Arcing chamber optimization of DC current-limiting circuit breaker using FEM

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Abstract: - The paper presents the calculation of the magnetic field in the arcing chamber of the current-limiting circuit breaker of the direct current 1250 A, 750 V. Current-limiting circuit breakers play an important role in electrical low-voltage circuits. Due to the high short-circuit currents it is necessary a very short time to switch off the defective branch. For this the current limiting circuit breakers are conceived as elaborated solutions especially for the arc quenching system, meaning the path of current and the arcing chamber. In this paper the authors present few optimization solutions of some quenching systems which will lead to more performing constructive choices. The finite element software package ANSYS is use for calculation of the magnetic field components.

Key-Words: - arcing chamber, magnetic field, current-limiting circuit breaker, finite element method, software package ANSYS, optimization, numerical simulation

1 Introduction

Computer-aided analysis of field distribution for evaluating electromagnetic device or component performance has become the most advantageous way for preliminary design and prototyping. Analytical methods have limited uses and experimental methods require dedicated structures and are time consuming and expensive.

A typical magnetic field problem is described by defining the geometry, material properties, currents, boundary conditions, and the field system equations. The computer requires the input dates, the numerical solution of the field equation and output of desired parameters. If the values are found unsatisfactory, the design is modified and parameters are recalculated. The process is repeated until optimum values for the design parameters are obtained [1].

The software package ANSYS can be used for investigation of the magnetic field distribution (the magnetic flux density, the magnetic field strength and the magnetic vector potential) and basic electromagnetic characteristics (inductance and electromagnetic force) of the arcing chamber of the current-limiting circuit breaker of the direct current 1250 A, 750 V.

This program is based on the finite element method for solving Maxwell equations and can be used for electromagnetic field modeling where the field is electrostatic, magnetostatic, with eddy currents, time-invariant or time-harmonic, and the structure may include permanent magnets [2].

The Finite Elements Method (FEM) assures sufficient accuracy of electromagnetic field computation and very good flexibility when geometry is modeled and field sources are loaded [1].

2 Arcing chamber of the current – limiting circuit breaker

The direct current is used in urban transport that is trolleybuses, trams and underground railways. The supply voltage for urban transport is 600 V or 750 V up to 1000 V.

Arcing chamber of the current – limiting circuit breaker uses for the electric arc extension through electrode effect for arc quenching, the magnetic blow-out system (realized with ferromagnetic plates) [3].
2.1 The physical model of the arcing chamber

The construction plan of the current path is presented in Fig. 1. It includes the output terminals A, B, the conducting bars 1, 2, the brake contacts 3 (lasting contacts) and 4 (arc brake contacts), the slopes 5, 6 placed in the arcing chamber CS. Within the arcing chamber there are the ferromagnetic plates 7, the insulated plates 8 and in the outside of it there are the ferromagnetic shapes 9.

The slopes have a smooth surface and they are made of copper because this material gives a good mobility and a high thermal conductivity. The ferromagnetic shapes 9 intensify the magnetic field and direct it to the arcing chamber so that a stronger ascending force acting on the electric arc base (along the slopes) and also on the electric arc, inside of the arcing chamber, is obtained.

The accessional circulation of heating air and the intensification of the magnetic field (produced by ferromagnetic plates 7) bring the arc extinction by direct acting on the arc core and by restrained displacement of the arc base. Thus, the electric arc flows through the arcing chamber. The force acting on the arc core, placed into the magnetic field (generated by the electric current which follows to be broken), is proportional to the current strength, the magnetic field strength and the length of the arc column [3].

Fig. 1. The sketch of the current – limiting circuit breaker [3]

The physical model partially reproduces the conditions inside of the current-limiting circuit breaker’s arcing chamber [4]. This model represents the current path, made of copper, dimensions of 10x15 mm², with parallelepiped shape. The current path is crossed by a 8.33 x 10⁵ A/m² density current. The two plates made of a ferromagnetic material, have a shape of trapezoidal prism, with 190 mm small end length, 250 mm length of the large end, 60 mm in height and 3 mm thickness. Electric arc slopes are made of copper, 30 mm width and 6 mm thickness.

2.2 Analysis of three-dimensional electromagnetic problems by FEM

Due to the physical model asymmetry, the three-dimensional modeling of magnetostatic field was necessary. In a three-dimensional case it is described by the elliptic Laplace-Poisson equation. The basic of this equation solution by FEM consists of finding correct approximation of vector potential components \( A_x(x, y, z) \), \( A_y(x, y, z) \) and \( A_z(x, y, z) \) by basic functions inside of the finite element. In the Cartesian coordinate system the equation must be approximated as:

\[
\nabla^2 A(x, y, z) = u(x, y, z),
\]

(1)

where \( A(x, y, z) \)-potential vector of a magnetic field, with \( (x, y, z) \in V \), \( V \)- modeling volume and \( u(x, y, z) \)-the right part depending on currents which create he magnetic field [5].

The boundary conditions for de magnetostatic problems can be of the first part: \( \vec{A}(x, y, z) = f_1(x, y, z) \), or the second part: \( \frac{\partial \vec{A}(x, y, z)}{\partial n} = f_2(x, y, z) \), where \( \vec{n} \) is a normal to the boundary surface. Expression (1) in the Cartesian coordinates system for electromagnetic processes can be written as:

\[
\frac{1}{\mu_r}\left(\frac{\partial^2 \vec{A}}{\partial x^2} + \frac{\partial^2 \vec{A}}{\partial y^2} + \frac{\partial^2 \vec{A}}{\partial z^2}\right) = -\mu_0 \vec{J},
\]

(2)

where \( \mu_r \) is the relative magnetic permeability of the model material, \( \mu_0 \) is the magnetic constant, and \( \vec{J} \) is the current density [1].

Numerical simulation is carried out by using the finite element package ANSYS.

ANSYS analysis assumes three stages: preprocessor, solver and postprocessor. The preprocessor is used for drawing the problems geometry, defining materials, defining boundary conditions, also the mesh is generated and the loads are applied on the elements. ANSYS includes a variety of elements which can be used in modeling the electromagnetic phenomenon [2].

In the present application, for the modeling of the magnetostatic field we choose the SOLID97 element, which permits three dimensional magnetic field modeling in planar and asymmetric problems. This element is based on the vector magnetic potential formulation and is suitable for the non-linear magnetostatic field. The element is defined by eight nodes and the material properties.

Also in this phase we choose and define the materials. For the path of current and the slopes copper has been chosen. For the two ferromagnetic plates, steel from ANSYS library has been chosen with the material...
properties contained in the emagM3.SI_MPL, emagM54.SI_MPL and emagVanad.SI_MPL files. The arcing chamber along with the path of current are put together in a box and inside of it air has been defined as material property.

ANSYS offers the possibility of constructing the geometric model as well as importing it from a CAD program [2].

Next step in preprocessor phase is mesh generation and load applying upon the elements. We used a mesh with 3335 nodes and 1606 triangular elements. The finite element mesh of the arcing chamber is shown in Fig.2.

Current density applies directly to the finite elements which form the conductors (the slope). The current density is given in SI units (A/m²). The applied boundary conditions are Dirichlet condition, A=0.

The solver takes a set of data files that describe problem and solves the relevant Maxwell’s equations to obtain values for the magnetic field through the solution domain [2].

The primary unknowns are nodal values of the magnetic vector potential and their derivatives are the secondary unknowns (flux density).

3 Results

A graphical program displays the resulting fields in the form of contour and density plots. The program also allows the user to inspect the field at arbitrary points, as well as evaluate a number of different integrals and plot various quantities of interest along user-defined contours. The path for the displayed charts is chosen between two points placed symmetrical one from another on the trapezoidal ferromagnetic plate at a distance of 160 mm and 15 mm spaced from the current path.

It’s also possible to save the plotted results in EMF (Extended Metafile) format.

The BH curve presents real dependency of magnetic flux density on magnetic flux intensity in ferromagnetic materials. It is a non-linear dependency which means higher requests for calculation process. The nonlinear B-H curve of the ferromagnetic material used for the slopes is presented in Fig. 3, Fig. 5 and Fig. 7.

The arcing chamber model along with the current path are built-in together in a box, inside of which air has been defined as material property.

The magnetic flux density spectrum in ferromagnetic shapes is represented in Fig. 4, Fig. 6 and Fig. 8 for the three ferromagnetic materials used [4]. Thus, for the emagM3 steel is obtained a 2.082 T maximum value for the magnetic flux density; for emagM54 steel maximum value is 1.933 T and for cobalt-vanadium steel emagVanad the maximum value is 2.236 T.
Comparing the magnetic flux density spectrums in the three cases we can observe that maximum blow-out effect is obtained by using emagVanad for the ferromagnetic shapes. For this material we obtain an optimal distribution for the magnetic field in the circuit breaker arcing chamber, which leads to a rapid movement of the electric arc towards the ferromagnetic plates. Arc quenching and arc voltage limiting occurs in base of the niche effect principle along with the electrode effect [4].

Fig.5 Magnetization curve of the emagM54

Fig.6 Distribution of magnetic flux density for the emagM54

Fig.7 Magnetization curve of the emagVanad

Fig.8 Distribution of magnetic flux density for the emagVanad

Fig.8 Variation of magnetic flux density depending on the ferromagnetic material type
The distribution of magnetic flux density in the ferromagnetic plates 7 and 9 is shown in Fig. 9, Fig. 10 and Fig. 11 for the angle of slopes of 120°, 110° and 130°. Therefore, for the slope with an angle of 120° a maximum value is obtained for a magnetic flux density of 2.030 T, for the slope with an angle of 110° a maximum value is obtained for a magnetic flux density of 1.275 T as well as the slope with an angle of 130° a maximum value is obtained for a magnetic flux density of 1.542 T.

As it is observed from this analysis, the magnetic blow-out effect is conditioned as the ferromagnetic material type used as well as the slope angle. The recommended optimum value for the slope angle is 120°.

**Fig. 9** Distribution of magnetic flux density for the slope angle of 120°

**Fig. 10** Distribution of magnetic flux density for the slope angle of 110°

**Fig. 11** Distribution of magnetic flux density for the slope angle of 130°

**Fig. 12** Variation of magnetic flux density depending on the slope angle

### 4 Conclusions

The obtained results by simulation using ANSYS package confirms that this numerical computation of magnetostatic field in the current-limiting circuit breaker’s arcing chamber leads to an accurate result. It’s well known that in electromechanical construction of a switching device, the arcing chamber along with current paths and contacts, represents the all-important elements concerning switching performances of these in normal operating conditions as well as in fault operating. Using EmagVanad for ferromagnetic plates and value for the slope angle of 120° a maximum blow-out effect is obtained. Therefore, an optimal distribution of the magnetic field in the circuit breaker arcing chamber leads to a rapid movement of the electric arc towards the ferromagnetic plates.
References:


