Modeling the arrangement of drill holes for orthogonal biasing in controllable inductors for power electronic converters

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Keywords

«Device modelling», «Device optimization», «Magnetic device», «Hardware (not only Software)», «Passive component»

Abstract

Magnetic devices are essential components of power electronic converters. Unfortunately, they usually are also the bulkiest and heaviest components in the converter system. Controllable magnetic devices using active premagnetization are a promising approach regarding further volume and weight reduction. One method of active premagnetization is orthogonal biasing. To be able to use this method, drill holes in the ferrite core material are necessary. Because of the material's fragility and brittleness, manufacturing ferrite cores is a difficult and expensive process. For this reason, an effective arrangement of the drill holes is critical.
In this paper a basic model of drill hole arrangement based on congruent circle packing is presented for circular and square core cross sections. 2D-FEM-simulations and measurement results are made for comparison and verification. The deviations between calculation and measurement results are discussed and opportunities for model improvement are given.

Introduction

The reduction of volume, weight and costs is an essential goal in the development process of power electronic converters. By constantly improving wide band gap technologies, such as SiC and GaN semiconductor power devices, the switching frequency of novel converter systems is further increasing. A higher switching frequency can be an option to reduce the volume and thereby the weight and costs of the magnetic devices. However, even with the usage of higher switching frequencies, magnetic devices remain the bottleneck regarding a significant volume and weight reduction of the converter system.
According to [1], a promising approach regarding further volume and weight reduction are controllable magnetic devices. If an additional winding (auxiliary winding) is wound on or introduced within the core material the auxiliary current impacts the magnetic core's saturation in the closer

vicinity of the auxiliary winding. Thereby, the characteristic of the magnetic device can be affected actively, which enables an additional degree of freedom regarding the device's design process.
As it is shown in [2], there are three different methods to design controllable magnetic devices. Their different designs, impacts and effects on the magnetic component are also explained in detail in the above-mentioned reference. One of the presented methods is orthogonal biasing which is the method investigated in this paper.
To realize this method, drill holes through the ferrite core are needed to introduce the auxiliary winding. However, manufacturing ferrite is a complex process because of the material's fragility and brittleness. Special tools like an Ultrasonic/Sonic Driller/Corer (USDC) are needed to guarantee precise machining and avoid damage to the core material. The use of these tools is very expensive, especially if many small drill holes are required. Furthermore, the core's effective magnetic cross section becomes smaller the more holes are drilled into the ferrite material. Assuming an unchanged main current through the magnetic device, a reduced cross section area leads to a higher flux density and thus to higher core losses.
For these reasons, the question arises as to the minimum number of drill holes as well as their arrangement for a given auxiliary current to achieve a maximum saturation effect of a defined core section. In this paper, a basic model for the arrangement of drill holes for circular and square magnetic cross sections is presented, discussed and verified by simulation as well as measurement results.

Systematization of orthogonal biasing

Orthogonal biasing is one of three different methods of active premagnetization. It can be seen as a special variant of mixed biasing, which is also called "Virtual-Air-Gap" (VAG)-principle. The VAG-principle is investigated and discussed in [3].
If an auxiliary current flows through the auxiliary winding, a small area of the ferrite material around the drill hole gets saturated. Thereby, the local permeability in this area decreases which has an impact of the magnetic core's overall reluctance. The higher the auxiliary current, the higher the core's overall reluctance. The impedance value of the magnetic device thus becomes controllable.

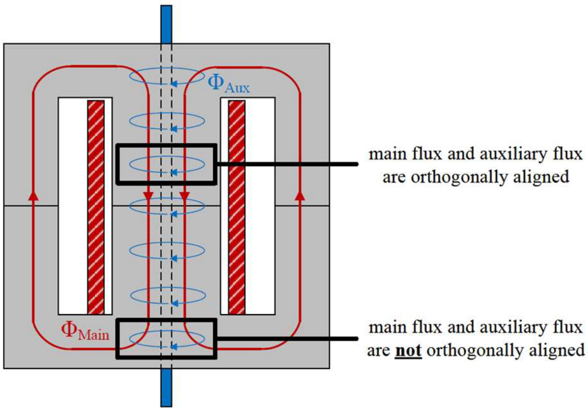
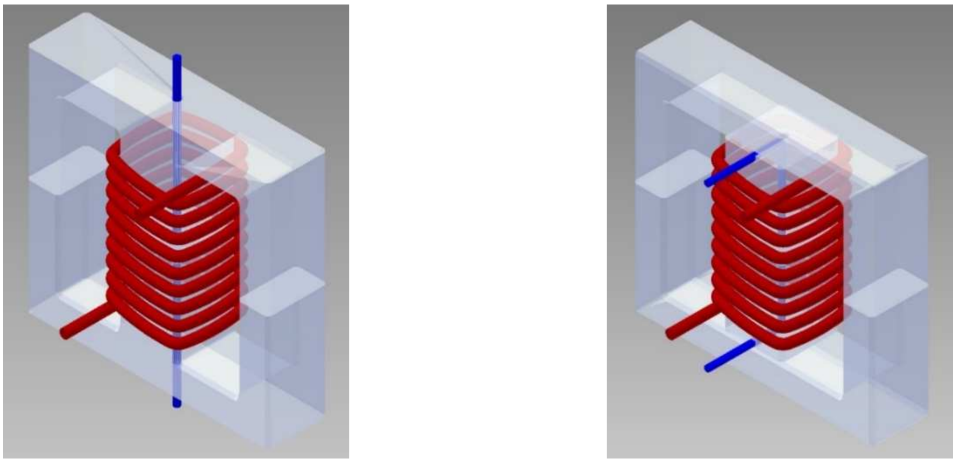


Fig. 1: Orthogonal biasing of an E-core (center leg). Main flux (red) and auxiliary flux (blue) are orthogonally aligned in the center leg but not in the yokes of the core

If a magnetic core section is orthogonally biased, main and auxiliary magnetic fluxes are orthogonally aligned. In theory, according to the superposition principle, both fluxes should not affect each other. Thereby, mathematical modeling becomes significant simpler. However, practical investigations show influences between main and auxiliary windings, e.g. due to the core geometry as the following example illustrates (see Fig. 1): If a center leg of an E-core should be affected by orthogonal biasing, the easiest way of machining is to drill a hole through the middle of the center leg and the yoke and introduce an auxiliary winding into the hole. Within the center leg itself, main and auxiliary magnetic flux are orthogonally aligned. However, within the yoke of the E-core the direction of the main flux changes because it closes in the outer legs. The auxiliary flux on the other hand remains in circles around the auxiliary winding. As a result, main and auxiliary magnetic flux are not orthogonally aligned in the yoke, which has an impact on the magnetic devices' characteristic.

Preliminary considerations of modeling and measurement prototypes

An exclusively orthogonal biased core is difficult to design due to the implementation of the auxiliary winding which must be introduced into and brought out of the core section. As mentioned in the previous section, drilling through the center leg of a ferrite core, e.g. an E-core as it is shown in Fig. 2 a), leads to a section within the yokes, where main and auxiliary magnetic fluxes are not orthogonally aligned because of the main flux's change of direction (see Fig. 1). This will lead to non-orthogonal biasing effects and with that a non-negligible impact on the magnetic device's characteristic in high auxiliary current ranges with negative effects on the model's accuracy.



a) b)

Fig. 2: Possible variants of the E 80/38/20 core for simulation and measurement verification of the model; light blue: ferrite core; red: main winding; dark blue: auxiliary winding

To avoid the described impact in the yoke of the E-Core, an alternative implementation of the auxiliary winding was investigated, as it is shown in Fig. 2 b). The leg of a core, e.g. the center leg of an E-core, is cut out an manufactured with a drill hole and a groove in which the auxiliary winding is placed. Thereby, no drilling through the yoke is needed. However, two small air gaps between center leg and yokes remain due to the cutting.

Both variants were simulated using the 3D FEM simulation software JMAG. SUMIDA Fi324 was used as ferrite material. For the variant shwon in Fig. 2 b) two air gap lengths between the center leg and the yokes of 0.1 mm each were assumed due to cutting off the centerleg from the yokes and glue it again.
The 3D FEM simulation results of the alternative variant in Fig. 2 b) show a negligible impact within the yokes. However, a non-negligible impact in the center leg around the outgoing of the auxiliary winding is ascertainable (see Fig. 3). Furthermore, the air gaps introduced into the core by cutting the center leg weaken the impact of orthogonal biasing on the magnetic device. These effects are also associated with higher manufacturing effort of the auxiliary winding's implementation than drilling a hole through the yoke and the center leg. For these reasons, it was decided to use the implementation variant shown in Fig. 2 a) for simulation and measurement verification, being aware of the described additional impact of the core section within the yokes which will lead to deviations of the model's calculations from the measurement results, especially if the auxiliary current increases. The manufactured cores for measurement verification are shown in Fig. 4.

Further considerations regarding general conditions were made to limit the number of the investigated shapes of a core's magnetic cross section. According to [4], the most frequent aspect ratio of an E-core's center leg is 1:1, which is a square. Moreover, there are numerous core geometries with circular (center) legs. Thus, the model will focus on circular and square cross sections.

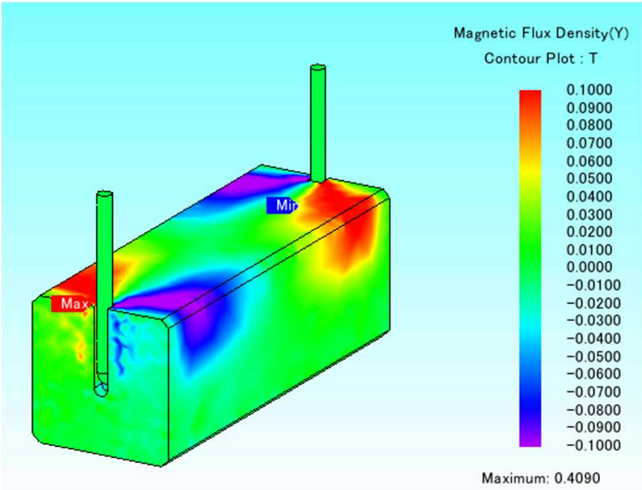


Fig. 3: Magnetic flux density (y-portion) around the outgoing of the auxiliary winding in the center leg of the E-core variant shown in Fig. 2 b) (main winding, yokes and outer legs are hidden)

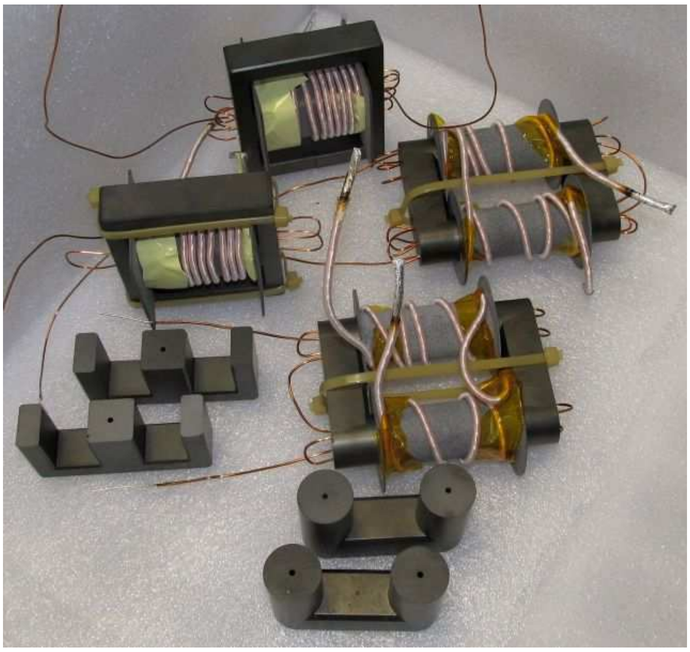


Fig. 4: Magnetic cores (URR 70/50/22 and E 80/38/20) with drill holes for measurement verification

Modeling the arrangement of drill holes for circular cross sections

It is assumed that the auxiliary magnetic flux caused by the auxiliary current, which is used for orthogonal biasing, flows in perfect circles around the auxiliary winding. The auxiliary magnetic flux density at the outside of the auxiliary winding is anti-proportional to the radius and decreases with $\frac{1}{r}$. Thus, the arrangement of the drill holes can be attributed to packing of congruent circles which is a well investigated mathematical field. Because of that, the optimal arrangement is well known and in parts mathematically proven. The best ways to pack two up to 20 congruent circles in a circular cross section is shown in [5].
To simplify the decreasing magnetic flux density, the material around the drill hole is divided in three different areas: saturated, "half-saturated" and unsaturated. By increasing the auxiliary current, the area will increase until the maximum radius of the circle is reached. The areas and their increase are shown in Fig. 5.

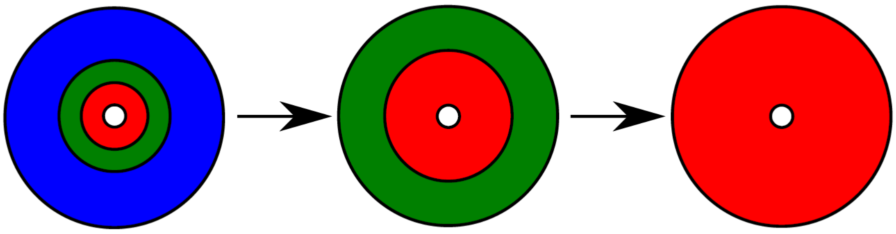


Fig. 5: Simple saturation model of the material around the drill hole of a circular cross section. The different areas increasing according to the increasing auxiliary current;
red: saturated area; green: “half-saturated” area; blue: unsaturated area

It is obvious that the best packing density in a circular cross section is achieved by drilling a single hole in the middle of the magnetic core’s leg. However, to achieve a maximum biasing effect it has to be ensured that the maximum auxiliary current is high enough the saturate the complete cross section. If the auxiliary current is limited, more than one drill hole could be needed. As already mentioned, drilling holes in ferrite material is a very expensive. Furthermore, a reduction of the magnetic core’s cross section goes along with each additional drilling hole. For these reasons it seems reasonable to drill as few holes as possible to an upper limit of ten drill holes. According to [5], circular cross sections with one, four and seven drill holes have the highest packing density. Using seven drill holes, a maximum packing density of 77,78% can be achieved. A higher maximum packing density is only achieved if 19 drill holes are manufactured (80,32%).
A pair of URR 70/50/22 cores is used for modeling. Originally an URR 70/65/22 should be used but its legs had to be shortened due to the maximum drilling depth of the USDC tool. The holes were drilled in both legs.
To model the differential inductance of the core under the impact of orthogonal biasing the magnetic equivalent circuit of the core is calculated. Due to the increasing auxiliary current the circular effective area of the cross sections of both legs is decreasing until both legs are completely saturated, as it is shown in Fig. 5 c). In case of more than a single drill hole maximum saturation is achieved when the borders of the circles touch each other as it is shown in [5]. Thereby it is assumed that only the legs but not the yoke are affected by the orthogonal biasing because a strict orthogonal alignment of main and auxiliary flux is assumed.

Verification through measurements for circular cross sections

To verify the calculation model presented in the previous section, small signal measurements are executed using a Keysight 4980A Precision LCR Meter. Several URR 70/50/22 cores made of Fi324 (SUMIDA) were manufactured with one, four and seven drill holes according to the arrangements presented in [5]. The differential inductance value of the magnetic device in dependence of the auxiliary current is measured.
Because of deviations of the initial inductance values for $\mathrm{I_{Aux}} = 0$ A between calculation model and measurement results the relative values of the device’s inductance are used. The relative deviation between calculated and measured values are shown in Fig. 6.

The results in Fig. 6 show deviations smaller than 10% for auxiliary currents up to $\mathrm{I_{Aux}} = 1$ A. For higher auxiliary currents, the deviations increase significantly. The main reason for this is assumed to be the impact of the yoke where main flux and auxiliary flux are not orthogonally aligned, as already discussed in the sections “systematization of orthogonal biasing” and “preliminary considerations of modeling and measurement prototypes”. The more material is saturated through a high auxiliary current and/or a high number of drill holes, the higher the impact of the yoke section. Most deviations are negative which means that saturation in measurement results is higher than calculated.
Furthermore, 2D FEM simulations using FEMM 4.2 show that the saturation around the drill hole is not a circle if more than one drill hole is used (see Fig. 7). This also results in deviations between the calculation model and the measurement results. The reason for this is the vectorial superposition of the individual fields at the points of contact.

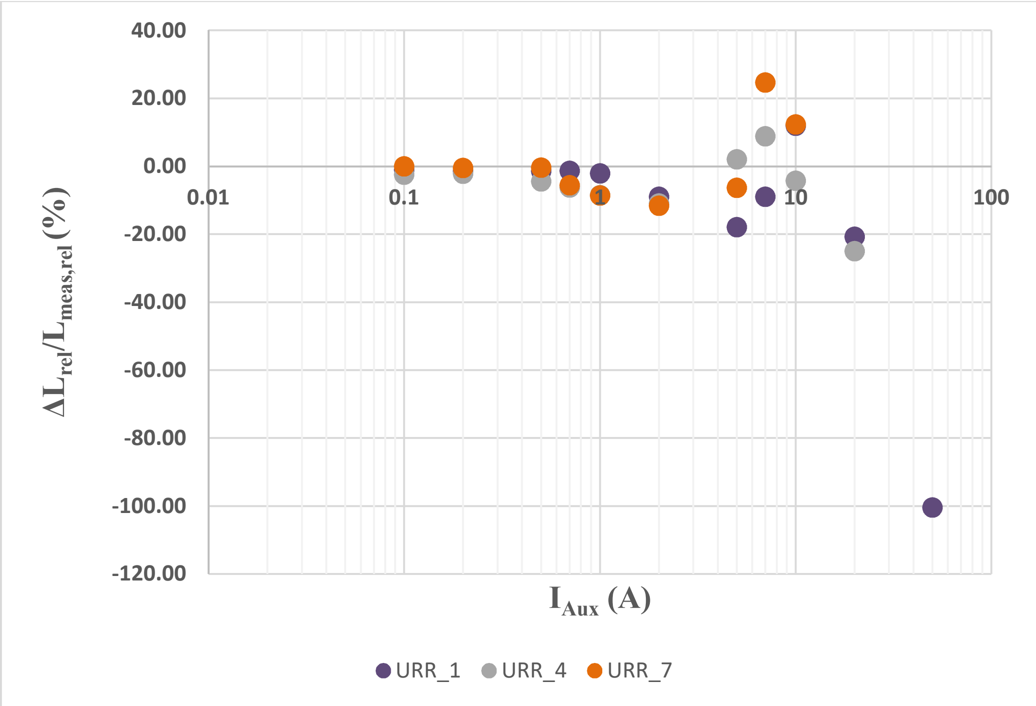


Fig. 6: Relative deviation of relative inductance value between calculation model and measurement results for an URR 70/50/22 core with one, four and seven drill holes within each leg

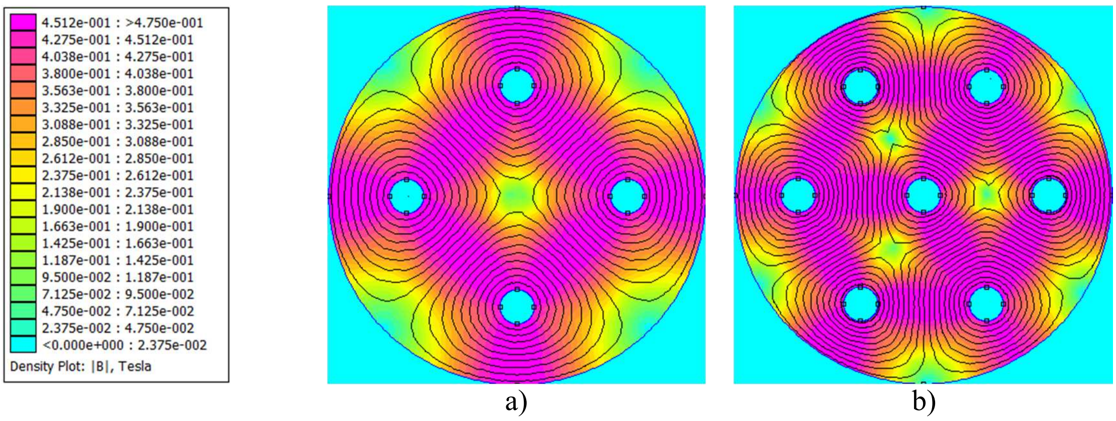


Fig. 7: Simulated magnetic flux density distribution of an URR 70/50/22 core's leg with four and seven drill holes ($I_{Aux} = 5\ A$)

Modeling the arrangement of drill holes for square cross sections

In a first step, the calculation model described in the section "modeling the arrangement of drill holes for circular cross sections" and shown in Fig. 5 is adapted to square cross sections as it is shown in Fig. 8, following the approach of circle packing.

The best ways to pack one up to 20 respectively 27 congruent circles in a square cross section are shown in [6] and [7]. According to the given references, the highest maximum packing densities using less than ten drill holes are achieved manufacturing one, four or nine holes (all 78,54%) which are thus the arrangements of investigation. A higher maximum packing density is achieved if 30 drill holes are manufactured (79,2%).

A pair of two E 80/38/20 cores is used for modeling. The holes are drilled through the center leg of the core. The calculation of the magnetic equivalent circuit is equivalent to the URR core in the previous mentioned section.

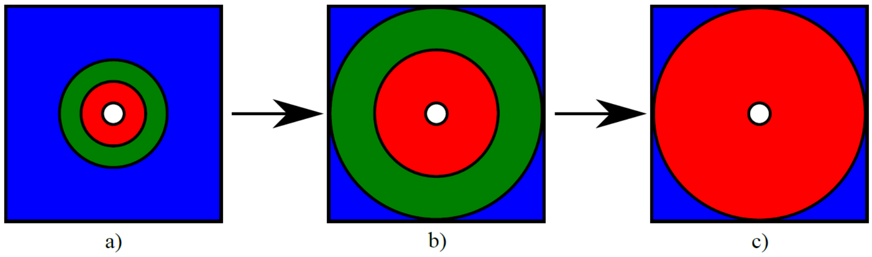


Fig. 8: Simple saturation model of the material around the drill hole of a square cross section. The different areas increasing according to the increasing auxiliary current;
red: saturated area; green: “half-saturated” area; blue: unsaturated area

The cross section is also simulated using 2D FEM software FEMM 4.2. As Fig. *9* shows, a circular expansion of the magnetic flux density is only present with small auxiliary currents. If the auxiliary current further increases a star-shaped density distribution is formed which finally leads into a cross-shaped density distribution. The reason for that is, that the distance from the middle of the drill hole to the middle of the outer edge of the square is shorter than the distance from the middle of the drill hole to the corner of the square. As a result, more cross-sectional area is available in the diagonal for the auxiliary magnetic flux which leads to a lower flux density in this area.

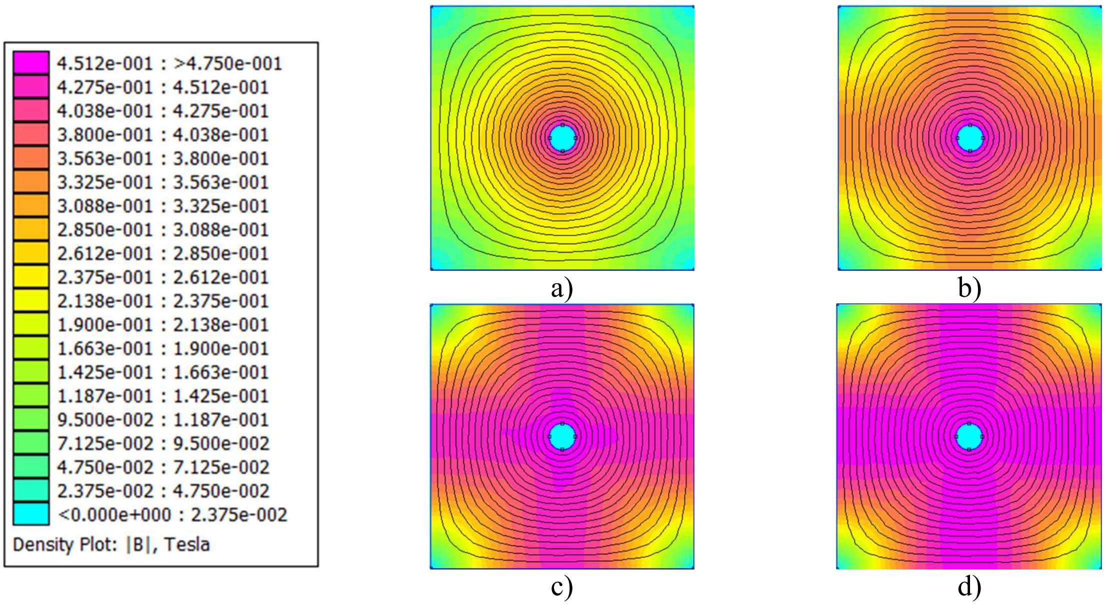


Fig. 9: Simulated magnetic flux density distribution of an E 80/38/20 core’s center leg with a single drill hole; a): $I_{Aux} = 1\ A$; b): $I_{Aux} = 2\ A$; c): $I_{Aux} = 5\ A$; d): $I_{Aux} = 10\ A$

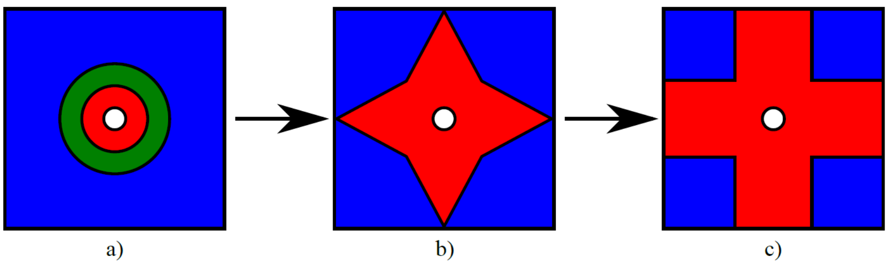


Fig. 10: Improved saturation model of the material around the drill hole of a square cross section. The different areas increasing according to the increasing auxiliary current;
red: saturated area; green: “half-saturated” area; blue: unsaturated area

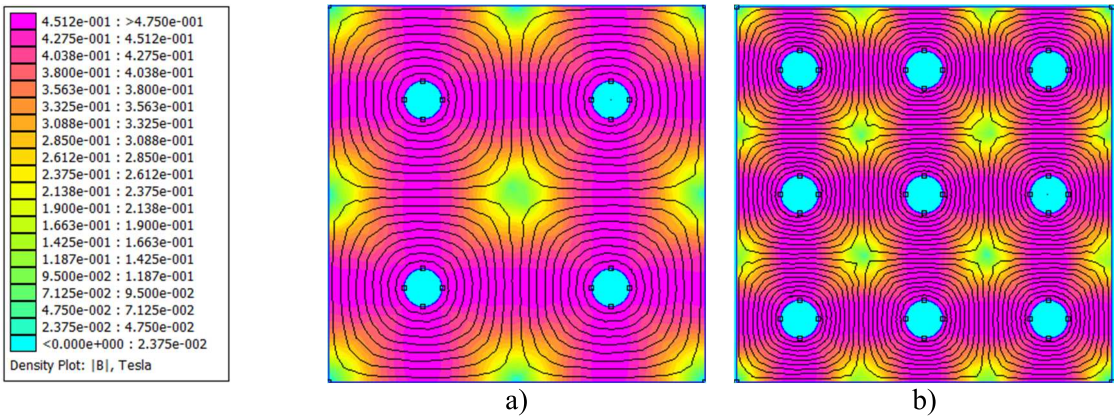


Fig. 11: Simulated magnetic flux density distribution of an E 80/38/20 core's center leg with four and nine drill holes ($I_{Aux} = 5\ A$)

According to the simulations results the calculation model is adjusted as it is shown in Fig. 10. A significant advantage of the investigated square cross sections is that the calculation model is easily transferable from a single drill hole to four or nine drill holes just by decreasing the square's edge length (see Fig. 11). Despite the different flux distribution, the arrangement of the drill holes according to circle packing remains unchanged.

Verification through measurements for square cross sections

Again, several E 80/38/20 cores made of Fi324 (SUMIDA) with one, four and nine drill holes according to [6] and [7] are manufactured and measured in small signal measurement using a Keysight 4980A Precision LCR Meter. The relative deviation between calculated and measured values are shown in Fig. 12. The circular-shaped markings represent the simple circular model (see Fig. 8) whereas the cross-shaped markings represent the improved model (see Fig. 10).

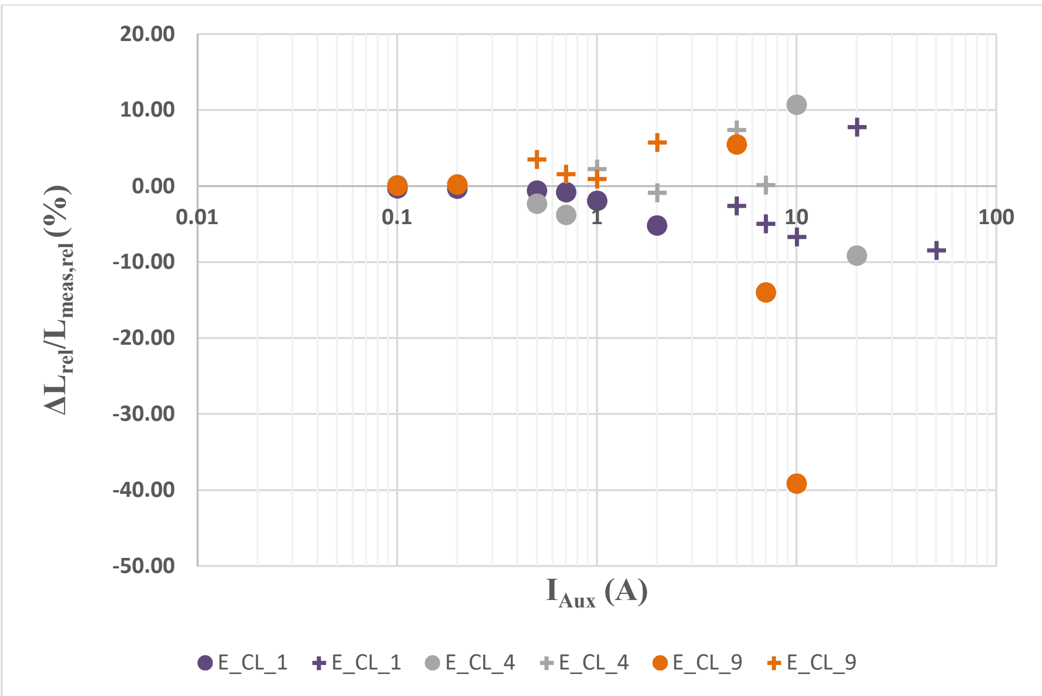


Fig. 12: Relative deviation of relative inductance value between calculation model and measurement results for an E 80/38/20 core with one, four and nine drill holes within the center leg (CL); circular-shaped markings: simple model; cross-shaped markings: improved model

Discussion and opportunities for improvement

The presented calculation model using a magnetic equivalent circuit is very simple and should be seen as a first approach regarding this topic. Still, most of the relative deviations between calculation model and measurement results are smaller than 20% for circular cross sections and smaller than 10% for square cross sections. However, there are plenty of opportunities for model improvement.

Just a few parameters used in the calculation model base on measurements of the used URR and E cores whereas most of the parameters is taken from the datasheets. These datasheet parameters are usually determined by measuring small toroidal cores which can lead to deviation if large core geometries are used as in this paper. Initial measurements of the core geometries that should be used in the application to gain more precise parameters for calculation will generate a higher accuracy of the model. However, the measurement of the cores is accompanied by an increased effort regarding time and available equipment.
Another opportunity for improvement is the division of the cross section. In the presented model the section is divided into an unsaturated, a "half-saturated" and a saturated area in dependence of the magnetic flux density. To achieve a higher accuracy of the calculation model, the division should be finer by increasing the number of different areas. Another approach could be to generate a function of the auxiliary magnetic flux as it is presented in [8]. Using that approach the magnetic flux density can be calculated very detailed in every point of the cross section. However, a computer-aided evaluation should be programmed for this approach.

The improved model for square cross sections is easily transferable from cores with a single drill hole to cores with more than one hole. Regarding circular cross sections a transferability to an increased number of drill holes is not trivial. Further investigations have to be executed to generate an improved calculation model with higher accuracy.
The most significant factor for deviations between calculation model and measurements is the impact of the yoke. Especially if a magnetic core with many drill holes is used, the saturation of the yoke as a large impact even by using medium auxiliary currents. Further investigations regarding the implementation of the auxiliary winding as they are presented in the section "preliminary considerations of modeling and measurement prototypes" should be made and evaluated in terms of their technical manufacturability. A more promising approach is to include the impact of the yoke in the calculation model.

It should be mentioned that the deviation shown in this paper might strongly depend on the selected operation point. Especially if high auxiliary currents are used to premagnetize the core what leads to a strong impact of the yoke, the materials hysteresis curve deforms as it is shown in [2]. Further investigations with regard to the impact of the operation point are useful.

Conclusion

Magnetic devices tend to be the bottleneck regarding volume and weight reduction in power converter systems. Even the constant improvement auf wide band gap semiconductor power devices and the associated increase of the switching frequency can only provide limited relief.
A promising approach regarding further volume und weight reduction are controllable magnetic devices using active premagnetization. One method of active premagnetization is orthogonal biasing. To be able to use this method drill holes within the magnetic core material are needed to introduce an auxiliary winding. Especially ferrite is a very fragile and brittle core material making its manufacturing complex and expensive. For this reason, the minimum number of drill holes as well as their arrangement for a given auxiliary current to achieve a maximum saturation effect of a defined core cross section is essential. In this paper, a basic model for the arrangement of drill holes for circular and square magnetic cross sections based on congruent circle packing was presented.

An exclusively orthogonal biased core is difficult to design because of the implementation of the auxiliary winding. Within the yoke of a magnetic core, magnetic main flux and magnetic auxiliary flux are not orthogonally aligned what leads to a significant impact of the yoke section regarding the controllability of the magnetic device. Two variants of a possible implementation of the auxiliary winding were simulated using 3D FEM software. Because of a significant larger manufacturing effort in connection with a non-negligible impact in the center leg around the outgoing of the auxiliary winding, it was decided to use the stanadard variant, being well aware of the yoke's negative impact on the models accuracy.

Calculation models for circular and square cross sections based on congruent circle packing were developed. Circle packing is a well investigated field in mathematical research which is why the optimal arrangement is well known and in parts mathematically proven. To calculate the inductance value of the magnetic device under the impact of orthogonal baising a magnetic equivalent circuit model was used. A leg of an URR 70/50/22 core was used for circular cross sections while the center leg of an E 80/38/20 core was used for square cros sections. The magnetic flux density distirbution was simulated using a 2D FEM software. Its results were compared to the calculation model. Because of a cross-shaped distribution of the magnetic flux density in square cross sections, the related calculation model was improved.

Both mentioned cores were manufactured with different number of drill holes and their inductance value was measured in small signal measurements.
The relative deviations of the relative differential inductance values of calculation and measurements show a good fitting (smaller than 10% deviation) for small auxilairy currents up to $I_{Aux} = 1$ A for circular cross sections respectively $I_{Aux} = 5$ A for squre cross sections. Most values are smaller than 20% deviation for circular cross sections and smaller than 10% deviation for square cross section. For larger auxiliary currents the impact of the yoke decreases the model's accuracy significantly as expected.

Because of the calculation models simpleness it can be seen as a first approach regarding the search for the most effective drill hole arrangement. However, its accuracy should be improved and further investigations regarding general arrangement of drill holes should be executed.

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