIs, are compared in terms of power losses, volume and operating temperature. In Section 4, the SSO analysis algorithm results are validated through experimental tests. The analysis and relevant results of FCPIs are herein specifically referred to a 465 kHz/3.3 V/1.5 A buck converter operating in continuous conduction mode. Nevertheless, the proposed concepts and SOO analysis algorithm can be extended to other topologies and operating modes. The concept of SSO is applicable in general with reference to the operating conditions imposed to whatever FCPIs in terms of volt-second integral, average current and ripple current. Critical discussion and practical limitations of the present SSO analysis algorithm are also provided in Section 4. Design guidelines for SSO-compliance are eventually given in Section 5.

2. FCPIs operation and main related issues

2.1. FCPIs current waveform prediction

A correct modeling of FCPIs in whatever possible operating condition is a very important issue in SMPSs design. Let us refer to a buck converter with $V_{in} = 5$ V, $V_{out} = 3.3$ V, $f_s = 465$ kHz, and consider a FCPI of nominal inductance value $L_{nom} = 15$ μH. In Fig. 1(a), the experimental *L vs I* characteristic of a Coilcraft MSS7341-153 is depicted [10]. Accordingly, Fig. 1(b) shows the simulated current wave-shapes of such inductor working with average current $I_{L,av}$ such that the inductor peak-to-peak current ripple falls entirely within the weak-saturation region (red waveform, with $I_{L,av} = 1$ A), or within the roll-off region (green waveform, with $I_{L,av} = 2$ A), or within the deep-saturation region (blue waveform, with $I_{L,av} = 3.5$ A). Such simulated waveforms are obtained by means of the non-linear inductor modeling provided in [8]. For each value of the average current $I_{L,av}$, the operating point swings along the *L vs I* curve during the switching period T_s, as highlighted in Fig. 1(a). In particular, the inductor current wave-shape is cusp-like in the roll-off region and its inductance swings over the range from about 3 μH to 12 μH delimited by current ripple extremes.The behavioral model proposed in [8] describes the non-linear inductance vs current characteristic of FCPIs by means of the following analytical function of $L(i_L)$: