

2D NUMERICAL SIMULATION OF MAGNETIC FIELD IN LOW-VOLTAGE CIRCUIT BREAKER

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Abstract. *Low Voltage Circuit Breakers is used for the switching process in power distribution and control system. This process is accompanied by the occurrence of the electric arc between the fixed and mobile contact pieces of the apparatus. The electric arc is introduced into the quenching chamber formed of ferromagnetic iron splitter plates, divided into short arcs and then the arc may extinguish after passing the current through zero. Behavior of the electric arc in the extinguishing chamber influences the performance of these devices, the ferromagnetic material leading to the improvement of these performances. This article presents the calculation of the magnetic field components in the extinguishing chamber of the low-voltage circuit breaker of the 2000 A, 690 V manufactured by Schneider Electric and to describe the physical phenomenon and mathematical calculation of the electric arc in LVCB. The Ansys Multiphysics program is used to determine the spectrum of magnetic field components. This program is based on the finite element method for solving Maxwell equations.*

Keywords: *circuit breaker; extinguishing chamber; Finite Elements Method; software Ansys Multiphysics.*

1. INTRODUCTION

A circuit breaker is an electromechanical device designed to switch the rated current and fault currents. The electric arc is a key resource for the electricity interruption process. It is not possible to obtain the circuit interruption without experiencing the electric arc. The electric arc is physiological for the interruption and has not to be avoided, only controlled for improving the performance of the interruption. The interruption is successful if the arc was extinguished. The electric arc tends naturally to expand in the surrounding space. Thus, the design of extinguishing chambers of circuit breakers is very important and must be properly dimensioned.

Different papers [1-5] presented the study of low voltage switching devices. Lindmayer [1] analyzed the influence of extinguishing chamber wall materials and contact material on the arc extinction process. The behavior electric arc in low voltage circuit breakers is influenced by the complex interactions of current flow, magnetic forces, gas flow, heat conduction, and radiation. Brice at al [2] made a short review of conventional circuit breaker and proposed the that a new form at circuit interruption for low-voltage AC

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concerning use polymer into low-voltage switchgear. Slade et al. [3] investigated the influence of the contact system and material position on the arc interruption parameters.

In literature [4] the influence of gas composition and gas flow on the arc root mobility were reviewed and [5] were presented the arcing phenomena including arc motion, arc root, arc column and arc electrode in low voltage current limiting circuit breakers. Analytical calculation is very difficult for complex geometry and experimental methods require dedicated structures, time consuming and expensive. The software package ANSYS can be used for examination of the magnetic field distribution of the extinguishing chamber of the low voltage circuit breaker of the current 2000 A, 690 V. The ANSYS Multiphysics program has all the necessary modules to use the finite element method, for any linear and nonlinear structures. With this program, can be performed static, dynamic, transient and transfer analysis for the analysis of electrical, magnetic, and thermal processes. The Finite Elements Method (FEM) ensure enough precision of electromagnetic field calculation and very good adaptability when the geometry is shaped, and field sources are loaded.

2. FEM APPLICATION FOR TWO-DIMENSIONAL PROBLEMS OF STATIONARY MAGNETIC FIELD

2.1. THE PHYSICAL MODEL OF THE ARCHING CHAMBER

An ordinary magnetic field calculation problem is defined by the shape of model geometry, the material properties of the component elements, current value, load, and boundary conditions. The calculation demands the input dates such as the coordinate system, the real constants and the types of elements, solving the numerical model described by the magnetic field equations and output dates of wanted magnetic field parameters such as magnetic vector potential, magnetic induction and magnetic field strength. Numerical methods based on the use of modern computing technology have a wide area of applicability. Although approximate, if they meet certain criteria control of the calculation error, the numerical methods lead to acceptable results being much more attractive than the analytical ones. The electric arc developed between the contact pieces is inserted into the extinguishing chamber and then divided into a few segments equal to the number of intervals between the V-shaped ferromagnetic plates. All the short arcs connected in series produce their own anode and cathode drops, and their cumulative results in an important arc voltage drop. The construction plan of the arcing chamber for the model submitted for modelling is presented in Fig. 1.

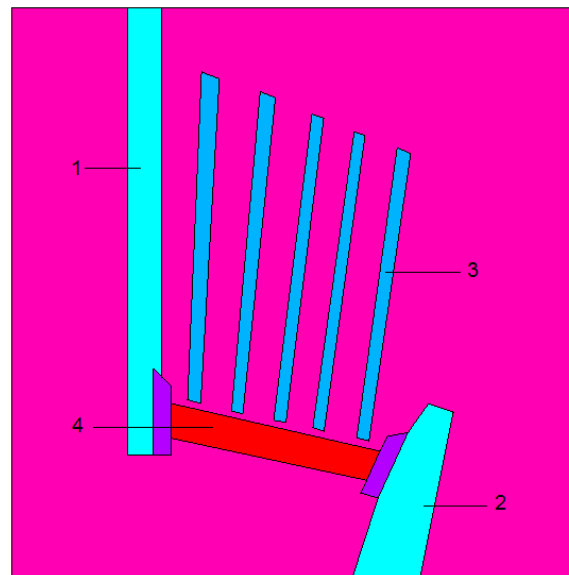


Figure 1. The physical model of the extinguishing chamber: 1 - the current path with fixed contacts; 2 - the current path with movable contacts; 3 - splitter plates; 4 - conductor bar.

The general construction of the circuit breakers includes, with small differences: the current path with fixed contacts (Fig. 1 (1)), the current path with movable contacts (Fig. 1 (2)) and splitter plates (Fig. 1 (3)). The two electrical contacts are connected by a conductor bar (Fig. 1 (4)). In low-voltage circuit breakers, ferromagnetic plates play the role of magnetic field concentrators. Magnetic permeability is 1 for metal. The model of the extinguishing chamber shown in Fig. 1 includes the current path in parallelepiped shape. It is made of copper and has dimensions of $5 \times 2.7 \text{ mm}^2$. The current path is traversed by a current with $14.814 \cdot 10^6 \text{ A/m}^2$ density current. The splitter plates made of a ferromagnetic material have a “V-shaped”, with 80 mm and 3 mm thickness. The analysis by simulation was made a very simplified 2D model that excludes the effect of other causes that influence the displacement of the arc.

2.2. ANALYSIS OF TWO-DIMENSIONAL MAGNETIC FIELD BY FEM

Finite element methods (FEM) use the most often a variation principle. According to the calculations of variations, solving a differential equation in a certain domain and under certain boundary conditions is equivalent to minimizing in that domain a functional quantity corresponding to the given differential equation and boundary conditions.

Generally, the finite element approximation is based on partial differential equations as expressions of the solutions defined by a partition of the field study in disjoint elements, called "finite elements", giving the name of the method [6]. These finite elements must be designed so that they can be reconstructed as faithfully as possible the real structure analyzed. In principle, these links must be designed to allow a numerical convergence to the exact solution, when the structure is discretized in finite elements with smaller and smaller dimensions. For simplicity, consider the plane-parallel magnetic fields. In this case, the magnetic vector potential has the Oz axis, and in the transverse planes $z = \text{constant}$ it is presented as a scalar field $A(x, y)$. To begin with, the case of plane-parallel fields is considered, in which the vector potential is oriented in the Oz direction. In this case, the Dirichlet conditions (C_D) and Neumann conditions (C_N) turn into:

$$A(x, y) = f(P), \quad P \in C_D \quad (1)$$

$$-\frac{1}{\mu} \frac{dA}{dn} = g(P), \quad P \in C_N \quad (2)$$

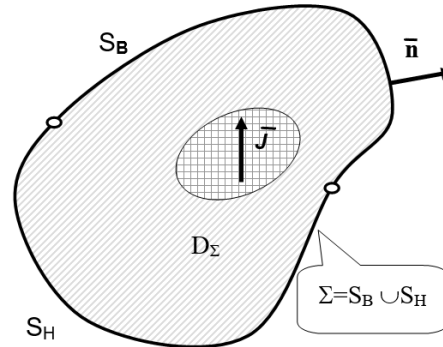


Figure 2. Computing domain for the two-dimensional problem.

Considering a stationary magnetic field problem in a domain where there may be current-carrying conductors, the field equations are:

- The magnetic circuit law:

$$\oint_{\Gamma} \overline{H} d\overline{l} = \oint_{S_{\Gamma}} \overline{J} d\overline{S} \Rightarrow \text{rot}(\overline{H}) = \overline{J} \quad (3)$$

- The magnetic flux law:

$$\oint_{\Gamma} \overline{B} d\overline{S} = 0 \Rightarrow \overline{B} = \text{rot} \overline{A} \quad (4)$$

- Form of the Law of the connection between magnetic induction \overline{B} and the intensity of the magnetic field \overline{H} for linear and isotropic materials without permanent magnetization:

$$\overline{B} = \mu \overline{H} \quad (5)$$

From these relationships it results:

$$\overline{H} = \frac{1}{\mu} \text{rot} \overline{A} \Rightarrow \text{rot} \left(\frac{1}{\mu} \text{rot} \overline{A} \right) = \overline{J} \quad (6)$$

$$\text{rot}(\text{rot} \overline{A}) = \mu \overline{J} \quad (7)$$

that means:

$$\text{grad div} \overline{A} - \Delta \overline{A} = \mu \overline{J} \quad (8)$$

The relationship

$$\operatorname{div} \bar{A} = 0 \quad (9)$$

is applied in stationary and quasi-stationary regimes in static domains and represents the calibration condition Coulomb of the potential vector \bar{A} . The Poisson relation for the magnetic field is obtained

$$\Delta \bar{A} = -\mu \bar{J} \quad (10)$$

The calculus domain D_Σ is bordered by the closed surface $\Sigma = S_D \cup S_N$; $S_D \cap S_N = \emptyset$ and it is shown in Fig. 2. On this surface, border conditions are imposed, by one of the two main types.

- Homogeneous Dirichlet conditions:

$$n \times A|_{S_B} = b, \quad P \in S_B \quad (11)$$

coming from the boundary condition expressed by the normal component of magnetic induction \bar{B} .

- Neumann conditions:

$$n \times \left(\frac{1}{\mu} \operatorname{rot} A \right) \Big|_{S_H} = h(P), \quad P \in S_H \quad (12)$$

coming from the boundary condition expressed by the tangential component of magnetic field intensity \bar{H} .

The spatial domain is discretized into triangular finite elements. Based on the variational principle, the magnetic field problem described by Poisson's equation can be solved according to the Rayleigh-Ritz method by minimizing energy functional on the considered magnetic field. Functional is a function that depends on another function and has the property that those values of the function for which it has an extreme are exactly the solutions of the Poisson equation. These solutions satisfy the imposed boundary and uniqueness conditions. In this application the main unknown is the magnetic vector potential.

This vector has the orientation of an axis of the coordinate system, and the vector magnetic potential has the form $\bar{A}[0, 0, A_z(x, y)]$. Conduction currents have also only components after the Oz axis. Therefore, in the cross-section planes, the current density J has the character of a scalar field (x, y). The functional reduces to:

$$\mathfrak{F}(A_z) = \int_D \left\{ \frac{\nu}{2} \left[\left(\frac{\partial A_z}{\partial x} \right)^2 + \left(\frac{\partial A_z}{\partial y} \right)^2 \right] - J_z A_z \right\} dx dy - \int_{\Gamma_N} \nu g_N(x, y) A_z d\Gamma_N \quad (13)$$

where the domain D is a surface plane, Γ_N is plan boundary and with ν was noted the magnetic reluctivity. The magnetic vector potential is calculated equal to the functional zero [6]:

$$\delta \mathfrak{F}(\bar{A}) = 0 \quad (14)$$

In two-dimensional problems of the stationary magnetic field, the vector magnetic potential depends on the x and y coordinates of the system. The magnetic induction is written as [7]:

$$\vec{B} = \text{rot} \vec{A} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ 0 & 0 & A(x, y) \end{vmatrix} = \vec{i} \frac{\partial A}{\partial y} - \vec{j} \frac{\partial A}{\partial x} = \vec{k} \times (-\text{grad} A) \quad (15)$$

The square of magnetic induction is:

$$\vec{B}^2 = (\text{rot} \vec{A})^2 = \begin{pmatrix} \frac{\partial A}{\partial y} \\ -\frac{\partial A}{\partial x} \\ 0 \end{pmatrix} = \left(\frac{\partial A}{\partial y} \right)^2 + \left(\frac{\partial A}{\partial x} \right)^2 = (\text{grad} A)^2. \quad (16)$$

3. SIMULATION IN ANSYS

Numerical modelling of the magnetic field in the extinguishing chamber of the low voltage circuit breaker was performed using the software package ANSYS Multiphysics. This software supposes three steps. The first step is the Preprocessor where the input data are entered, the physical environment of the problem is defined, the physical model of the domain is drawn, the discretization network of the model is built. The discretization network may have irregular topology. Also, in the preprocessing phase, the properties of the materials for each region are defined, the load and boundary conditions are applied. The Solver is a second step of the program which performs the numerical model solution. Among direct numerical methods used to solve the nonhomogeneous systems of algebraic equations, we can say that there is the direct Gauss elimination method, the LU factorization method, the Cholesky method, etc. Within the iterative methods, the Jacobi method, Gauss-Seidel, and successive relaxation methods were assessed. The iterative methods are characterized by the fact that the considered system solution is obtained at the limit of a range of values which represent solutions for different successive iterations. To solve nonlinear equations the gradient method and the Newton-Raphson method are used. The third step is Postprocessing which provides the physical-engineering interpretation of numerical solution given by processor, which means, generally, the graphical solution with numerical and chromatic indications. After obtaining the solution, the program enables viewing the results [8].

The PLANE53 element is used to solve two-dimensional magnetic field problems. This element offers the possibility to model the magnetic nonlinearities. The ferromagnetic material used for the splitter plates is a steel chosen from the ANSYS library and having the properties in the emagVanad.SI_MPL folder. This domain was discretized in several 20454 triangular finite elements uniformly distributed and is shown in Fig. 3.

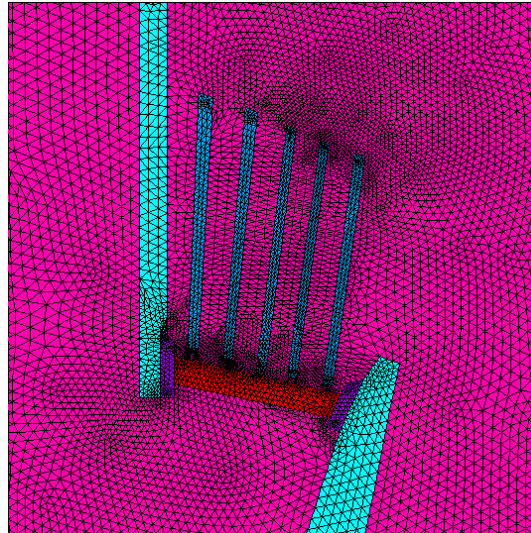


Figure 3. Meshing the model with triangular elements.

The loads and boundary conditions are applied to the two-dimensional calculation problem on the finite element model [9]. The applied boundary conditions are Dirichlet condition $A=0$ when A is vector magnetic potential. The loads applied to the plane model to the mesh during solution are automatically transferred by ANSYS. The current density is given in SI units (A/m^2). To observe the influence of the splitter plates on the magnetic flux density distribution, the magnetic field intensity distribution and the magnetic vector potential is computed, and the magnetic flux lines are drawn. In Fig. 4 there are represented the distribution of magnetic flux density.

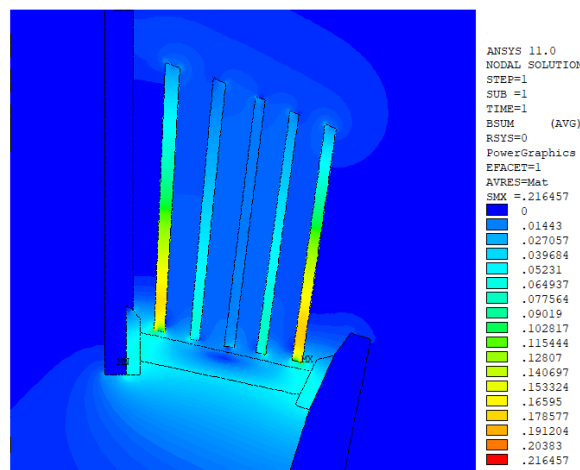


Figure 4. The distribution of the magnetic flux density.

The maximum value of the magnetic flux density is obtained at the base of plates. In this region, the magnetic flux density has a maximum of 0.216 T. Fig. 5 there are represented the distribution of the magnetic field lines.

Therefore, it is aimed to increase the arc voltage for obtaining a short lifetime for the electric arc. The increased of the arc voltage is realized by increasing the arc's length and by its intensive cooling. The plates are placed alternately so that the next is symmetrical to the first one. So, the electric arc has a tease form, which leads to an extension of its length [9]. The distribution of the magnetic field intensity in the interest area – conductors is presented in Fig. 6.

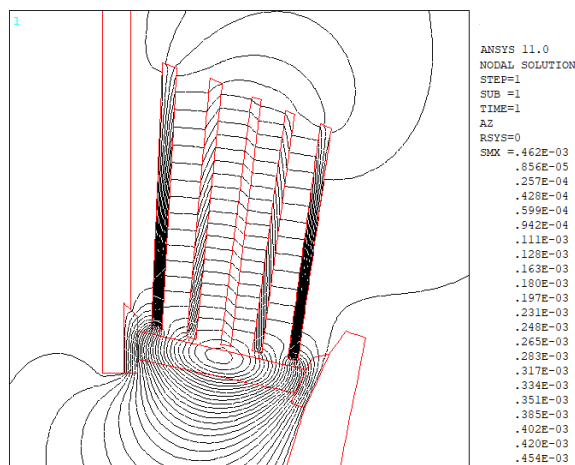


Figure 5. The distribution of the magnetic field lines.

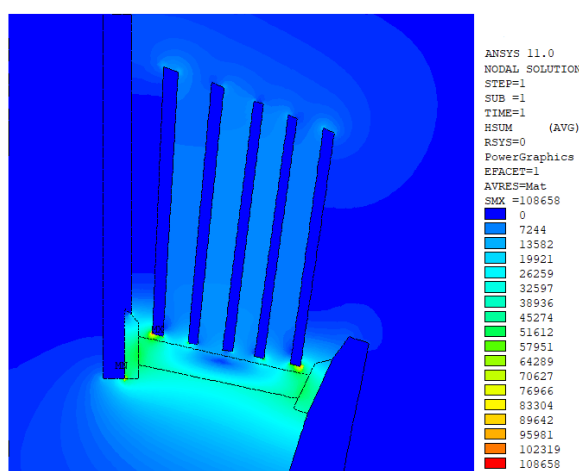


Figure 6. The distribution of the magnetic field intensity in the interest area – conductors.

Regarding the extinguishing chamber, factors with the greatest influence are the geometry splitter plates and properties material they are made, quantity and their arrangement. Moreover, the shape of the plates also has a highly influential on the distribution of the magnetic flux density and on the extent of the force acting on the arc. First, to relieve the formation of the main arc enough separation should be ensured between the contacts and the plates (3.2 to 4.7 mm). Likewise, the thickness of the plates cannot be very small to prevent melting, because of the high temperature generated by the arc (1.4 to 2.4 mm). The plates must be they placed very close to each other, to avoid welding of adjacent splitter plates (1.3 to 1.6 mm) [10]. In Fig. 7 the ferromagnetic plate and the conductors are represented.

Fig. 8 shows flux density distribution in the interest area – conductors the magnetic field lines which cross the ferromagnetic plate. Generally, the use of ferromagnetic material in the making of the plates deforms the magnetic field produced by the arc, causing the occurrence of a magnetic force that attracts the arc toward the region of the plates.

The spectrum of the magnetic flux density and magnetic force that appear on the arc varies on the position of the arc. As an example, Fig. 9 shows the magnetic field intensity distribution.

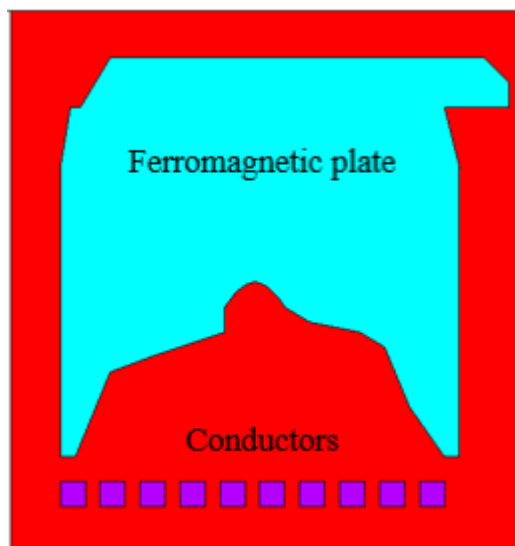


Figure 7. The area ferromagnetic plate – conductors.

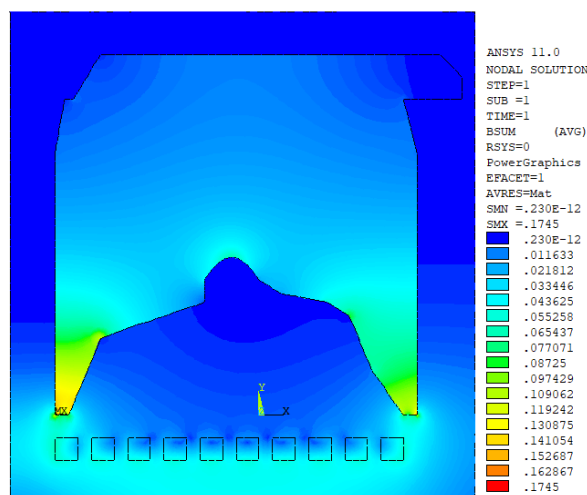


Figure 8. The flux density spectrum in the interest area – conductors.

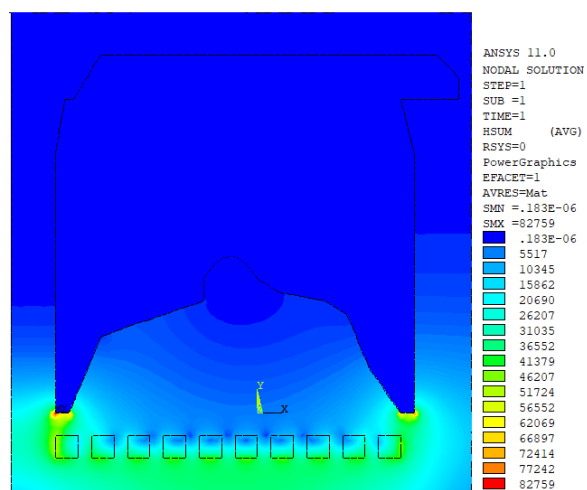


Figure 9. The distribution of the magnetic field intensity in the interest area – conductors.

Then the magnetic field intensity is computed from the flux density:

$$\{H\} = [\nu] \cdot \{B\} \tag{17}$$

where: $\{H\}$ is magnetic field intensity vector, $[v]$ - reluctivity matrix [11]. The maximum value of the magnetic field intensity is obtained at base plates. In this region, the magnetic field intensity has a maximum of 82759 A/m. Fig. 10 shows the current density vectors distribution.

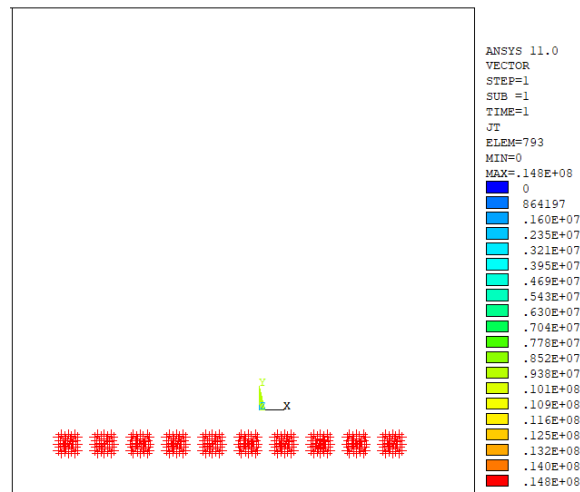


Figure 10. The current density vectors by conductors.

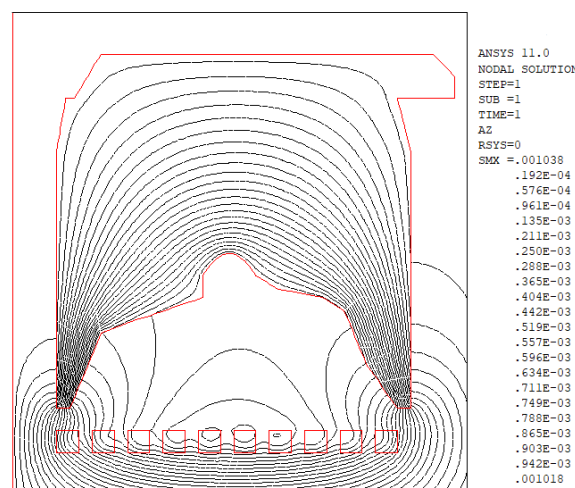


Figure 11. The magnetic equipotential lines in the interest area – conductors.

The material properties of ferromagnetic splitter plates also have a great influence on the behavior of the arc, as it is responsible for the cooling of the arc and the appearance of magnetic forces that push the electric arc into the extinguishing chamber. Generally, mild steel is used to manufacture the splitter plates used in low voltage circuit breakers extinguishing chamber. Also, to facilitate the movement of the arc on the plates and to reduce erosion and surface conductivity, the ferromagnetic splitter plates can be made of copper or galvanized silver [5].

Fig. 11 shows the magnetic field lines which cross the ferromagnetic plates. The magnetic field components can be visualized and as graphics. The force that applies over the ferromagnetic plates is obtained via stress tensor methods [9].

$$\vec{F} = \oint_{\Sigma} \left[(\vec{B} \cdot \vec{n}) \cdot \vec{H} - \frac{1}{2} \mu_0 H^2 \vec{n} \right] d\Sigma \quad (18)$$

where \bar{n} denotes the direction normal to the surface Σ at the point of interest. Hence, we have obtained the following results: the total value of the magnetic force is 0.733 N in central contacts area and a maximum value of 0.871 N is obtained in the lateral areas.

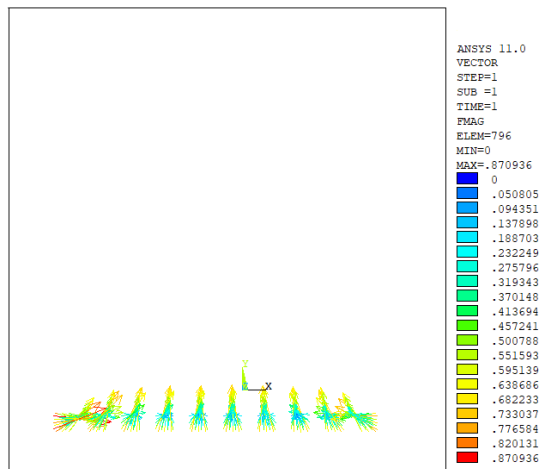


Figure 12. The magnetic force vectors.



Figure 13. The Low Voltage Circuit Breakers.

Fig. 12 shows that the magnetic force vectors are oriented towards the ferromagnetic splitter plates. Thus, the electric arc is drawn to the divided ferromagnetic splitter plates and then extinguished. The low voltage circuit breaker analyzed in this paper was designed and manufactured Schneider Electric (Fig. 13).

4. CONCLUSION

This paper we described numerical computations of magnetic field in the extinguishing chamber. The obtained results by modeling using ANSYS Multiphysics software confirms that this numerical computation of magnetostatics field in the low voltage circuit breaker extinguishing chamber establish to an exact result. Using a computer software electromagnetic field can achieve an optimization of the construction extinguishing chamber. Optimization can be achieved according to the most important elements of low voltage circuit breakers that influence the disconnection process, splitter plates and electric contacts. It can also make an optimization according to shape, quantity, arrangement, and material of the ferromagnetic splitter plates.

REFERENCES

- [1] Lindmayer, M., Marzahn, E., Mutzke, A., R  ther, T., Springstubbe, M., *IEEE Transactions on Components and Packaging Technologies*, **29**(2), 310, 2006.
- [2] Brice, C.W., Dougal, R.A., Hudgins, J.L., *IEEE Transactions on Industry Applications*, **32**(5), 1005, 1996.
- [3] Slade, P.G. *Electrical Contacts Principles and Applications*, CRC Press Taylor & Francis Group, 2014.
- [4] McBride, J.W., Pechrach, K., Weaver, P.M., *IEEE Transactions on Components, Packaging and Manufacturing Technology*, **25**(3), 427, 2002.

- [5] McBride, J.W., Review of arcing phenomena in low voltage current limiting circuit breakers, *Proceedings of the Institution of Electrical Engineers*, **148**, 1, 2001.
- [6] Andrei, H., Fluerau, C., Virjoghe, E.O., Enescu, D., Popovici, D., Husu, A.G., Andrei, P.C., Predusca, G., Diaconu, E., *Numerical Methods, Modelling and Simulation Applied in Electrical Engineering*, Electra Publishing House, Bucuresti, 2011.
- [7] Silvester, P.P., Ferrari, R.L. *Finite Elements for Electrical Engineers*, Third Edition, University Press Cambridge, 1996.
- [8] Virjoghe, E.O., Enescu, D., Stan, M.F., Ionel, M., *Finite Element Analysis - New Trends and Developments, Finite Element Analysis of Stationary Magnetic Field*, Ed. Intech, 2012.
- [9] Virjoghe, E.O., Enescu, D., Ionel, M., Arching chamber optimization of DC Current-Limiting Circuit Breaker Using FEM, *Proceeding of the 9th International Conference on Electric Power Systems, High Voltages, Electric Machines*, Genova, Italia, 208, 2009.
- [10] Iturregi, A., Torres, E., Zamora, I., Buigues, G., *Przegląd Elektrotechniczny (Electrical Review)*, **88**(1a), 104, 2012.
- [11] Kesim, M.T., Yu, H., Sun, Y., Aindow, M., Alpay, S.P., *Corrosion Science*, **135**, 12, 2018.
- [12] Li, S., Cui, X., Li, G., *International Journal of Mechanical Sciences*, **134**, 244, 2017.
- [13] Li, X., Chen, D., *IEEE Transactions on Components and Packaging Technologies*, **28**(4), 877, 2005.
- [14] Li, X., Li, R., Sun, H., Kari, T., Chen D., *IEEE Transactions on Plasma Science*, **37**(3), 463, 2009.
- [15] Piqueras, L., Henry, D., Jeandel, D., Scott, J., Wild, J., *International Journal of Heat and Mass Transfer*, **51**(19-20), 4973, 2008.
- [16] Rong, M., Yang, F., Wu, Y., Murphy, A.B., Wang, W., Guo, J., *IEEE Transactions on Plasma Science*, **38**(9), 2306, 2010.
- [17] Sakata, M., Enami, Y., *Fuji Electric Review*, **60**(3), 195, 2014.
- [18] Wang, J., Kang, Y., Wang, C., *Journal of Alloys and Compounds*, **686**, 702, 2016.
- [19] Wu, Y., Rong, M., Sun, H., Wang, X., Yang, F., Li, X., *Journal of Physics D*, **40**, 795, 2007.
- [20] Yang, F., Rong, M., Wu, Y., Sun, H., Ma, R., Niu, C., *Plasma Science and Technology*, **14**(11), 974, 2012.