Classification and research of electro-technical devices with unclosed magnetic core

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Abstract. The article is describes the classification and study of the magnetic field and its power parameters for unclosed magnetic core electrotechnical devices. The ANSYS simulation software has been used. The features of structures based on an open-loop magnetic system (iron separators), an open magnetic system (concentrators), and a hybrid magnetic system are shown. The magnetic field patterns and force characteristics are obtained as a result of numerical calculations created on the finite element method (FEM) in the ANSOFT software. Results of experiment: the electrotechnical device with unclosed magnetic core allows due to its design and configuration, of the magnetic field, the use of concentrators with different attachments to improve the power parameters of the magnetic field, ponderomotive force and operational properties of these devices.

1. Introduction

The progress in the technical equipment of the service sector needs requires the development and design of not only economical, high-quality and reliable electrical devices. The efficiency of such devices is low, but quality, reliability and functions possibility, they should have good power parameters and characteristics that can be obtained as a result of calculations of the electromagnetic processes of electro technical devices, namely, the value of induction and magnetic field strength, ponderomotive forces [1, 2]. These devices also include unclosed magnetic core electro-technical devices. The calculation of electromagnetic processes also makes it possible to obtain magnetic field patterns (the distribution of the power and equipotential lines of the magnetostatics and alternating magnetic fields) characterizing the operation of such devices. For electric and electro-technical devices with unclosed magnetic core can be referred as a movable devices with a linear trajectory of motion, or static devices. DC and AC electromagnets and permanent magnets can be used. Such devices can also include linear induction machines with liquid metal working medium, for example, pumps [3, 4], linear induction motors, for example, linear vehicles [4], linear electromagnetic motors with open magnetic core, which are synchronous reactive salient-pole machine for drive of reciprocating, shock and vibration action in hammers, in presses, pumps and compressors [3].

In addition, electro-technical devices with unclosed magnetic core can be represented by static devices. Static devices can be used in manufacturing, in electric power and heat power engineering, in agriculture and in agricultural processing, in everyday life, in medicine, in transport. In this case, their main purpose is to increase the octane number of petroleum products, improve the quality of oil, clean and preserve food and water. In addition, such devices can be used as electromagnetic locks, switching and relay protection, environmental cleaning, in physical and medical devices to increase the magnetic induction.

At the present time, there is great interest in multifaceted problems, namely related tasks - a joint examination of processes that are different in physical reasons. To such problems one can also assign
tasks of interdisciplinary type – "energy-economy" or "electrical engineering-economics". Of particular interest in the electric power industry, electro mechanics, and electrical engineering are problems of the "chain-field" type [3], where can be used a combination of well-known software packages, like ANSYS and MATLAB.

2. Research of the magnetic processes
The research includes mathematical modelling, simulation of the magnetic processes of electrotechnical devices with magnetic conductors of various design are carried out using 2D, axisymmetric, 3D field models, based on the complexity of their geometry, on the basis of equations for electromagnetic fields [2, 3]. Such modelling is performed on the basis of FEM method [5, 6, 7, 8] implemented in many well-known software products – ANSYS, ELCUT, COMSOL Multiphysics. Finite element networks with a large number and with a small number (preliminary, verification, training models) can be used on a desktops PC or high-performance computers. To modeling the magnetic field of electrical devices with the unclosed magnetic core, the following assumptions are accepted assumptions:

- the magnetic properties of the electrical steel of the model are specified either by the relative magnetic permeability $\mu = \text{constant (1000, 2000)}$ or by the magnetization curve of the steel embedded in the software product or introduced by the researcher;
- $\mu_{\text{air}} = 1$, $\mu_{\text{copper}} = 1$;
- the winding current is constant;
- modeling magnetostatic task;
- zero-boundary conditions of the task.

According to the Help section in the Maxwell 3D Help menu, the mathematical model of the problem being solved is a magnetostatics vector model for electrotechnical devices with an unclosed magnetic system [3]:

$$\text{rot } \vec{H} = \vec{J},$$  \hspace{1cm} (1)

$$\text{div } \vec{B} = 0,$$ \hspace{1cm} (2)

$$\vec{B} = \mu \mu_0 \vec{H}. \hspace{1cm}$$ (3)

A three-dimensional magnetostatics solver considers a magnetic field as follows [9]:

$$\vec{H} = - \text{grad} \varphi_m = \frac{\vec{B}}{\mu} = \frac{1}{\mu} \text{rot} \vec{A} \hspace{1cm}, \hspace{1cm}$$ (4)

where $\varphi_m$ is the scalar magnetic potential [2], $\vec{A}$ – is the vector magnetic potential.

2.1. Open-loop magnetic system
Iron separators [10] can be attributed to open-loop magnetic devices. The electromagnet of the iron separator consists of a П-shaped or Ш-shaped core with poles made of magnetically soft materials and a winding made of insulated aluminium or copper wire that is connected to a power DC supply.
Electromagnet it is intended for extraction of metallic particles from dry mixture and water, transported through a conveyor or a pipeline or as lifting electromagnets.

The core of the П- shaped type is made of electrical steel sheets, $I_w = 2600$ A.

The voltage at the winding terminals $U = 40$ V, current $I = 4$ A. The main dimensions of the iron separator are shown in figure 1 in mm, and the results of simulation and calculation process in figure 2 and figure 3.
2.2. Open magnetic system
An open magnetic system is a magnetic core with a winding (supplied with a constant or alternating current) and ferromagnetic attachments of an alternating cross-section nozzle (figure 4). Knife-shaped and saddle-shaped nozzles can also be used.

![Figure 4. Open magnetic system (1 – concentrator, 2 – winding, 3 – nozzle).](image)

Such systems allow you to concentrate, amplify or expand the scope of the device, and the results of simulation and calculation are shown in figure 5.

![Figure 5. The simulation results for a concentrator with a truncated cone attachment – a graph of the distribution of magnetic induction axial Br and radial Bz components.](image)

2.3. Combined magnetic system
The article proposes and investigates an electrotechnical device with an unclosed magnetic core or a combined system consisting of an iron separator (open-loop magnetic system) and a concentrator with various variable cross-section nozzles (open magnetic system). The modeling of two-dimensional and three-dimensional models of electrical devices based on the FEM with using multi-physical software is widely used to research electromagnetic processes in electrical systems and devices [11, 12]. A 3D model of the iron separator with three concentrating nozzles of a knife-like shape is considered in figure 6.
**Figure 6.** The 3D model of the combined magnetic system, prepared and showing in SolidWorks software.

Figure 7 shows a picture of the magnetic field of the system with three magnetic field concentrators with knife-shaped nozzles.

**Figure 7.** The distribution of magnetic field (from bottom to top).

Figure 8 shows the results of calculations of the force characteristics of the field of a combined magnetic core, namely, distribution of the forces vector (B) along the length of the conveyor belt along the corresponding contours, which are shown in figure 7.
According to the data obtained, it can be concluded that the magnetic field has an uneven distribution under the poles and is concentrated in the air gap between the poles of the iron separator and around the concentrators.

3. Conclusion
The research of various designs of an unclosed static magnetic system, their magnetic field of direct currents and its power characteristics (magnetic induction and magnetic intensity) has shown that the value of magnetic induction in the air gap between the poles of the iron separator without concentrators can be 30% less than for a combined magnetic core with concentrators of various shapes and quantities.

Combined magnetic systems enhance the power characteristics in the inter-pole gap. They change the configuration of the magnetic field and this leads to an increase in ponderomotive forces (30%) for the extraction of metal particles from the medium being cleaned, and also increases the volume of the medium being cleaned. The maximum values of the power characteristics can be obtained for a combined magnetic system with three knife-like nozzles.

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