

Identification of the Magnetic Permeability of Ferrite Materials based on Time Domain Measurements

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The development of models for the modeling and numerical simulation of the electromagnetic behavior of electronic-based systems (EBS) - in order to predict their electromagnetic compatibility (EMC) with other electrical devices - requires a good knowledge of the specific materials to be used in such EBS. Ferrite materials are often used for inductors, such as those found in electromagnetic interference (EMI) filters. Common mode chokes (CMC) are a prominent example of such inductors. Unfortunately, the frequency-dependent dispersive permeability of such ferrite materials is often unknown, so the complex permeability must be determined by measurement such that certain model parameters can be fitted to the observed behavior. These material models can then be used for developing a digital twin of the EBS to pre-estimate the EMC behavior. In the present work a time domain measurement based approach is proposed which enables the determination of the frequency-dependent permeability of a CMC by using the Fast Fourier Transform (FFT) of the time domain measurement signal. A comparison of the proposed method to a frequency domain based method is presented.

Index Terms—Conducted emissions, Electromagnetic interference, Ferrite material, Magnetic material modeling

I. INTRODUCTION

With the push for decarbonisation has come an increased demand for modern power electronic devices. Such advanced power electronic devices, such as DC-DC converters, typically rely on switching transistors. With the introduction of advanced semiconductor materials such as Silicon Carbide and Gallium Nitride, switching frequencies have been increased, resulting in lower heat dissipation and higher integration density [1]. However, these gains come at the cost of increased electromagnetic (EM) emissions and the need for countermeasures such as EMI filters. In modern EBS design and development, pre-estimation of the EM behavior of the EBS by means of a digital twin has become state of the art, hence, also the EMC related countermeasures have to be modeled accordingly [2]. A commonly used device is the common mode choke (CMC), which is typically based on a ferrite core material. Due to the non-ideal dispersive behavior of the ferrite core material, proper modeling of these components is required to account for both frequency and DC bias related influences. In [3] a numerical optimization based method is proposed, which relies on the Kramers-Kronig (KK) relationship [4] and frequency domain impedance measurement data. By exploiting the KK relationship the real part of the complex permeability of the ferrite core material can be estimated from the losses of the material. A different approach is proposed in [5], where the parameters of a general 2nd order dispersion model for the complex permeability are optimized to fit the measured frequency domain data. State-of-the-art surrogate models are used to reduce the computational burden of obtaining the dispersion model parameters. The main drawback of the two above discussed methods lies in the sophisticated measurement

devices like vector network analyzers (VNA) or impedance analyzers which also require a proper calibration strategy to eliminate the influence of the test setup on the measured quantities. To overcome this problem a time domain oscilloscope measurement is proposed. The obtained results are compared to the frequency domain approaches.

II. TIME DOMAIN MEASUREMENT METHOD

The goal of the time domain measurement method is to extract the frequency-dependent complex permeability of the ferrite sample from a transient response recorded in the time domain. The measurement setup is fairly simple: initially, a capacitor is charged, then connected to a coil on a ferrite core under investigation, and the voltage of the coil is recorded by an oscilloscope during the discharge process. The circuit model and a principle sketch of this measurement setup are shown in Fig. 1. The current source represents the initial charge Q , and the serial RL circuit models the ferrite-cored coil with the wire resistance R and inductance $L = L(\omega) = \mu_r(\omega)L_0$. The latter is a frequency-dependent complex-valued parameter, which is directly proportional to the relative permeability $\mu_r(\omega) = \mu'(\omega) - j\mu''(\omega)$ of the ferrite, in the case of a closed, e.g., toroidal core. The proportionality factor L_0 is calculated using the dimensions of the core and describes the inductance of the coil in absence of the core material [6]. The voltage $u(t)$ is recorded, its spectrum $U(j\omega)$ is calculated by using FFT, finally $L(\omega)$ can be expressed therefrom by elementary circuit theory. Note that the wire resistance R is typically negligible compared to the real part of $j\omega L(\omega)$, i.e., ferrite loss dominates over wire loss. Furthermore, the parasitic capacitance of the winding can also be neglected, since the external capacitance C is chosen to be much larger.

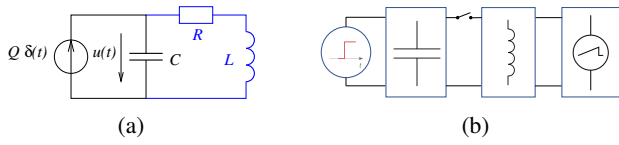


Fig. 1: (a) Circuit model of the time domain measurement. The Dirac delta source current represents the initial charge, the blue RL circuit models the coil under test. (b) Block diagram of the measurement setup. The charged capacitor is connected to the coil under test and the transient voltage $u(t)$ is recorded.

Though the procedure above yields both the real part μ' and the imaginary part μ'' of the complex permeability, the latter can be very small at low frequencies, hence the relative error of the identification may be unacceptably high. To increase the accuracy, the Kramers-Kronig relation is applied, which expresses the function $\mu''(\omega)$ from $\mu'(\omega)$ in terms of an integral transform. Therefore, only the real part $\mu'(\omega)$ needs to be obtained from the spectrum of the circuit's response.

A. Example and preliminary results

As an example, the ferrite-cored CMC Würth 744825410 is considered (the same as discussed in [5]). There are two windings on a toroidal core, each has 10 turns, one of them is used in the experiment, the other one is open. A 4.7 nF capacitor is charged to a few volts. The time function of the voltage during discharge is recorded using a PicoScope 2205A with a bandwidth of 25 MHz, recording a total of 10k samples. As the relaxation frequency of the ferrite material is below 1 MHz, the achievable bandwidth is well suited. The record with noise filtering is shown in Fig. 2. Though the function looks similar to the impulse response of linear RLC circuits, note that this is a more complex circuit, as the inductance is frequency-dependent due to the ferrite core.

The results of the proposed time domain identification are compared to the reference data provided by the manufacturer of the CMC [5] and are shown in Fig. 3. The agreement is acceptable as the results obtained for μ' (up to the relaxation frequency of the material) fall within the confidence interval of the reference measurement, which itself is given by the manufacturer as $\pm 30\%$. Furthermore, the reference data shows negative values for μ'' at low frequencies (≤ 10 kHz), suggesting a non-physical material behaviour. In contrast, the identified μ'' does not exhibit this negative value, giving a more realistic material characteristic. Also, the observed relaxation frequency at about 600 kHz [5] is accurately predicted by the time domain method.

III. SUMMARY AND OUTLOOK

A time domain measurement based approach is proposed for the determination of the unknown frequency dependent complex permeability of a CMC ferrite core material. The main advantages of the time domain method are its simplicity (a cheap and widely available oscilloscope is needed only), robustness against the parasitic capacitance of the turns, and speed. A possible extension of the method could be to imply

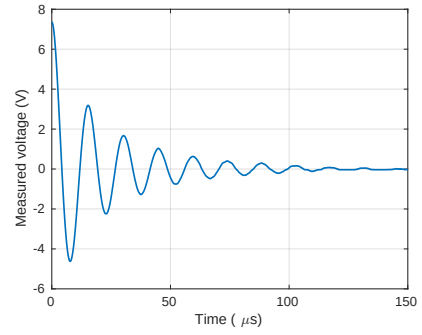


Fig. 2: Measured voltage $u(t)$ at the terminals of the CMC over time during the discharge.

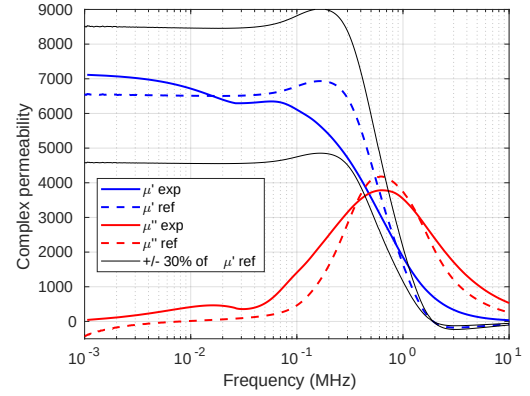


Fig. 3: Complex permeability: result from the experiment ("exp") and reference from the manufacturer's datasheet ("ref"), along with the $\pm 30\%$ tolerance interval of μ' .

DC bias (using the 2nd winding on the same core) and perform similar studies on $\mu(\omega)$ at different operating points. A key point of the method is to find an expression between the inductance $L(\omega)$ and the core permeability $\mu(\omega)$ for the specific inductor under test. In the case of a closed toroidal core, this is a simple linear proportionality. The determination of this relation for other inductor shapes, e.g. stacked planar coils as can be found in SMT ferrite beads, is a matter of ongoing research activities.

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