Influence of air-gap length and cross-section on magnetic circuit parameters

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Abstract:
Air-gap is one of the most crucial part of magnetic circuits, especially in high power inductors. It significantly modifies parameters of magnetic devices by increasing of saturation current, linearizes B-H curve of magnetic circuit and causes decreasing of the inductance. Therefore, the optimal selection of a shape and dimensions of air-gap is very important from designing point of view. This paper is focused on the presentation of optimal dimensions of the air-gap with rectangular cross-section as a function of air-gap length and cross-section ratio. The COMSOL Multiphysics® software was used for simulation of the magnetic field distribution for chosen cases in the exemplary magnetic circuit. The AC/DC module was applied for the calculations. By varying of the geometry parameters optimal solutions for this kind of magnetic circuit are concluded. The presented results are dedicated to magnetic designers to prepare inductor cores designs optimally.

Keywords: magnetic circuit, air-gap, magnetic core.

1. Introduction

Magnetic inductors are one of the most important components in power electronic devices. They are implemented as high frequency filters, magnetic energy storages, EMC chokes, magnetic fault current limiters, etc.

Designing of inductive components is a complex problem, where electrical and magnetic issues must be taken into account. From electrical point of view such aspects must be regarded as: the skin and the proximity effects, current densities and power losses of windings, insulation between turns and layers, voltages, currents, frequency and temperature of operation. From magnetic point of view the important aspects are: inductance parameters, saturation flux density level, saturation current in windings, magnetic permeability of core material, fringing flux effects, cross-sections and dimensions of window area of a magnetic core.

Inductors, used in power electronic applications, are very often designed with air-gapped magnetic core. Implementation of air-gap influences on the shape of B-H curve of magnetic circuit, decreasing the effective inductance and increasing saturation current of an inductor. Designing of an inductor with air-gap is a very complicated because magnetic material is described by nonlinear characteristics of B-H curve, saturation and power losses. Moreover, high sensitivity of magnetic material on manufacturing process must be taken into account. Additionally, implementation of air-gap increases fringing flux phenomenon what must be taken into account because of electromagnetic interferences (EMI) aspects, due to the fact that fringing flux causes higher propagation of electromagnetic disturbances.

Specific geometry of a magnetic core with air-gap and interdependence of magnetic and electric parameters circuit parameters cause difficulties in description of magnetic circuit by analytical formulas. Exemplary equations for an idealized magnetic circuit were published by Saxena [1] and by McLyman [2]. More advanced analysis (considering of fringing flux aspects) are published by Kazimierczuk [3].

Formulas, given in mentioned publications, are very helpful in some rough estimation of designed inductor parameters but they can be difficult to implement in sophisticated and advanced solutions. They rather presents deep physical approach of discussed problems than engineering point of view. During daily design process, more effective is a knowledge how the parameters of air-gap length and cross-section of magnetic core influences on a magnetic circuit conditions. This kind of approach in a limited range is presented by Legg [4].

Currently, implementation of numerical methods (e.g. FEM methods) allows to prepare effective design and optimization of magnetic inductors. This paper is focused on presentation of a methodology of magnetic circuit calculation with implementation of FEM software COMSOL Multiphysics® .

2. Problems of magnetic circuit with air-gap

Implementation of air-gap in a magnetic circuit influences the parameters of magnetic inductor. Additional reluctance of air in the magnetic circuit changes B-H curve, decreasing inductance and increasing saturation current of magnetic inductor. Air-gap is used in applications where there is a risk of magnetic saturation, especially in switch-mode power supplies (SMPS) and high frequency filters. The phenomenon of magnetic saturation must be taken into account during design process because saturation of magnetic core causes loss of inductance, increasing of current in the circuit and increasing of power losses. The exemplary comparison of B-H curve for a magnetic core without and with air-gap is presented in Figure 1.

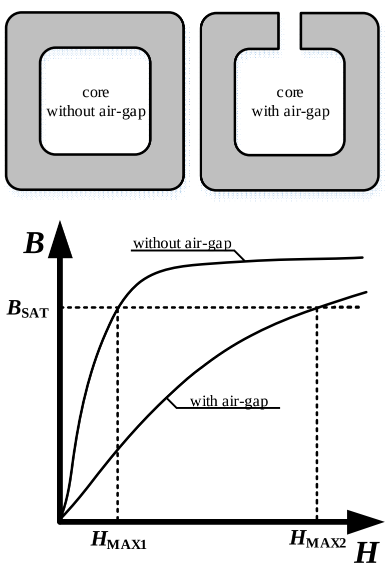


Figure 1. Comparison of B-H curve for magnetic core without and with air-gap.

Additionally, the presence of air-gap causes fringing flux phenomenon. Fringing flux means that flux lines of the magnetic field do not occupy only the area of magnetic core cross-section but also are present around this area. Finally, flux lines are present in bigger area than the cross-section of magnetic core what can cause electromagnetic interactions with other components of power electronic circuit. The problem of fringing flux is described in Figure 2.

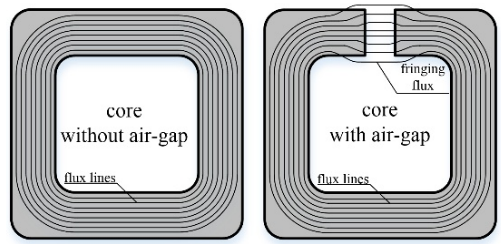


Figure 2. Flux lines distribution in magnetic cores: without air-gap and with air-gap (fringing flux can be observed).

Detailed knowledge about the influence of air-gap length and cross-section on the parameters of inductors is very important for design process which fulfils project requirements and industrial standards. From designing point of view, the most crucial information for a designer is a level of fringing flux in the inductor air-gap. It can be assumed that the best situation is when the fringing flux is minimalized and flux lines occupy the same cross-section in air-gap area as in the magnetic core. Based on these assumptions, designing and optimization process can be treated as determination of total magnetic flux amount in the magnetic core cross-section compare to the magnetic flux in the air-gap area with the same cross-section as magnetic core. This problem is illustrated in Figure 3.

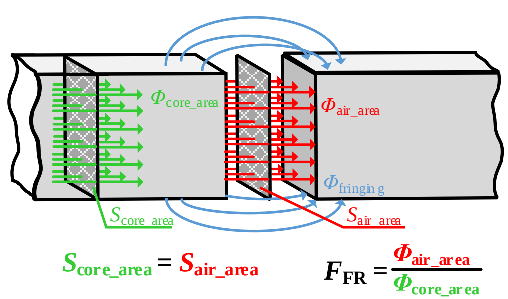


Figure 3. Definition of factor of flux ratio in an exemplary magnetic core with air-gap.

Basing on these assumption, fluxes ratio factor F_{FR} as described by formula:

$$F_{FR} = \frac{\Phi_{air\_area}}{\Phi_{core\_area}} \quad (1),$$

where: F_{FR} – factor of magnetic fluxes ratio, Φ_{air_area} – magnetic flux in an air-gap area with cross-section like in a magnetic core, Φ_{core_area} – magnetic flux in a core area with cross-section of a magnetic core, can be implemented.

In the idealised case, when a magnetic flux occupies an air-gap area with the same cross-section as a magnetic core $F_{FR} = 1$. In a real case $F_{FR} < 1$, what means that a fringing flux exists in an air-gap area. It must be mentioned that F_{FR} depends on wide range of parameters as: shape of magnetic cross-section, length of air-gap, ratio of cross-section dimensions permeability of a magnetic core and air-gap. In addition term "air-gap" is a commonly used term of slot inside a magnetic core, however this slot can be filled by specific material with other than air parameters.

3. Assumptions of analyses

The base model, used in analyses, is described in Figure 4. This is a part of a magnetic core with defined shape, dimensions and material parameters. In this paper following assumptions of analyses have been made:

- a rectangular shape of a magnetic core;
- constant area of a magnetic core cross-section S_{core_area} (dimensions a and b are variable but $S_{core\_area} = a*b = \text{const}$);
- variability of air-gap length d in the given range ($0.1a \le d \le 3a$);
- linear parameters of magnetic core material with one specified value of magnetic permeability;
- neglecting of magnetic core saturation;
- air parameters of air-gap and environment;
- F_{FR} factor is a result of analyses.

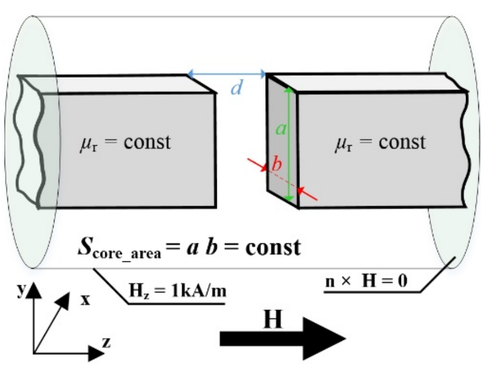


Figure 4. Basic model of analyses

4. Use of COMSOL Multiphysics

4.1 Mathematical description

Numerical simulations of the presented basic model (Figure 4) were prepared using the Magnetic Fields Interface. This interface allows calculating of magnetic field distribution basing of two equations:

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{J_e} \\ \mathbf{B} = \nabla \times \mathbf{A} \end{cases} \quad (2),$$

where: ∇ – nabla operator, **H** – vector of magnetic field intensity, **Je** – generated current density, **B** – vector of magnetic flux density, **A** – magnetic vector potential. This system of equations is implemented to each finite element of the model. Solving of given equations allows obtaining of magnetic flux distribution in simulated model.

Two surfaces which are at the top and the bottom of the analysed model, were described as a perfect magnetic conductor, according to formula:

$$\mathbf{n} \times \mathbf{H} = \mathbf{0} \quad (3),$$

where: **n** – normal vector, **H** – vector of magnetic field intensity. This equation sets the tangential component of the magnetic field and the surface current density to zero.

The magnetic flux in the core is produced by external vector of magnetic field. The existence of this external magnetic field is guaranteed by additional boundary condition applied to others surfaces of model with proper component ($\mathbf{H_x}$=0; $\mathbf{H_y}$ = 0; $\mathbf{H_z}$ = 1000A/m).

4.2. Sequences of analyses

COMSOL analyses of a magnetic circuit with adjusted air-gap and cross-section were done basing on the algorithm, presented in Figure 5.

The presented algorithm starts with declaration of input data: cross-section of the magnetic core S_{core_area}, permeability of the magnetic material μ_r, value of external magnetic field H_z. Additionally, two controlling parameters n_a and n_d are declared (both parameters are used as indicators of iteration process in model calculations). Next, the length of dimension a is determined as a function of indicator n_a. Basing

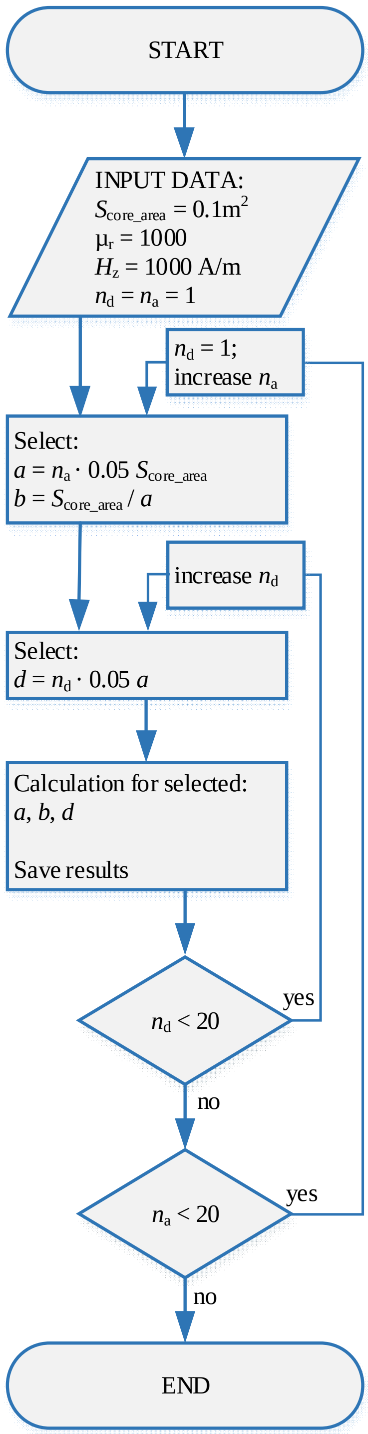


Figure 5. Algorithm implemented for calculations of basis model

on value of parameter *a*, the parameter *b* is calculated. Next, the length of air-gap is determined as a function of parameters n_d. This way, parameters *a*, *b*, *d* are used for calculation of one case of model, where obtained results are saved. Next, the indicator n_d is increased and the calculation loop is repeated (in this loop the variability of air-gap length is determined). The next loop operates with the indicator n_a (in this loop the variability of magnetic core cross-section is determined). The presented algorithm allows calculations for wide range of magnetic cross-section and different length of air-gap.

4.3 Models description

The implemented FEM model was 3D type and it was based on equations provided by the AC/DC module and the Magnetic Field interface. Model based on the Global Cartesian coordinate system.

Each iteration of model geometry (for iteratively changes of *a*, *b*, *d* parameters) was solved by the Stationary, Linear solver. Consuming of solution time and required memory space was varying in the wide range, as it is presented in Table 1. These variations are depended from numbers of degrees of freedom, which are required to be solved.

Table 1: Comparison of solution parameters

	Minimum	Maximum
Time	8 s	312 s
Physical memory	12.52 GB	14.62 GB
Virtual memory	13.60 GB	14.86 GB
Degrees of freedom	157 162	4 058 514

The model geometry was described by parameterized dimensions what allows easy adjustment of magnetic core cross-section (parameters *a* and *b*) and length of air-gap (parameter *d*).

The 3D model geometry is shown in Figure 6. It consist of two parts of magnetic core with rectangular shape of cross-section and dimensions *a* and *b*. Between these parts there is a space of air-gap with the length of parameters *d*. Parts of magnetic core and air-gap are surrounded by cylindrical volume, described by air material parameters.

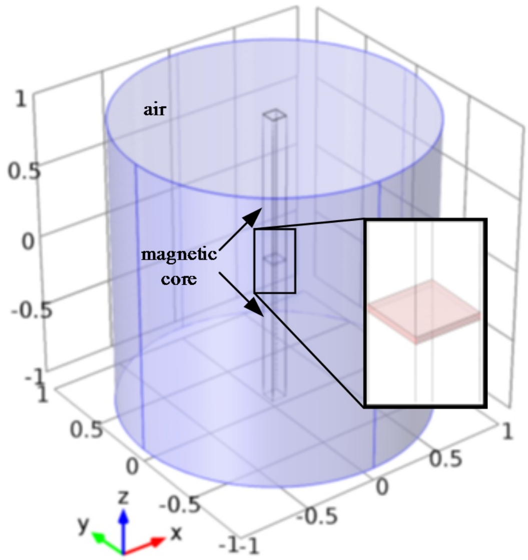


Figure 6. Geometry of analysed magnetic core with air-gap.

The model utilizes materials from the COMSOL Material Library. The assumed material parameters of analyses are collected in Table 2

Table 2: Material parameters of COMSOL models

Material	Relative permeability
Air	1
Air-gap	1
Magnetic core	1000

4.4 Meshing of FEM Model

The appropriate meshing process is crucial for obtaining correct results of analyses. In the presented model one type of mesh elements was used (a free tetrahedral shape). The size of elements was declared in the range from 0.003 (minimum) to 0.07 (maximum). Full analysed model is composed of varied number of elements (less than 1000000) depending on geometry with quality higher than 0.19.

Figure 7 shows the mesh of the model. It is characterised by varying density (the mesh is finer in smaller volumes, e.g. air-gaps and rarer in the outer part of model).

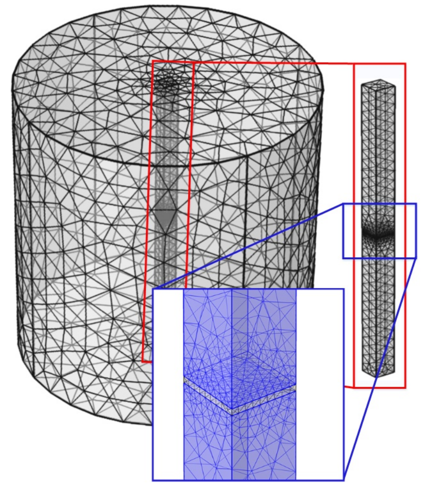


Figure 7. FEM model of analysed magnetic circuit (in the air-gap volume meshing is finer).

5. Results of magnetic analyses

Results of FEM analyses, obtained from COMSOL model, bases on the amplitude of the magnetic flux density. The exemplary magnetic flux distribution for four analysed cases is presented in Figure 8.

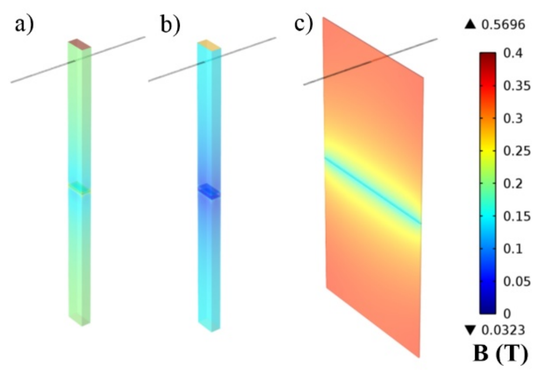
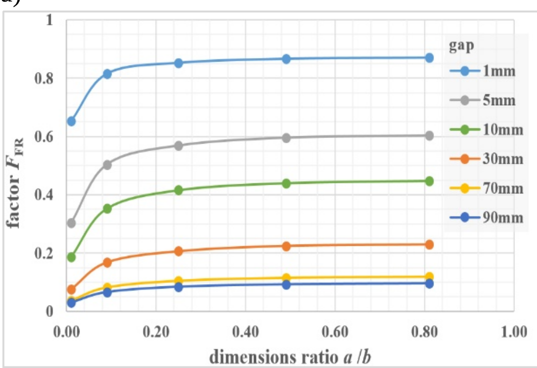


Figure 8. Magnetic flux distribution for exemplary cases of FEM analyses: a) base case with given ratio of cross-section and given length of air-gap, b) case with the same (as case “a”) ratio of cross-section and bigger length of air-gap, c) case with different ratio of cross-section and the same length of air-gap (as case “a”).

The comparison of magnetic flux distribution in the case of the same cross-section ratio and different length of air-gap (Figure 8a and 8b) allows concluding that increased length of air-gap reduces the average value of magnetic flux density in the magnetic core. Additionally in the region of air-gap, magnetic flux density is reduced to much smaller values than in the region of magnetic material domains. Also, changes of cross-section ratio of the magnetic core influences on the magnetic flux distribution (Figure 8a and 8c) In the case of rectangular cross section magnetic flux densities are higher than in the square cross-section. This phenomenon is caused by more uniform distribution of reluctances in the square shape of cross-section.

Selected results obtained in simulation process for calculated cases are collected as graphs in Figure 9. Given results can be very useful for engineer during design process of magnetic circuits with air-gaps.

a)



b)

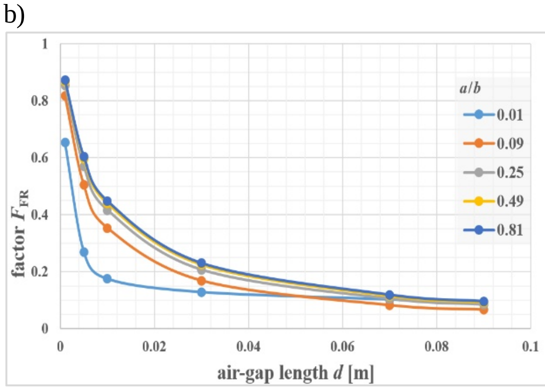


Figure 9. Exemplary characteristics of simulated cases: a) factor F_{FR} as a function of a/b dimensions ratio for different lengths of air gaps, b) factor F_{FR} as a function of air-gap length for different dimensions ratio a/b. Lines are to guide the eye.

7. Conclusions

In the presented analyses model with simplified assumptions was implemented, however obtained results allowed to formulate the following conclusions:

- COMSOL Multiphysics® software is a useful software for electromagnetic calculations of complex and sophisticated geometries,
- FEM analyses allows to determine optimal dimensions of magnetic core cross-section, magnetic core dimensions ratio and level of fringing flux,
- FEM calculation allows to optimise the magnetic circuit for specific requirements of applications (no fringing flux, strictly defined fringing flux, etc.),
- Determining of optimal length of air gap and dimension ratio of magnetic core cross-section is a one of the most crucial aspects in a designed process of optimised inductors,
- Obtained results are useful for design engineers in the optimisation process of inductors and transformer designs.

8. References

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9. Acknowledgements

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