A Method to Estimate the Magnetic Flux Density in Inhomogeneous Space and New Shielding Materials

J. Wiznerowicz, H.-P. Beck

Abstract

In times of growing fear of damages of health supposedly caused by electric and magnetic fields, it becomes more and more important to calculate magnetic fields in early states of any project. Often, the field analysis with FEM is very complicated because of the huge number of different parameters to be known. This method also takes long computing time. In the Institute of Electrical Power Engineering at the Technical University of Clausthal a new method to estimate the magnetic flux density even in magnetic inhomogeneous space basing on Biot-Savart’s law was developed. It proves to have short modelling and computing time, especially for power electronic equipment. It can be a useful assistance in the development of optimized conductor systems and new shielding materials.

Introduction

For several years already, risks of damages in health caused by magnetic fields have been discussed in the European Union. In 1996, in consequence of this discussion the German federal government published the 26\textsuperscript{th} ordinance to enforce the federal law of protection against immissions [1]. In the ordinance limits for the magnetic flux density are given. They amount to 300 µT at a frequency of 16,7 Hz and 100 µT at a frequency of 50 Hz. To comply with these limits it is efficient to calculate the expected flux density in the environs of any electrical device in advance of building it. The method of calculation has to be fast and easy to use. Often, the common FEM does not answer this purpose. Consequently, a new method had to be developed.

1 Biot-Savart’s Law

With Biot-Savart’s Law it is possible to compute the magnetic flux density caused by an electric current in any conductor. For that, it is not necessary to subdivide space like it is if using FEM. For further explanations in Fig. 1 a sketch is given. It shows a conductor C with two dot-formed current sources at its ends. To calculate the magnetic flux density in point P some vectors are introduced. The magnetic flux density in point P is

\[ B(r) = -\frac{\mu I}{4\pi} \int_C \frac{(r-r') \times ds'}{|r-r'|^3} \]

(1)

Fig. 1:
For Biot-Savart’s Law
The validity of equation 1 is given in magnetic homogeneous space, only. First, the object of interest will be shieldings with a good conductivity. Later shieldings with a high permeability will be investigated.

2 Conductive shieldings

The effect of field-damping is based on induced currents in shieldings. In Fig. 2 a sheet metal is shown. A magnetic flux $\Phi$, which is a function of time $t$, crosses the sheet from the back to the front. In the sheet metal this flux induces the eddy current $i_{\text{ind}}(t)$. This current causes a second magnetic flux, which damps the first one.

To quantify the field damping, at the Institute of Electrical Power Engineering a procedure for substitution of eddy currents by currents in finite conductor loops has been developed [2]. Those loops are represented by dotted lines in Fig. 2. The loops are placed in dependence of the conductivity of the sheet metal and the frequency. The sum of the currents flowing in the loops equals the induced current $i_{\text{ind}}(t)$. The largest current flows near the edge of the sheet metal.

With the loops substituting the induced current and the primary currents causing the magnetic flux in the sheet metal it is possible to calculate the magnetic flux density with consideration of the shielding. For that purpose equation (1) is used.

3 Shieldings with high permeability

An element of equation (1) is the permeability $\mu$ of the space. Therefore Biot-Savart’s Law is valid in magnetic homogeneous space only. To enable a correct use of equation (1) for inhomogeneous space also, it must be extended. Thus, a new method of mirroring was developed. Normally, it is necessary to mirror all currents including the mirror currents on all borders between two different permeabilities. In this case, the mirror currents are stationary and their amount is constant. The number of mirror currents might be infinite, which is difficult to handle.

To avoid infinite mirroring the mirror currents can be made variable. Then it is enough to mirror the original currents on the borders between permeabilities once. In Fig. 3 an example is shown.

The original current $I$ flows on the $z$-axis. Parallel to the $x$-$z$-plain in the distance $a$ a sheet metal with the permeability $\mu_2 > \mu_1, \mu_3$ can be found. To calculate to magnetic flux density below the shielding, it is possible to use $I$ and the first mirror current $I^{(1)}$. Within the shielding the mirror currents $I^{(2)}$ and $I^{(3)}$ are used, above the shielding the mirror current $I^{(4)}$ is sufficient to calculate the magnetic flux density. All four mirror currents are stationary, but their amount depends on the permeabilities $\mu_1$ to $\mu_3$, the geometric parameters $a$ and $d$ and especially the co-ordinate $x_P$ of the point P, in which the flux density is to be calculated.
4 Comparison between measurement and calculation

To verify the new method of mirroring some measurements were made. In Fig. 4 the principle of the measurement arrangement is shown. In the left of Fig. 4 there is a conductor system. In the conductors the current \( I = 100 \, \text{A} \) flows at a frequency of 50 Hz. About 0.2 m in front of the vertical part of the conductor system is a sheet metal with a breadth of 1 m. Another 0.1 m in front and on a level with the middle of the steel sheet the magnetic flux density has been measured and calculated.

First, a steel sheet with the thickness of 3 mm was used. It was assumed, that the conductivity of steel equals the conductivity of iron, which is \( 10 \, \text{m}/(\Omega \, \text{mm}^2) \). Furthermore the relative permeability of steel was assumed to be 90. The results are shown in Fig. 5.

The magnetic flux density in the middle of the sheet reaches an amount of nearly 45 µT without shielding. On the edges it amounts 22 µT, only. If a shielding is taken into

![Fig. 3: Example for modified method of mirroring](image)

![Fig. 4: Measurement arrangement](image)

![Fig. 5: Measurement and calculation of magnetic flux density with a steel shielding](image)
consideration, the amount of the flux density is reduced to nearly 25 µT in the middle of the sheet and 20 µT on the edges. The calculation shows similar results to the measurement.

In another measurement arrangement in the left of the steel sheet according to Fig. 4 a copper sheet with the thickness of 3 mm was placed. Steel and copper sheet were insulated against each other. Results of this investigation are shown in Fig. 6.

![Fig. 6: Measurement and calculation of magnetic flux density with a combined copper-steel shielding](image)

Because of the second sheet metal the magnetic flux density without shielding is a little bit lower than in Fig. 5. The distance between conductors and calculation point, respectively between conductors and measurement points is a little enlarged. In the middle of the sheet, the flux density is reduced from about 42 µT to 13 µT. On the edges no reduction can be measured. In this state, the calculation is not able to take effects on edges into consideration. However, the shielding is nearly 40 % better than the single steel shielding.

5 New shielding materials

With the new calculation method it is possible to vary the shielding parameters conductivity and permeability quickly. This way new shielding materials with optimized parameters can be developed.

Therefore the flux damping was calculated. The arrangement for calculation is shown in Fig. 7. The flux density has been determined on the level of the middle of a sheet metal. The damping has been calculated from the mean value of the flux density. Distances are as in Fig. 4, the metal sheet is 2 m tall.

A single metal sheet is used. In Fig. 8 the flux damping $D_S$ depending on conductivity $\gamma$ and relative permeability $\mu_r$ of the sheet is shown.

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Conclusions

The new method of mirroring is a quick procedure to estimate the magnetic flux density. It is based on Biot-Savart’s Law and uses it correctly even in magnetic inhomogeneous space. The results show, that a single shielding should have a large permeability, while the conductivity is nearly without influence on the flux damping.

References


The authors would like to thank Deutsche Bahn Systemtechnik for ordering and supporting the investigations described in this paper.

Authors

Dipl.-Ing. Wiznerowicz, Jan
Institute of Electrical Power Engineering
Technical University of Clausthal
Leibnizstraße 28
D-38678 Clausthal-Zellerfeld
E-mail: wiznerowicz@iee.tu-clausthal.de

Prof. Dr.-Ing. Beck, Hans-Peter
Institute of Electrical Power Engineering
Technical University of Clausthal
Leibnizstraße 28
D-38678 Clausthal-Zellerfeld
E-mail: beck@iee.tu-clausthal.de