UNIVERSITY OF PERUGIA
PHD WORKSHOP

Modeling of magnetic materials and DC-DC converters for medium-high frequency power applications

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In this work, different approaches to the modeling of magnetic materials and power converters are proposed. The main problematics to be considered when these devices work at medium-high frequency are underlined, showing how they influence the way the model them.

Introduction

Power converters play a crucial role in the nowadays life. The increasing electrification in many sectors, from both the industrial and the domestic areas, and the large diffusion of renewable energy sources (with the respective storage systems) comes to a growing necessity of devices for the electric power conversion with high performances under multiple points of view (efficiency, power density, reliability, costs…). The performance optimization of power converters can be done by intervening on several aspects: materials (especially for the magnetic parts, to limit the losses of the inductors), components (electronic devices to reduce the switching losses) and architectures (for example DAB or resonant converters, wired or wireless, to work at high frequency with high efficiency). The advantages achievable in the power converters performances increasing the working frequency, drive the development of specific models and design approaches for these devices and their sub-parts.

Modelling of ferrites magnetic cores

Ferrite magnetic cores are widely used in power electronics because of their possibility to work at high frequency (up to several tens MHz). Two main loss mechanisms afflict magnetic cores: static hysteresis losses, and dynamic losses, which are caused by eddy currents and excess losses. Two kinds of eddy currents can be considered for ferrites due to its bi-phasic nature: intragranular and intergranular eddy currents. Intergranular eddy current losses generally dominate other kinds of losses when ferrite cores work at high frequencies. A simple analytical model to predict the losses of these cores due to inter-granular eddy currents is proposed [1].

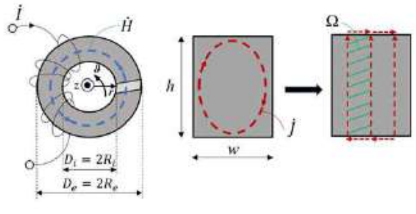


Figure 1: Sketch of the toroidal ferrite core; sketch of the current path in the real and simplified model.

Under some hypothesis about the paths of the eddy currents and about the behaviour of the magnetic field, the electric field can determined in analytical way.

$$E(r) = E(R_i) - NI\frac{j\omega\mu_{eq}}{2\pi}log\left(\frac{r}{R_i}\right)$$

Where:

$$E = E_g\delta_g + E_b\delta_b$$

Losses due to inter-granular eddy currents can be derived as:

$$P_{Loss}[W] = \iiint Re[EJ^*]dV = Re[\sigma_{eq}]\iiint |E|^2 dV$$

The model is compared with measurements on a T38 ferrite and with a FEM model which works without approximations on electric and magnetic fields.

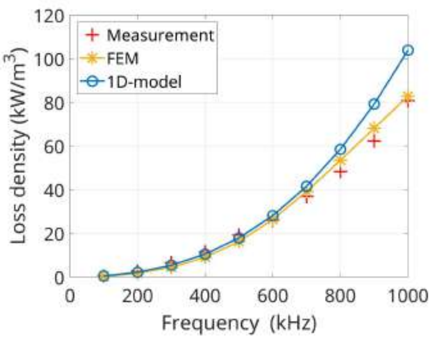
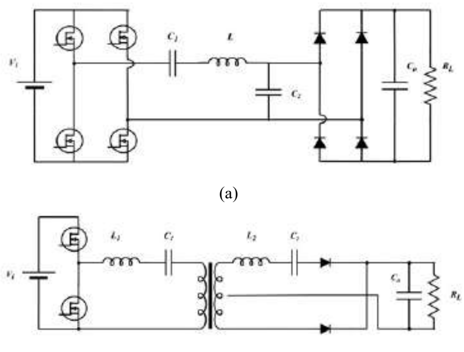


Figure 2: Comparison between predicted and measured losses.

Modelling of DC-DC Resonant Converters

The key-aspect which drives the development of DC-DC converters is the increase of the working frequency. In this way, both the power density and the efficiency of the converter can increase. For this reason, the most common topology adopted for this purpose is the resonant converter. Resonant converters are used both in wired and wireless applications. Some typical topologies are shown in Fig. 3.



(a)

(b)

Figure 3: LCC converter (a), CLLC converter (b).

One of the most popular strategy is based on Extended Describing Function (EDF) approach. It is based on the concept that, when the converter works exactly or near its resonant conditions, the LC dipoles filter all the harmonics from the input voltage waveform, except the fundamental one. In this way, the converter can be studied as a sinusoidal circuit. With this assumption, it is quite easy to derive a model able to study the converter both in transient and steady-state conditions, and there is also the possibility to derive the Small Signal Model (SSM) for the circuit. The SSM gives the possibility to design several closed loop control strategies where a specific control variable (for example the working frequency, the duty cycle, the load) is controlled to obtained the requested value for the output voltage [2]. The results of some control strategies for different needs designed using the converters SSM are reported in Fig. 4-5-6.

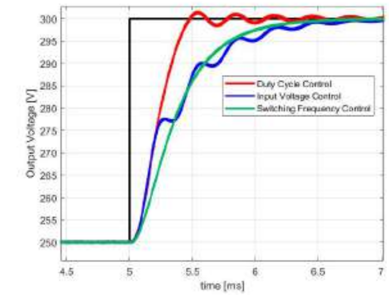


Figure 4: Different control strategies when the setpoint output voltage is changed in a Series-Series compensated Wireless converter.

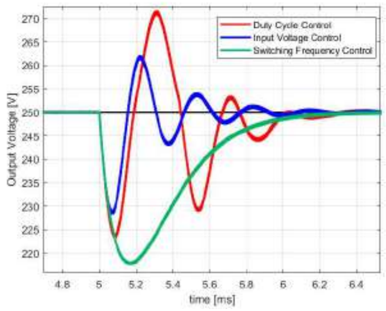


Figure 5: Different control strategies when a load variation occurs in a Series-Series compensated Wireless converter.

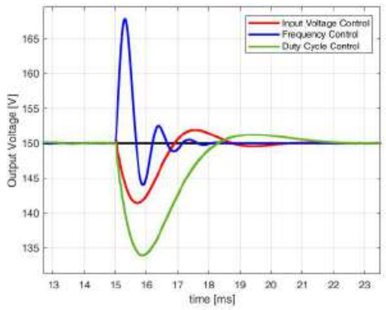


Figure 6: Different control strategies when a misalignment occurs in a Series-Series compensated Wireless converter.

However, the described model correctly works when some hypotheses are verified, in particular:

- The converter works quite near its resonant frequency;
- The non-linear behaviour and the losses of the magnetic components are neglected;
- An ideal behaviour of the switching components is assumed.

For now, the attention has been focused on the second aspect, trying to use an equivalent circuit to model the static losses of an inductor used in an LLC resonant converter [3]. The variable resistance to model the static losses can be defined as follow:

$$R_{hs} = \lambda_{hs}\frac{N^2 S}{l} \qquad \lambda_{hs} = \frac{2\pi^2 f_w^2 B_{max}^2}{W_{loss}}$$

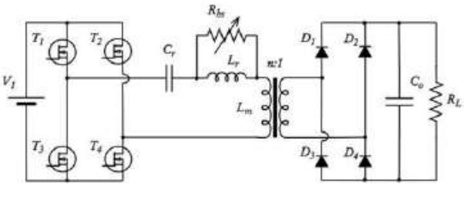
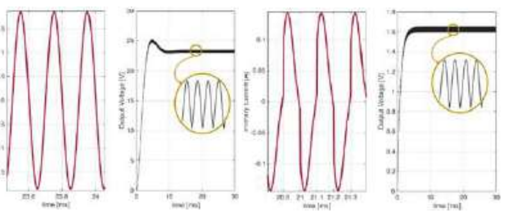


Figure 7: LLC converter considering the magnetic static losses of the resonant inductor.



(a)

(b)

Figure 8: . Comparison in terms of Primary Current and Output Voltage when an ideal inductor (a) or a real one (b) is considered.

References

[1] Bertolini, V., Stella, M., Scorretti, R., Faba, A., and Cardelli, E., “Eddy current losses model and physical parameters evaluation for ferrite magnetic cores in frequency domain”, Journal of Magnetism and Magnetic Materials, vol. 594, 2024. doi:10.1016/j.jmmm.2024.171905.

[2] V. Bertolini, F. Corti, E. Cardelli and A. Reatti, "Control Strategies for Output Voltage Regulation in a SS Compensated Wireless Charging System," 2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON), Palermo, Italy, 2022, pp. 896-901, doi: 10.1109/MELECON53508.2022.9842927.

[3] V. Bertolini, M. Stella and R. Scorretti, "Circuit Modelling of Static Magnetic Losses of Ferrite Cores and Application on an LLC Converter," IEEE EUROCON 2023 - 20th International Conference on Smart Technologies, Torino, Italy, 2023, pp. 429-433, doi: 10.1109/EUROCON56442.2023.10198989.