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Thermal impact of the magnetic field as a harmful effect of preparing the device structure

***Abstract**. The article presents one of the aspects of the construction work of the device being created, i.e. the arrangement of the elements generating the magnetic field. When constructing the device, first of all, their arrangement is taken into account due to the position in the electrical diagram of the device, the method of power supply, and the distribution of signals. The article presents one aspect of the interaction of these elements, taking into account the mutual magnetic and thermal interactions.*

***Streszczenie.** W artykule przedstawiono jeden z aspektów pracy konstrukcyjnej przy tworzonym urządzeniu – rozmieszczenia elementów generujących pole magnetyczne. Przy konstrukcji urządzenia w pierwszej kolejności bierze się pod uwagę ich rozmieszczenie ze względu na pozycję w schemacie elektrycznym urządzenia, sposób zasilania, rozprowadzenie sygnałów. Artykuł przedstawia sposób analizy jednego z aspektów wzajemnego oddziaływania tych elementów uwzględniających wzajemny wpływ pola magnetycznego i warunków termicznych. (**Oddziaływanie termiczne pola magnetycznego jako szkodliwy element przygotowania konstrukcji urządzenia**)*

Keywords: magnetic field, thermal influence, device design.
Słowa kluczowe: pole magnetyczne, oddziaływanie termiczne, projektowanie urządzeń.

Introduction

During the construction of an electrical device, at the stage of starting work related to the mechanical structure, a decision is made regarding the arrangement of the planned devices. At this stage of work, the weight and dimensions of the device are most often taken into account. The mechanical strength of the supporting elements (shelves, casing walls), especially when planning the arrangement of large-sized elements, is of decisive importance here. Large cross-sectional cables, the weight of magnetic circuits, etc. are important. At this stage, phenomena that are not visible at the initial stage are rarely taken into account, i.e. the impact of electrostatic and magnetic fields and heat. These phenomena become visible when the device starts operating and the energy flow begins.[1, 2]

In this article, the authors draw attention to the possibilities of predicting the elimination of similar problems using tools that have long been well known to designers, namely computer simulation. The method is relatively cheap, but requires some effort and knowledge.

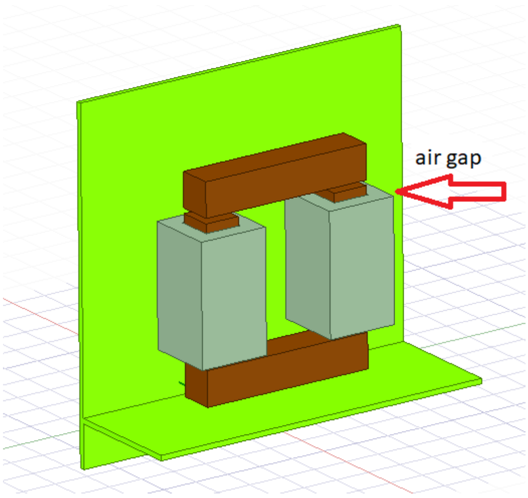

Fig. 1 Electrical device (choke with air gap) placed near the steel casing of the device

Figure 1 illustrates the problems that may be encountered in the work of a designer of electrical devices, including power supply, filtration and operation of power supply devices. The choke is placed near the steel outer casing. The purpose of the choke is to filter current in the energy conversion process. The choke has an air gap whose task is to filter the DC component of the pulse-waveform, e.g. in a DC-to-DC power converter. The air gap is the source of the leakage flux, which reaches the steel wall of the casing within its influence range. The rapidly changing high harmonic field of the waveform being filtered may cause heating of components located within the range of the leakage field in the air gap. The authors' goal is to conduct a virtual experiment to check whether this position does not cause excessive heating of the casing. The effect of eddy currents in the wall sheet may raise the local temperature to dangerous levels and create a fire hazard. There are no ready-made formulas that could determine such temperature. What remains is the virtual experience.

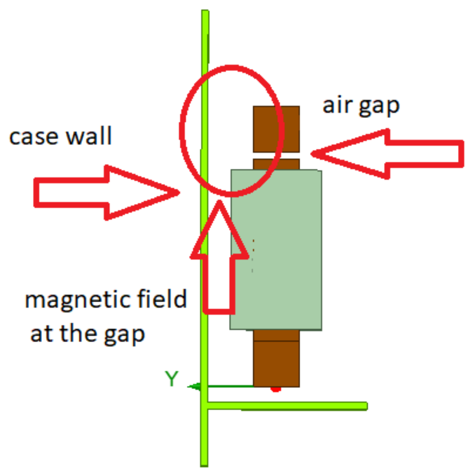

Fig. 2. Area of influence of the harmful air gap leakage field (marked with a red oval in the drawing)

Calculation methodology

The simulation studies were based on the Ansys software environment using the finite element method. Three packages were used simultaneously for the simulation: Maxwell to calculate ohmic losses in the area affected by the magnetic field, IcePack allowing for the analysis of thermal energy flow in areas considered by the designers as potentially dangerous to the structure, and, additionally, the Simplorer to generate forced quantities in the analyzed example. This was done due to the need to take into account the forced currents in the analyzed objects (parameters of current pulses flowing through the choke with an air gap) and changes in the parameters of devices with magnetic circuits with changing dimensions (change in the size of the air gap of the electric choke). In order to analyze the object for a wide range of parameters (change in air gap dimensions causing change in circuit inductance), an additional simulation of the operation of a simple power electronic circuit was used using the Simplorer package. The influence of current on magnetic circuits allows for the calculation of both forces and moments acting on the components of the device (the possibility of moving them under the influence of these forces) as in formula (1), [3]

(1) $$\vec{F}=\int\left[\frac{1}{\mu_0}B(B\cdot\vec{n})-\frac{1}{2\mu_0}B^2\cdot\vec{n}\right]dC$$

where $\vec{F}$ is the force generated under the influence of the resulting magnetic field, and $\vec{n}$ is the unit vector forcing the direction of the acting force.

The heating process of the element is described by formula (2) and results from the amount of energy calculated as ohmic losses in volume dV.

(2) $$E=\oint(OhmicLoss)dV$$

Eddy currents generate thermal energy according to formula (3)

(3) $$P=i^2R$$

where *P* is the power converted into heat and

(4) $$R=\frac{\rho l}{s}$$

R is the resistance resulting from the properties of the material from which the thermal energy is emitted (taking into account the resistivity), in this case steel. This type of calculation treatment allows to calculate the actual value of energy transferred by the choke coil to the steel sheet material of the casing by using a specialized calculator that can be found in the Maxwell software. Additionally, this function can be performed by passing the calculations to a Maxwell-linked program called IcePack. This is Ansys software that can calculate the steady-state temperature of a steel sheet through proper data coupling (2,3,4). Please note that the results can only be interpreted as "steady state". The dynamic state can be observed using the additional "transient" module, which allows for the observation of dynamic changes in temperatures in the observed object. The authors' calculations allow obtaining static results of the temperature change of the observed object with the calculation of the maximum temperature. Using multiple programs in a "coupling" system requires several rounds of calculations. The flowchart of this type of procedure is shown in Figure 3.

Fig. 3. "Coupling" diagram of the temperature calculation process (two separate programs calculate the temperature)

These three packages allow for simultaneous analysis of the behavior of the system as an electromagnetic, thermal and electronic object. They allow you to study the behavior of an object for a wide range of parameters, and the use of a software coupling system (Ansys Coupling) means that changes to the analyzed parameters are made in all programs at the same time. Therefore, a change in the temperature of an object affects the parameters of all objects and materials (e.g. the dependence of resistance on material temperature). [1,2,4,5]

System power circuit

To calculate waveforms in electrical circuits, the electrical diagram shown in Figure 4 was used. Due to the authors' intentions regarding extensive testing of the tested system, the analyzed choke is involved in energizing the DC-to-DC power converter (LWinding1, LWinding2 coils), where it is necessary to separate this converter from the power source. This is due to the need to reduce the impedance of the power source regarding to the commutation processes of the DC-to-DC power converter.

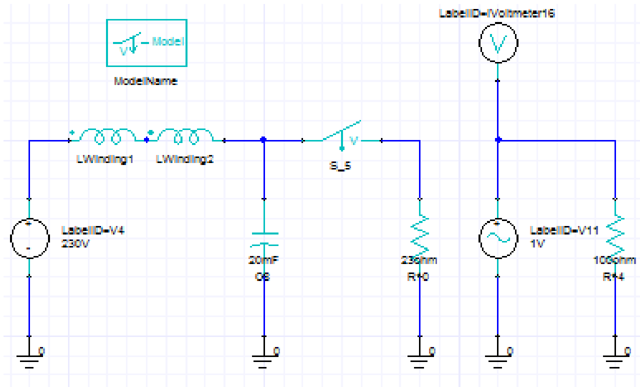

Fig. 4 Auxiliary diagram necessary to generate the correct way of powering the tested choke (Simplorer)

Figure 4 shows the method of forcing the flow of impulse current drawn from a DC voltage source through a low-pass gamma filter. The pulse converter is simulated as a voltage-controlled key, where the key control voltage is represented by a sinusoidal voltage source with parameters supervised by the Simplorer program (right side of the power electronics diagram separated from the main circuit). In this way, an impulse current flows through the choke, the distribution of which into a Fourier series allows the generation of harmonic waveforms, and the generation of eddy currents through the magnetic field created in the air gap. The air gap used separates the DC component of the waveform. This effect allows the elimination of the DC component of the current and thus the elimination saturation of the magnetic circuit. The lack of an air gap would cause saturation of the choke's magnetic circuit, reduce the inductance in the filter, change its parameters and deteriorate the quality of operation and parameters of the low-pass filter. The use of an air gap is therefore necessary. The authors would like to draw attention to problems related to thermal and electromagnetic interactions with the simultaneous analysis of the operation of electric circuits. Due to the extremely different mathematical descriptions of these types of environments, three types of software had to be used. The Ansys package makes this possible thanks to its "Coupling" system of interoperability between programs. The frequency of the current flowing through the choke is 500 Hz. The article analyzes the operation of the choke with various air gaps of δ.

Changing the thickness of the air gap causes a change in the density of the leakage magnetic field. Detailed numerical data will be presented on loss graphs as a function of the temperature of the sheet metal from which the casing was designed. The temperature of the sheet metal increases due to these losses. The study presents preliminary data showing the temperature of the casing sheet after the virtual experiment. In the choke shown in Figure 1, the air gap thickness is designed depending on the size of the DC component of the current, which is filtered in the control process of the designed device. The air gap thickness increases many times during its correction regarding the saturation of the choke core and deterioration of the properties of the gamma filter. In order to demonstrate the phenomenon, several virtual experiments were performed. The Ansys environment allows this type of calculation. However, since it is not sufficient to use only one computing environment for this type of calculations, Ansys allows for multiple calculations, using a system to combine the results of calculations in one environment for use and calculations in another. Calculations performed in the Maxwell environment are given as an example. This program allows for calculations related to electromagnetism, forces, and moments where the components of the designed devices are able to move. Losses occur when converting electrical energy into mechanical quantities. Energy losses are a source of heat. Depending on its amount, problems arise with overheating of the working device, and in borderline cases, its destruction. Preventing such events allows you to increase the reliability of the device. This can be done much easier during virtual experiences than on a ready-made device intended for final use. [4, 5]

Calculation results

After performing some of the calculations, the authors present a visualization of the interpretation of the results.
The first part of the calculations was performed based on the Ansys Maxwell program in order to estimate the losses occurring in the casing material, i.e. steel sheet. Due to the ferromagnetic properties of steel and the presence of an alternating magnetic field, it was possible to calculate losses related to the conductive properties of the sheet (resistance) and the magnetic permeance of the steel casing. Eddy currents, which the Maxwell program allows you to calculate, are a source of losses, which are also a source of thermal energy generated in the device (choke) and the casing surrounding this device. The area of eddy current losses and their density are shown in Figure 5. The thickness of the air gap in the analyzed device is 1 mm. It can be seen that ohmic losses begin to occur within the volume of the steel casing.

Eddy current loss density data allows calculation of the casing temperature. The temperature distribution in the casing is shown in Figure 6. Isotherms are presented throughout the entire volume (thickness of the steel sheet) of the casing as isotherms with the same temperature. Calculations were made based on Ansys IcePack software. This package enables the observation of heated air and the ability to transfer heat energy to other elements located in the designed device, taking into account the expanding, heated air (its increased volume and density).

Calculations of the problem presented in this way with simultaneous "Coupling" calculations require a lot of: computing power, RAM and disk space. Nevertheless, for one data set, calculations using 4 CPU cores take over 23 hours. For the purposes of this description of the virtual experience, calculations were made for two sets of data extremely distributed in space.

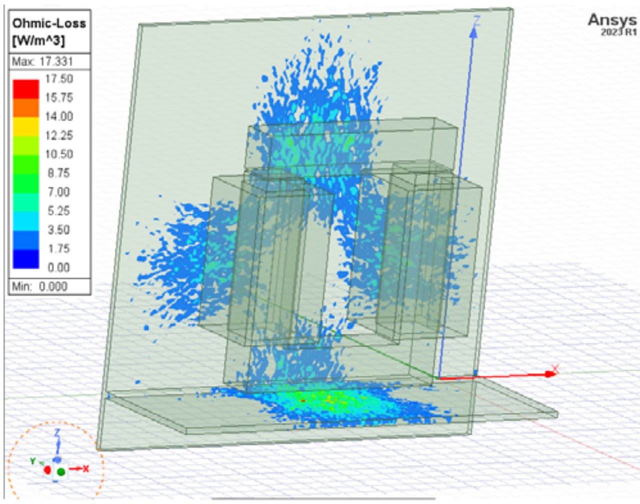

Fig. 5 Distribution and intensity of ohmic losses in the device casing with an air gap thickness of 1 mm

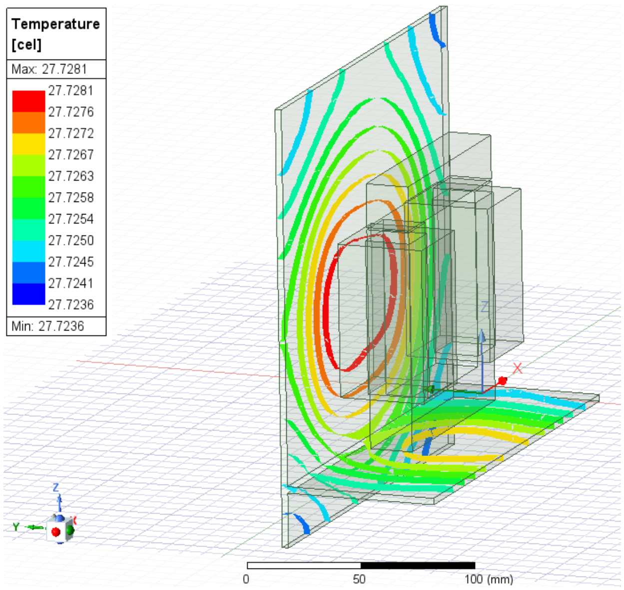

Fig. 6 Temperature distribution on and in the casing

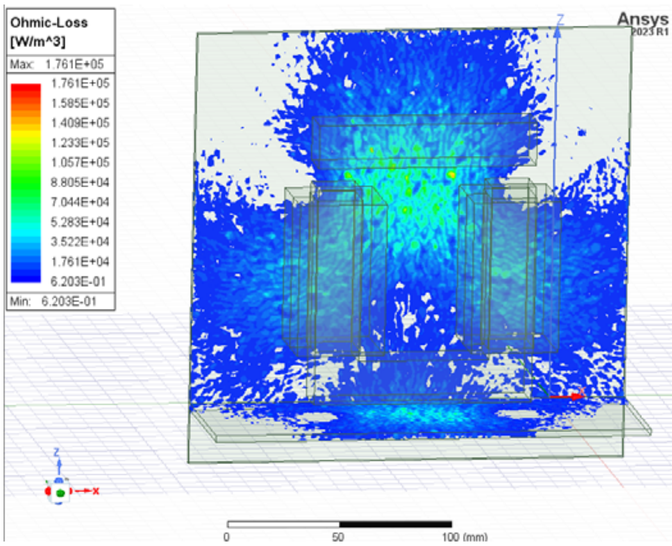

Fig. 7 Distribution and intensity of ohmic losses in the device casing with an air gap thickness of 7 mm

Figure 7 shows the ohmic loss densities for an air gap in the choke of 7 mm. The calculations made allowed to illustrate the relationship between the casing temperature

and the air gap thickness. These values are presented in Table 1 and Figure 8. The numerical data are presented in Table 1. It should be noted that in the virtual experiment, no changes were made to the displacement of the devices relative to each other. However, there is such a possibility. This allows for optimization of the arrangement of individual elements in the constructed device.
Comparing both values in Figure 8, one can notice the stabilization of the casing temperature at approximately 70 degrees Celsius. This is a temperature strongly felt by humans. The authors plan further research on this topic and linking the phenomenon of mutual thermal interactions with the release of energy in the remaining construction materials of the device (copper losses), as well as linking the propagation of thermal energy due to radiation.

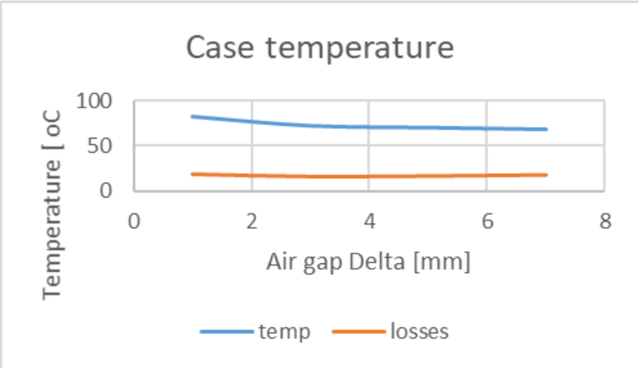

Fig 8. Distribution of casing temperature and ohmic losses at a power supply frequency of 500 Hz

Table 1. Numerical data based on Figure 8

No.	Air gap thickness [mm]	Temperature [°C]	Ohmic losses [W/kg]
1	1mm	82	18,87
2	3mm	72	15,96
3	5mm	70	16,60
4	7mm	68	15,50

Conclusions

Based on the simulations performed, it can be concluded that in the case under consideration there is a risk of high temperature affecting the structural elements of the device. The energy source is outside the device's electrical circuits. The magnetic field of the devices used (e.g. choke with an air gap) has a significant impact on the fire hazard of the constructed device. The authors intend to conduct further research in this direction. The dependence of the maximum temperature on the gap thickness, the frequency of the choke and the type of materials used significantly affects the design guidelines when working on the device. It also influences preventive measures to meet the conditions regarding compliance with the operating rules of the device in the event of fire or explosion hazards.
The Ansys software environment allows full use of simulations of this type of threats at the design stage.

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