3D Power Inductor: Calculation of Iron Core Losses

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Abstract: The work proposed in this article deals with the consideration of 3D geometric effects to evaluate the iron losses in magnetic devices used in power electronics. To carry out this work, we rely upon two existing models of iron losses calculation currently used in power electronics we couple with in a finite elements magnetic fields calculation code, COMSOL Multiphysics. The non-linear behavior of magnetic material is treated.

Keywords: Iron losses, Power Electronics, Magnetic Components, 3D Geometric Effects, Magnetic Non-linearity

1. Introduction

Designing magnetic components requires the well-known of electromagnetic losses they lead to. It is the losses due to current circulation inside windings (“copper losses”) and due to the temporal variation of magnetic field inside the cores (“iron losses”). However, the right evaluation of those losses is quite complex because they depend on frequency, amplitude, waveform, geometry and materials’ nature.

The work proposed in this paper deals with the consideration of 3D geometric effects and also the consideration of non-linearity to evaluate the iron losses in magnetic devices used in power electronics. To carry out this work, we rely upon two existing models of iron losses per unit volume calculation currently used in power electronics [2-9]. We coupled these two models with finite elements magnetic fields calculation software, COMSOL Multiphysics. Indeed, as they are volumetric models, instead of applying them at the macroscopic scale we can apply them at the element scale and so improve the iron losses estimation. Moreover, in order to imitate at best the 3D geometric effects, we must take into consideration the non-linear behavior of magnetic field otherwise we could have really high values in corners which could falsify our calculation.

The two models we use and the coupling procedure with COMSOL Multiphysics are presented on paragraph 2. Then, in paragraph 3, the calculation of volumetric (under unsaturated sinusoidal conditions) loss density is validated. In paragraph 4, the necessity of taking into account non-linearity and so saturation phenomenon is explained. Finally, in paragraph 5, the method is applied to the 3D Power Inductor of COMSOL model library.

2. Presentation of the Method

In first approach, under unsaturated sinusoidal waveform, iron losses in magnetic materials are estimated thanks to the following formula, called “Steinmetz Equation” (SE):

$$\overline{P_v(t)} = k f^{\alpha} \hat{B}^{\beta} \tag{1}$$

Where $\overline{P_v(t)}$ is the time-average power loss per unit volume, $\hat{B}$ is the peak flux density amplitude and f is the frequency of the sinusoidal excitation. The parameters k, α and β are determined thanks to power loss per unit of volume curves provide by manufacturers. Even if it restrain to the unsaturated sinusoidal excitation, this formula is interesting because those parameters are based on general specifications and easy to reach because they are given by the manufacturer.

However, in power electronics, the magnetic components do not only work under sinusoidal excitation but they can be brought to work under different kind of waveform. They are generally supplied by rectangular voltage with variable duty cycle. The magnetic flux density could so be triangular with a nonzero mean value and the previous Steinmetz formula cannot be applied correctly.

In the case of any waveform excitation, an interesting approach has been proposed by [5]. It consists in using an improved formula of the previous one and it is called “improved Generalized Steinmetz Equation” (iGSE):

$$\overline{P_v(t)} = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha} dt \tag{2}$$

Where $\overline{P_v(t)}$ is the time-average power loss per unit volume, $\frac{dB}{dt}$ is the temporal derivative of B(t), ΔB is the ripple of magnetic flux density, T is the period of B(t) and k_i a coefficient reliant on the B(t) waveform :

$$k_i = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi}|\cos\theta|^{\alpha}2^{\beta-\alpha}d\theta} \tag{3}$$

It should be noted that the formula (2) requires the knowledge of B(t) and could be used with any periodic waveform excitation with zero mean value. Moreover, it uses the same k, α and β parameters than for (SE).

However, a limit in the use of those formulas (1) & (2) appears when they are applied in a macroscopic way by considering an average flux density in magnetic cores. If it is commonly admitted that the magnetic flux density is homogeneous in a torus (low section and high radius torus), the cores use in power electronics could have more complex shapes. Thus, the magnetic flux density present high gradients that locally modify the iron losses and so the resultant global value [1]. In order to precisely take into account this inhomogeneous distribution of magnetic flux density in a complex shape component, the idea is to use results from element finite simulation method. So, instead of applying formulas (1) & (2) at a macroscopic scale, we apply them at an element scale to improve the estimation accuracy of iron losses. Furthermore, in order to take account of geometric effects in the corners of the magnetic core, which are the source of local saturation and field's redistribution, it is also necessary to model the non-linearity of the magnetic material. This non-linearity is implemented inside COMSOL Multiphysics material properties by defining the initial magnetization curve of the magnetic material.

Finally, a post-processing is realized from the results obtained thanks to COMSOL Multiphyisics software. Formula (1) is quite simple to use inasmuch as it requires just only one magnetostatic simulation to get the magnitude $\widehat{B}$ of magnetic flux density in each element. Besides, formula (2) requires the knowledge of temporal magnetic flux density $B(t)$ over a whole period T. There is two way to get $B(t)$. One way it to make several magnetostatic simulations (quasi-steady state assumption) or another way is to directly make a time-dependent simulation through COMSOL Multiphysics. Figure 1 shows the pattern of the method.

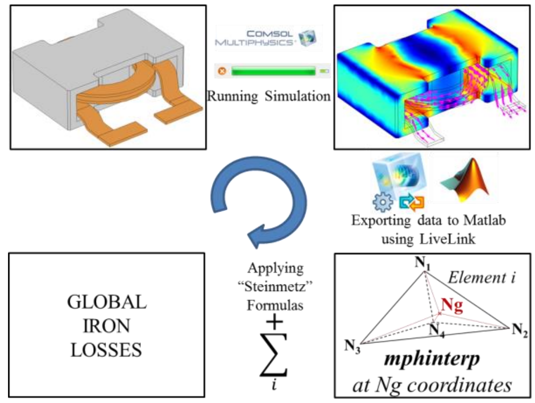
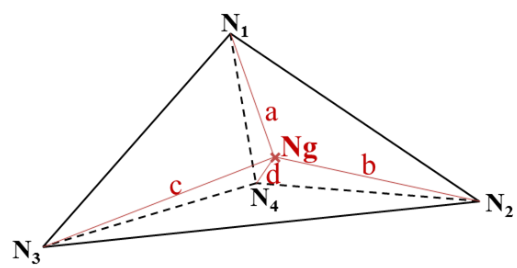


Figure 1. Process of the implemented method using COMSOL Multiphysics with MATLAB Livelink.

It should be noted that we need to calculate the magnetic flux density for each element. To do this, the use of mphinterp function could be avid in term of computation time. Another way to get the same information is to make the assumption that the flux density is homogeneous at an element scale (with the exception that mesh quality is good). So we can simply evaluate it by doing a geometric mean of flux densities calculated at each element peaks (Figure 2). A compromise has to be found between a good mesh quality and a reasonable computational time.



$$\left\|\overrightarrow{B(G)}\right\| = \frac{a^{-1}\left\|\overrightarrow{B(N_1)}\right\| + b^{-1}\left\|\overrightarrow{B(N_2)}\right\| + c^{-1}\left\|\overrightarrow{B(N_3)}\right\| + d^{-1}\left\|\overrightarrow{B(N_4)}\right\|}{a^{-1} + b^{-1} + c^{-1} + d^{-1}}$$

Figure 2. Alternative calculation of centroid magnetic flux density inside an element using geometric mean.

3. Preliminary validation of the formulas - k, α, and β parameters

In order to validate the formulas we will use in the method, we verified that under sinusoidal excitation, the two models (SE) and (iGSE) provide the same results. To do that, we identify the values of the parameters k, α, and β by fitting the datasheet curve with least squares method. The parameters given in the Table 1 correspond with 3F3 material from Ferroxcube [10] and are valid for different ranges of frequencies and magnetic flux density peaks at a temperature of 100°C.

f [kHz] – Bmax [T]	k	α	β
25 – 0.300	1.055e-3	1.544	2.704
100 – 0.250	1.045e-3	1.504	2.698
200 – 0.200	1.040e-3	1.489	2.578
400 – 0.150	1.037e-3	1.480	2.418
700 – 0.080	1.036e-3	1.483	2.256

Table 1. Values of k, α, and β obtained for 3F3 Ferroxcube material at 100°C.

Then we can use the formulas and validate the right agreement between formulas. The results are shown in Figure 3.

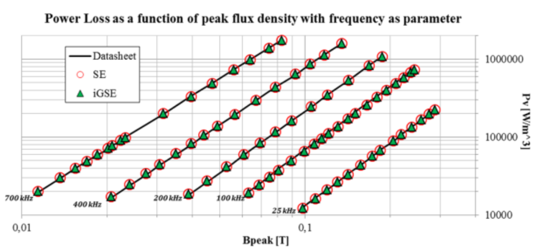


Figure 3. Preliminary validation of theoretical model for unsaturated sinusoidal supplying- 3F3 ferrite at 100°C.

As we mentioned earlier, iGSE formula requires the knowledge of temporal magnetic flux density B(t) over a period. So it is reliant on the number of points used to discretize it. That numerical error has been quantified by calculating relative error between SE and iGSE in sinusoidal excitation as a function of the number of point used for the discretization. To have a good precision (relative error lower than 0.1%) B(t) should have at least 30 points. This consideration is important and determines either the number of simulation you have to make in quasi-steady state assumption either the size of step time in time-dependent simulation.

4. 3D Geometric Effect and Magnetic Non-linearity

We present here the necessity of taking into account non-linearity of magnetic materials. Usually, the design of magnetic component is made in such a way that the magnetic flux density does not saturate in its average path. Yet, due to the dispersal and depending on the kind of core geometry, an amount of the whole volume could reach saturation level. Figure 4 illustrates this remark.

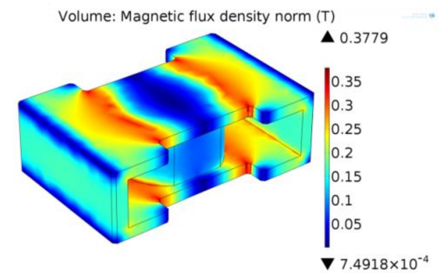


Figure 4. Magnetic flux density spreading inside the iron core.

Thus, to fully take advantage of this 3D calculation method, it is important to take into account magnetic non-linearity. Indeed, this non-linearity locally modify B(t) curves and eventually could lead to saturation which lead to a redistribution of flux density in the nearby elements. So, those modifications work on the iron losses calculation (when using iGSE formula). Figure 5 illustrates this remark by considering two different elements inside the core.

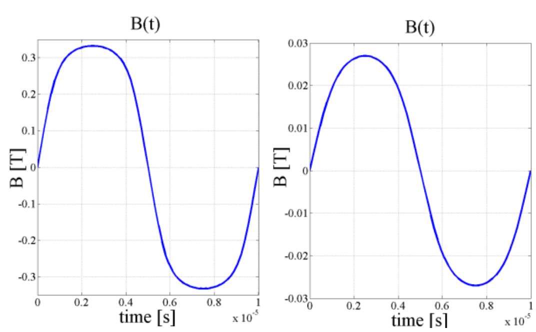


Figure 5. Left - B(t) for an element located in high magnetic flux area and Right - in a low one.

5. Application and Results

In order to illustrate the interest of the method by taking into account 3D geometric effect, Figure 6 presents the spreading, both of magnetic flux density norm and of iron losses. We can clearly see local aspects.

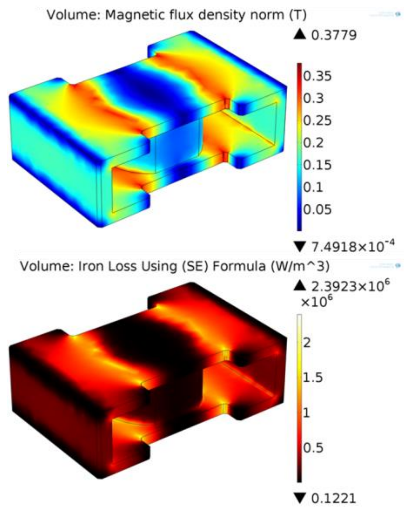


Figure 6. Example of volumetric distribution of the magnetic flux density and losses inside the iron core.

Then, we compare the results we get from classical approaches which uses an average magnetic flux density inside the core with the ones we get with our method. Two different current excitation conditions are studied: sinusoidal and triangular one.

The results we present here are obtained by discretizing the current wave and making for each discretized points a magneto static simulation. In order to validate this quasi-steady state assumption, time-dependent simulations has been realized and results of both simulations were consistent.

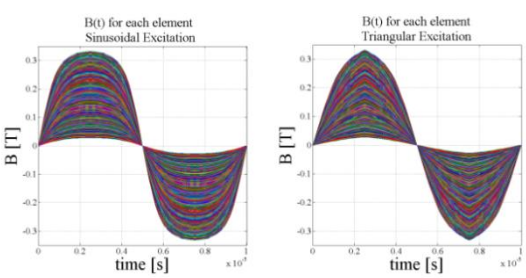


Figure 7. B(t) for each element. Left – 100 kHz sinusoidal current supplying. Right - 100 kHz triangular current supplying.

Then we compute iron losses in each element with those curves. Finally, we compute global losses in the entire iron core. The results are given in the Table 2.

Current Waveforms		
(SE) $kf^{\alpha}\widehat{B_{th\_ave}}^{\beta}V_{tot}$	**394W**	**394W**
(iGSE) $\left(\frac{k_i(\Delta B_{th\_ave})^{\beta-\alpha}}{T}\int_0^T\left\lvert\frac{dB_{th\_ave}}{dt}\right\rvert^{\alpha}dt\right)V_{tot}$	**394W**	**360W**
(SE1 + SE2) $\sum_{n=1}^{N_{area}} kf^{\alpha}\widehat{B(n)_{th\_ave}}^{\beta}V_{tot}$	**120W**	**120W**
(iGSE1 + iGSE2) $\sum_{n=1}^{N_{area}}\left(\frac{k_i(\Delta B(n)_{th\_ave})^{\beta-\alpha}}{T}\int_0^T\left\lvert\frac{dB(n)_{th\_ave}}{dt}\right\rvert^{\alpha}dt\right)V_{tot}$	**120W**	**108W**
(3DSE) $\sum kf^{\alpha}\widehat{B_{elem}}^{\beta}V_{elem}$	**113W**	**113W**
(3DiGSE) $\sum\left(\frac{k_i(\Delta B_{elem})^{\beta-\alpha}}{T}\int_0^T\left\lvert\frac{dB_{elem}}{dt}\right\rvert^{\alpha}dt\right)V_{elem}$	**111W**	**95W**

Table 2. Results of global losses from classical approaches (red) and our new approach (green)

Formulas (SE) and (iGSE) are computed using analytical results (Ampère's Law) for the magnetic flux density level by taking into consideration a unique magnetic state. Formulas (SE1+SE2) and (iGSE1+iGSE2) are also computed using analytical results (Ampère's Law + Gauss's Law) but this time by taking into consideration two areas and so two magnetic states. The large difference with those two results reveals that for such a geometry where the magnetic flux density is highly inhomogeneous, it is necessary to discretize the geometry. Thus, formulas (3DSE) and (3DiGSE) are much more precise because they take into account a number of magnetic states equal to the number of elements.

6. Conclusion and Perspectives

The new method presented here allows taking into account with a good accuracy, 3D geometric effects in iron losses calculation, in magnetic components for power electronics. As we have seen, those effects have a manifest contribution. Having a good knowledge of electromagnetic losses is primordial to thermally design a magnetic component and this method aims to improve their conception.

With the aim of completing the validation of this method, it is essential to compare numerical results with experimental ones. A campaign of measures will be realized.

As we noticed previously, the method can be modified to use a new improved formula which considers DC bias condition and relaxation phenomenon, for instance (i^2GSE), [7]:

$$\overline{P_v(t)} = \frac{k_i(\Delta B)^{\beta-\alpha}}{T}\int_0^T\left\lvert\frac{dB}{dt}\right\rvert^{\alpha}dt + \sum_l^n Q_{rl}P_{rl} \quad (4)$$

However, this improvement is much more restrictive because it needs new parameters which are not identifiable with datasheet.

As those losses depend on temperature and are heat sources, the following step is to couple this method with a thermal simulation to obtain an entire electro-magneto-thermal design.

7. References

1. J. Mühlethaler, J. W. Kolar, and A. Ecklebe, "Loss modeling of inductive components employed in power electronic systems," in *Proc. 8th Int. Conf. Power Electron.—ECCE Asia*, 2011, pp. 945–952.

2. M. Albach, T. Durbaum, and A. Brockmeyer, "Calculating core losses in transformers for arbitrary magnetizing currents a comparison of different approaches.", in *PESC 96 Record. 27th Annual IEEE Power Electronics Specialists Conference*, June 1996, vol. 2, pp. 1463–8.

3. J. Reinert, A. Brockmeyer, and R. De Doncker, "Calculation of losses in ferro- and ferrimagnetic materials based on the modified Steinmetz equation," *IEEE Transactions on Industry Applications*, vol. 37, no. 4, pp. 1055–1061, 2001.

4. J. Li, T. Abdallah, and C. R. Sullivan, "Improved calculation of core loss with nonsinusoidal waveforms," in *Proc. Ind. Appl. Conf., 36th IEEE IAS Annu. Meeting*, 2001, vol. 4, pp. 2203–2210.

5. K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," in *Proc. of IEEE Workshop on Computers in Power Electronics*, pp. 36–41, 2002.

6. W. A. Roshen, "A practical, accurate and very general core loss model for nonsinusoidal waveforms," *IEEE Trans. Power Electron.*, vol. 22, no. 1, pp. 30–40, Jan. 2007.

7. J. Mühlethaler, J. Biela, J. W. Kolar, and A. Ecklebe, "Core losses under DC bias condition based on Steinmetz parameters," in *Proc. of the IEEE/IEEJ International Power Electronics Conference (ECCE Asia)*, pp. 2430–2437, 2010.

8. C. R. Sullivan, J. H. Harris, and E. Herbert, "Core loss predictions for general PWM waveforms from a simplified set of measured data," in *Proc. Appl. Power Electron. Conf. Expo.*, 2010, pp. 1048–1055.

9. J. Mühlethaler, J. Biela, J. W. Kolar, and A. Ecklebe, "Improved core loss calculation for magnetic components employed in power electronic systems," in *Proc. of Applied Power Electronics Conference and Exposition (APEC)*, 2011.

10. http://www.ferroxcube.com/

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