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How to include frequency dependent complex permeability
Into SPICE models to improve EMI filters design?

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Electromagnetic interference (EMI) filters design is a rather difficult task where engi-
neers have to choose adequate magnetic materials, design the magnetic circuit and
choose the size and number of turns. The final design must achieve the attenuation
requirements (constraints) and has to be as compact as possible (goal). Alternating
current (AC) analysis is a powerful tool to predict global impedance or attenuation of
any filter. However, AC analysis are generally performed without taking into account
the frequency-dependent complex permeability behaviour of soft magnetic materials.
That’s why, we developed two frequency-dependent complex permeability models
able to be included into SPICE models. After an identification process, the perfor-
mances of each model are compared to measurements made on a realistic EMI filter
prototype in common mode (CM) and differential mode (DM) to see the benefit of the
approach. Simulation results are in good agreement with the measured ones especially
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I. INTRODUCTION

Static converters have made a lot of progress these last decades thanks to a better knowledge
of semiconductor power switches and the increase of switching frequencies which allows to reduce
drastically the volume of passive components (magnetic, and capacitors). Unfortunately, increasing
the switching frequency leads to generate a large amount of electromagnetic interferences (EMI).
Two types of disturbances exist: common mode (CM) and differential mode (DM). Usually, each
type of disturbance requires a specific magnetic component (an inductance designed with wind-
ning modes and materials well suited to every need) and specific capacitors (Cx(DM),Cy(CM)).
Scientists and engineers are then involved in the development of EMI filters design softwares.1,2
These approaches generally neglect the frequency dependent complex permeability (µ) of the soft
magnetic materials (with µ(f) = µ′(f) − jµ′′(f)). The real part µ′ gives an image of how much
energy can be stored whereas µ′′ gives an image of the losses. Two frequency-dependent complex
permeability models able to be included into SPICE models for AC analysis are presented here.
The first model is inspired by the magnetic field diffusion equation solution3 and the second one
is inspired by Nomura’s work.4 Both models are implemented thanks to behavioural sources and
Laplace equations available in Spice softwares. Their implementation in LTSpice® will be explained
in the second section. Results concerning the ability of each model to predict complex permeabil-
ity versus frequency on two different materials will be shown on the third section as well as all
simulation cases of the EMI filter to see the benefits of the approach on a realistic device. Dis-
cussion of all the results will be made in the fourth section. The last section will summarize the

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results and propose some prospects about using this approach in a future complete filter design tool.

II. COMPLEX PERMEABILITY MODELS AND IMPLEMENTATION IN SPICE

Due to their excellent magnetic properties (low losses, high $\mu_r$ and high $B_s$), nanocrystalline materials became more suitable for common mode inductors than laminated or powder iron and ferrites. In our case, we chose, for our EMI filter prototype, Nanophy cores ($\mu_r \approx 30000$) for CM and $K\mu_b$ cores ($\mu_r \approx 200$) for DM. Real and imaginary parts of complex permeability were extracted from impedance measurements made on each core thanks to an HP4294A impedance analyser. These measurements were, then, taken as reference to fit both models.

A. Complex permeability models

1. Diffusion’s like model

As nanocrystalline alloys have a relatively high electrical conductivity ($\sigma \approx 833$ kS/m), skin effect will necessarily occur, even if the layers thickness is very low ($\approx 18$ $\mu$m). Starting from the diffusion equation, the complex permeability $\mu$ can be expressed like (1),

$$\mu = \mu_{DC} \frac{\tanh \frac{j\omega}{\omega_0}}{\sqrt{\frac{j\omega}{\omega_0}}}$$

2. Nomura’s model

Nomura proposed a model that used two straight lines on a log-log plot via a generic equation (2) able to describe $\mu'$ or $\mu''$ versus frequency.

$$\mu(f) = \frac{10^{a_2 \log_{10}(f) + b_2}}{1 + 10^{(a_2-a_1) \log_{10}(f) + (b_2-b_1)}}$$  \hspace{1cm} (2)

$a_1$, $a_2$ are the slopes and $b_1$ and $b_2$ are $y$ intercepts of each line respectively. Thus, for a given material, we had to identify 4 parameters per curve ($\mu'$ and $\mu''$) so 8 parameters in total. These parameters were fitted numerically for better accuracy.

B. LTSPICE implementation

For both models implementation, a gyrator was used in order to separate electrical and magnetic physical domains. With this analogy, magneto-motive forces and flux time derivative (in AC analysis the flux time derivative $d\phi/dt$ becomes $j\omega\phi$) became equivalent to voltages and currents respectively. Both models implementation required current controlled voltage sources, behavioural voltage sources, spice directives and mathematical functions expressed in function of the Laplace operator ($s = j\omega$) instead of the frequency $f$.

1. Diffusion’s like model

The figure 1 shows an example of a single winding and a single magnetic circuit. In figure 1, $B_1$ and $B_2$ are current controlled voltage sources that represent the winding and the coupling between electrical and magnetic physical domains (gyrator). The behavioural source $B_{Re\,\mu_0}$ represents the magnetic circuit ($A_e$ is the magnetic circuit cross section, $MPL$ is the average magnetic path length and $\mu_0$ is the vacuum permeability). One can also see in figure 1, how (1) is programmed with a $\textit{func}$ SPICE directive. The other equation calculates the complex reluctance $\mathcal{R}$ as (3). It has to be mentioned that resistors $R3$ and $R1$ are fictitious resistors inserted here, in order to avoid to have only pure voltage sources linked in a current loop.

$$\mathcal{R} = \frac{1}{\mu_0\mu} \cdot \frac{MPL}{A_e}$$  \hspace{1cm} (3)
2. Nomura’s model implementation

Nomura\(^4\) used behavioural voltage sources (bvs) to reproduce the resistive and inductive behaviour of the total impedance of a common mode choke. In our case, the electrical inductive and resistive behaviours are modeled by using in the magnetic domain a capacitor \((C_\mu)\) and a resistor \((R_\mu)\) respectively\(^10\) linked in series.

\[
C_\mu = \frac{\mu_0 A_c (\mu'^2 + \mu''^2)}{\mu'MPL} \quad (4)
\]

\[
R_\mu = \frac{\mu''MPL}{\mu_0 \omega A_c (\mu'^2 + \mu''^2)} \quad (5)
\]

To sum up, the Nomura’s model needs two coupled current controlled voltage sources to represent the winding through a gyrator) and two behavioural sources to represent \(R_\mu\) and \(C_\mu\). Calculations of (2), (4), (5) are made via SPICE directives as explained before.

III. RESULTS

A. Material models results

The Nanophy and \(K_\mu\) materials were characterized and the parameters of the both models were identified by numerically fitting the simulated curves with respect to the measured ones. Nomura and diffusion’s like model parameters are listed in Table I.

The figure 2 shows the real and imaginary parts of complex permeability computed by both models compared to measurements for high (Nanophy) and low (K\(\mu\)) permeability cores. The shape of each curve is globally retrieved by both models. Nevertheless, one can see that (1) is limited in

| TABLE I. Nomura and diffusion’s like model parameters. |
|-----------------------------------------------|
| Nanophy cores (\(\mu_r \approx 30000\))         |
| Nomura’s model                  diffusion’s like model |
|---------------------------------|-----------------|
| \(a_1\)  \(a_2\)  \(b_1\)  \(b_2\) | \(\mu_\text{DC}\)  \(\omega_0\) (rad/s) |
| \(\mu'^\prime\) | -0.0116 | -1.1483 | 4.6099 | 10.30 |
| \(\mu'^\prime\) | 0.5303 | -0.8063 | 1.5041 | 8.368 |
| \(K_\mu\) cores (\(\mu_r \approx 200\))       |
| Nomura’s model                  diffusion’s like model |
|---------------------------------|-----------------|
| \(\mu'^\prime\) | 0.0003 | -1.56 | 2.356 | 13.84 |
| \(\mu'^\prime\) | 1.0054 | -0.627 | -5.29 | 6.745 |
FIG. 2. Real $\mu_r$ and imaginary $\mu_{im}$ parts of complex permeability computed by diffusion’s like model (1), Nomura’s model (2) and comparison with measurements for Nanophy cores (left axis) and $K\mu$ cores (right axis).

terms of accuracy compared to (2) especially for Nanophy cores in the whole frequency range. Other tests (not shown) made on materials with permeabilities $\mu_r \approx 3000$, $\mu_r \approx 30000$ and $\mu_r \approx 500000$ confirmed this tendency. So far, the only drawback of Nomura’s model is that it has more parameters to identify than the diffusion’s like model (8 versus 2 respectively). The identification process is then a bit more difficult and takes more time.

B. EMI filter prototype

The figure 3 shows the EMI filter scheme with common mode and differential excitation sources connections to test one or other mode. EMI filters nominal values for each component are listed in the Table II

The input impedance of this filter will be measured and the results will be be compared to 4 simulation cases, listed in the Table III, in each mode (common and differential) for each model.

Equivalent serial $R$, $L$, $C$ values for $C_x$ and $C_y$, capacitors (used for simulation cases B to D) are listed in the Table IV. In the same table are reported the dimensions and number of turns of each inductor (simulation cases C and D).

Impedance modulus and argument have been measured and simulated (4 cases) with the proposed models. Impedance modulus in common and differential modes are plotted in figures 4 and 5 respectively. Discussion about the results is on the next section.

FIG. 3. EMI filter scheme with common mode (red) and differential (green) excitation sources connections.

| TABLE II. EMI filter needed values. |
|------------------|----------|----------|----------|
| $L_{CM}$ (mH)     | $L_{DM}$ (μH) | $C_x$ (nF) | $C_y$ (nF) |
| 5.7               | 40       | 100       | 4.7       |
TABLE III. Simulation cases details.

| Case | Details |
|------|---------|
| A    | all capacitors and inductors are ideal |
| B    | capacitors are replaced by R-L-C serial model |
| C    | Inductors are replaced by diffusion’s like or Nomura’s models |
| D    | same as case C, plus parasitic capacitances in parallel of each winding. |

TABLE IV. Equivalent serial ESR, ESL, C values for $C_x$ and $C_y$ and core dimensions and number of turns for $L_{CM}$ and $L_{DM}$.

| Case | ESR (mΩ) | ESL (nH) | C (nF) |
|------|----------|----------|--------|
| $C_x$ | 76.5     | 54       | 98.5   |
| $C_y$ | 330      | 43.6     | 4.83   |
| $L_{CM}$ | 61.3      | 14.62    | 25     |
| $L_{DM}$ | 60.8      | 13.41    | 26     |

FIG. 4. Impedance modulus results in common mode excitation for all simulation case and both models.
capacitances\textsuperscript{11} that are resonating with stray inductances (connections mainly). To predict these very high resonance peaks, accurate numerical tools should be employed and are therefore out of the scope of this study.

V. CONCLUSION

Two analytical models able to predict the frequency dependent magnetic complex permeability behaviour were analysed in this paper. After identification, Nomura’s model showed that it has a better accuracy in the whole frequency range and is more robust (better adaptability to various materials). Nomura’s model seems to be a better choice even if it is a bit more difficult to identify. This tendency has to be confirmed by further work on other materials like ferrite or iron powders. Both models have been successfully implemented in LTSpice\textsuperscript{®} thanks to the tools available in the software, to simulate a realistic EMI filter. Both models showed that it is crucial to take into account the frequency dependant properties of magnetic material in the medium frequency range especially in common mode. Adding a parasitic capacitance on each winding allowed to retrieve the second resonance peak in both modes. Unfortunately, its value is very hard to predict analytically.\textsuperscript{11} That’s why Future work will focus on this task in order to have a full design tool accurate enough to do EMI filter virtual prototyping.

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1 C. Henkenius, N. Fröhleke, and J. Böcker, “Numerical optimization of passive line filter components for suppression of electromagnetic interference (EMI),” in \textit{Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE} (IEEE, Long Beach, CA, USA, 2016).

2 B. Narayanasamy, H. Jalainbo, and F. Luo, “Development of software to design passive filters for EMI suppression in SiC DC fed motor drives,” in \textit{Wide Bandgap Power Devices and Applications (WiPDA), 2015 IEEE 3rd Workshop on} (IEEE, Blacksburg, VA, USA, 2015).

3 \textit{Induction Machines} (Taylor & Francis, 1995).

4 K. Nomura, N. Kikuchi, Y. Watanabe, S. Inoue, and Y. Hattori, “Novel spice model for common mode choke including complex permeability,” in \textit{2016 IEEE Applied Power Electronics Conference and Exposition (APEC)} (2016) pp. 3146–3152.

5 A. Roch and F. Leferink, “Nanocrystalline core material for high-performance common mode inductors,” \textit{IEEE Transactions on Electromagnetic Compatibility} \textbf{54}, 785–791 (2012).

6 “APERAM.”

7 “Hp4294a datasheet.”

8 D. C. Hamill, “Lumped equivalent circuits of magnetic components: The gyrator-capacitor approach,” \textit{IEEE Transactions on Power Electronics} \textbf{8}, 97–103 (1993).

9 D. C. Hamill, “Gyrator-capacitor modeling: A better way of understanding magnetic components,” in \textit{Applied Power Electronics Conference and Exposition, 1994. APEC ’94. Conference Proceedings 1994., Ninth Annual (1994)} pp. 326–332 vol. 1.
10 F. Mesmin, F. Sixdenier, H. Chazal, and A. Kedous-Lebouac, “Improvement of EMI filters performance by taking into account frequency-depandent magnetic material properties,” in Proceedings of the 18th Conference on the Computation of Electromagnetic Fields (Compumag 2011, Sydney, Australia, 2011).

11 G. Grandi, M. K. Kazimierczuk, A. Massarini, and U. Reggiani, “Stray capacitances of single-layer air-core inductors for high-frequency applications,” in Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS ’96, Conference Record of the 1996 IEEE, Vol. 3 (1996) pp. 1384–1388 vol. 3.