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Approach for electrodynamic force for compensation in low voltage circuit breaker WP 630-1.2 type

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Abstract: Undesirable repulsive force between contact members due to both a current path shrink near a real contact area and/or so-called pinch effect is particularly onerous for power switch applications, and results in either contact floating or bouncing which are associated with an electric arc following contact welding. This problem is of great importance for any circuit breaker especially for compact low voltage vacuum circuit breakers. To avoid contact floating at closure and during any inrush current under short circuit conditions, the electrodynamic repulsive force can be employed successfully if we use a special compensation system flexibly combined with the contact itself. However to select and design the compensation system properly, its efficiency has to be known. This paper presents an approach to obtain the electrodynamic force value depending on different shaped (rectangular, square, circle and arch) copper plates used in the compensator by using ANSYS for current values 40 kA RMS. Curve-fitting was done according to the calculating results, the optimization designing of compensation unit is based on them.

Key words: Compensation, Electrodynamic force, FEM (Finite Element Method)
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INTRODUCTION

Undesirable repulsive force between contact members in any contact system can be due to both a current path shrink near a real contact area and/or so called pinch effect related to an explosive increase of metallic vapor pressure at contact breaking (Holm, 2000; Kharin *et al*., 2002). It is particularly onerous for power switch applications, and results in either contact floating or bouncing which are associated with an electric arc and following contact welding (Królikowski *et al*., 1985). The higher the current value is, the higher is the probability of a contact being repulsive. This problem is of great importance for any circuit breaker especially for compact low voltage vacuum circuit breakers.

To avoid contact floating at closure and during any inrushing of current under short circuit conditions, the electrodynamic repulsive force can be employed successfully if we use a special compensation system flexibly combined with the contact itself (Miedziński *et al*., 2002; 2004). However to select and design the compensation system properly, its efficiency has to be known. In this paper an approach to obtain the electrodynamic force value depending on different shaped (rectangular, square, circle and arch) copper plates used in the compensator by means of ANSYS for current values 40 kA RMS was done.

FEM ANALYSIS THEORY OF ELECTROMAGNETIC FIELDS

Electromagnetic fields are governed by the Maxwell's equations; electromagnetic fields analysis was used to solve the equations. It is always very difficult to obtain the analytic solution. Therefore, numerical calculation method is often used to obtain the solution according to the boundary and initial condition. FEM (Finite Element Method) is one of the most efficient and applicable numerical calculation methods.

The electromagnetic fields differential equation is (Jin, 2001):

$$\nabla \times (\mu_r^{-1} \nabla \times \boldsymbol{A}) = \mu_0 \boldsymbol{J}. \quad (1)$$

The first-type boundary condition is:

$$\Gamma_1: \boldsymbol{A}=\boldsymbol{A}_0. \quad (2)$$

The second-type boundary condition is:

$$\Gamma_2: n\times(\nabla\times\boldsymbol{A})=0. \quad (3)$$

The corresponding functional variation is

$$F(\boldsymbol{A}) = \frac{1}{2}\iiint_v \mu_r^{-1}(\nabla\times\boldsymbol{A})\cdot(\nabla\times\boldsymbol{A})\mathrm{d}v - \mu_0\iiint_v \boldsymbol{J}\cdot\boldsymbol{A}\mathrm{d}v, \quad (4)$$

where $\boldsymbol{A}$ is magnetic vector potential, $\boldsymbol{J}$ is applied source current density vector, μ is magnetic permeability.

Finite element analysis is dispersing functional variation in the regions, selecting the insert function, based on variation principle to obtain the equations solution by solving the limit value of functional variation under the boundary conditions (Moaveni, 1999). ANSYS FEM program can be used to derive and calculate all kinds of physical parameter, such as magnetic flux density $\boldsymbol{B}$ ($\boldsymbol{B}=\nabla\times\boldsymbol{A}$, curl of magnetic vector potential equals to magnetic flux density), magnetic field intensity H, magnetic force and the magnetic energy according to the results of magnetic vector potential $\boldsymbol{A}$ distribution (ANSYS 9.0 software, 2005).

Electromagnetic fields analysis based on nodal continuous magnetic vector potential method by means of ANSYS program was used to calculate the electrodynamic force value depending on different shaped copper plates in the compensator for the low voltage vacuum circuit breaker WP 630-1.2 type in this paper.

FINITE ELEMENT METHOD ANALYSIS OF COMPENSATION

FEM model

The compensation system is composed of two parallel copper plates which have same shape and can freely move relatively. The plates are isolated from each other (magnetic permeability $\mu_0=1$) (Flurscheim, 1975). Being the symmetry of the structure (Fig.1), 1/4 analysis model of two dimensions is generated.

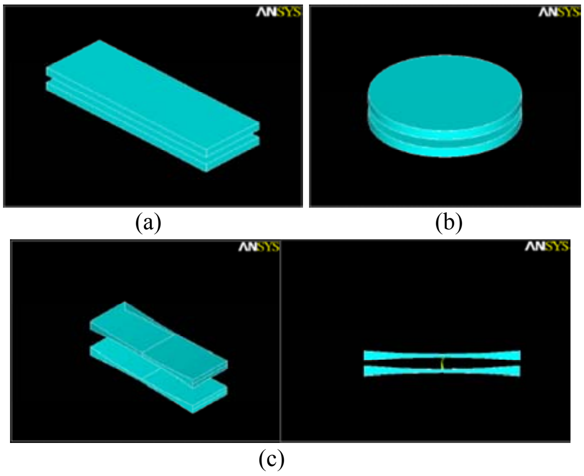

Fig.1 Analysis models of four shape plates
(a) Rectangle or square; (b) Circle; (c) Arch

Four types of shapes are chosen for compensator, they are rectangle, square, circle and arch, their volumes are equal approximately for comparison conveniently. Parameters are as follows: rectangle is 10800 mm^3 (90×30×4), square is 10800 mm^3 (51.96×51.96×4), circle is 11304 mm^3 ($\pi\times30^2\times4$), arch is 8997 mm^3 (Arch is the part of circle: $x^2+(y-508.25)^2=507.25^2$, length of chord is 90 mm, width is 30 mm, thickness of end is 6 mm, and centre thickness is 2 mm).

Centre distance between two plates is 10 mm, current is 40 kA RMS.

FEM analysis

The analysis results are shown in Fig.2.

Results of analysis

Calculating results of FEM are mapped and curve fitting by Matlab (Fig.3).

(1) Copper plates analysis of rectangular shape

The density distribution of magnetic force is constant value which equals to 18546.67 N/m.

Note: the section of plate is constant.

Magnetic force is 1669.2 N.

(2) Copper plates analysis of square shape

The density distribution of magnetic force is also

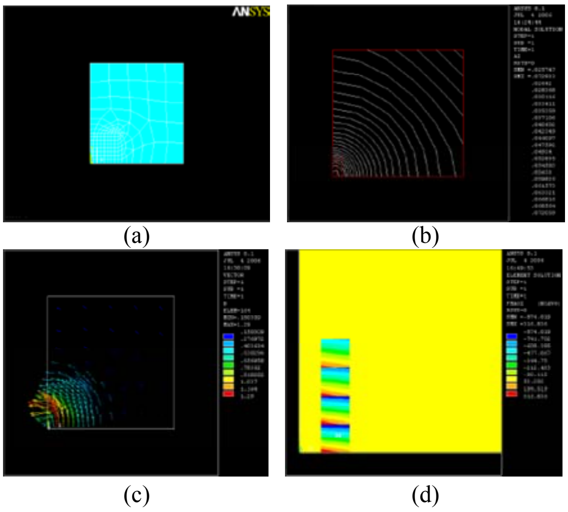

Fig.2 (a) Mesh; (b) Magnetic distribution; (c) Magnetic flux density vector; (d) F_{mag}-X contour on element

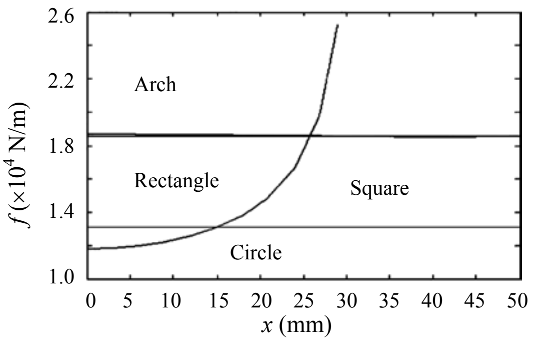

Fig.3 Distribution of magnetic force density

constant value which equals to 13102.56 N/m.

Magnetic force is 680.8 N.

(3) Copper plates analysis of circular shape (Table 1)

Circle equation: $x^2+y^2=30^2$.

Curve fitting (Fig.3) is

$$f(a)=(25x^2-383x+12774)\ \text{N/m}. \tag{5}$$

Magnetic force is

$$2\times\int_0^{30\times10^{-3}}(25x^2-383x+12774)\mathrm{d}x=766.1\ \text{N}. \tag{6}$$

Note: because the length (along x dimension) of plate is 60 mm, the model is half of it, so the force is double.

(4) Copper plates analysis of arch shape (Table 2)

Table 1 The density distribution of magnetic force f

x (×10^{-3} m)	y (×10^{-3} m)	a (×10^{-3} m)	f (N/m)
0	30.00	60.00	11816.42
3	29.85	59.70	11859.66
6	29.39	58.79	11993.08
9	28.62	57.24	12222.96
12	27.50	54.99	12577.94
15	25.98	51.96	13102.56
18	24.00	48.00	13828.22
21	21.42	42.85	14919.10
24	18.00	36.00	16662.20
27	13.08	26.15	19982.06
29	7.68	15.36	25228.20

a is the section width of circular plate

Table 2 The density distribution of magnetic force f

x (×10^{-3} m)	y (×10^{-3} m)	t (×10^{-3} m)	f (N/m)
0	1.0	2	18659.18
22.52	1.5	3	18597.74
31.84	2.0	4	18547.08
38.98	2.5	5	18508.84
45.00	3.0	6	18483.50

t is the section thickness of arch plate

Arch equation is $x^2+(y-508.25)^2=507.25^2$ (arch is the part of circle: $x^2+(y-508.25)^2=507.25^2$, length of chord is 90 mm, width is 30 mm, thickness of end is 6 mm, and centre thickness is 2 mm).

Curve fitting (Fig.3) is

$$f(t)=(-4x+18669)\ \text{N/m}. \tag{7}$$

Magnetic force is

$$2\times\int_0^{45\times10^{-3}}(-4x+18669)\mathrm{d}x=1680.2\ \text{N}. \tag{8}$$

Note: because the length (along x dimension) of plate is 90 mm, the model is half of it.

Discussion

Under the equivalent volume of plates, the magnetic forces of rectangle and arch are equal approximately; the value of circle and square are smaller than the half of others, since the density distribution of magnetic force is related to the length and sectional area of plates. The magnetic force density distribution of rectangle is constant and equals to 18546.67 N/m, and that of the arch is a lineal function, which is $(-4x+18669)$ N/m; length and width of rectangle are the same; rectangle thickness is 4 mm, arch's thickness is from 2 to 6 mm, so their magnetic force is almost the same. For square plate, the magnetic force density distribution is also constant and equals to 13102.56 N/m, the thickness is the same as that of the rectangle plate, its width and length are all 51.96 mm (2/3 of the rectangle length), the magnetic force of square plate is much smaller than that of rectangle plate. For circular plate, the thickness is also the same as that of the rectangle plate, its sectional width changes from 2 to 60 mm, larger than that of rectangle 30 mm, the length is only 60 mm (2/3 of the rectangle), the magnetic force density distribution of it is $25x^2-383x+12774$, therefore, the magnetic force of circular plate is much smaller than that of rectangle plate.

PROVING BY ANALYTIC METHOD

Calculating the magnetic force according to Biot-Savart field law is

$$F=\int_l I_1 B_x \mathrm{d}x=\frac{\mu_0 I_1 I_2}{4\pi}\int_0^l \frac{\cos\alpha_1-\cos\alpha_2}{d_x}\mathrm{d}x=\frac{\mu_0 I_1 I_2}{4\pi}K_\mathrm{h}. \quad (9)$$

The cross section of plate is relatively large and the two plates are close to each other, a sectional coefficient is introduced for considering the sectional effect on magnetic force (Zhang, 1961):

$$F=\frac{\mu_0 I_1 I_2}{4\pi}K_\mathrm{h}K_\mathrm{c}, \quad (10)$$

$$K_\mathrm{h}=\frac{2l}{d}\left(\sqrt{1+(d/l)^2}-d/l\right), \quad (11)$$

where K_h is a loop line coefficient, which is a function of the length and distance of two plates. K_c is sectional coefficient, it is the function of cross section (width, thickness) and distance of two plates, it can be looked up from the curve directly (Zhang, 1961).

Calculating by Eqs.(10) and (11), and comparing results with FEM method is shown in Table 3.

Table 3 Comparing results of two methods

I (kA)	*l* (m)	*a* (m)	*t* (m)	*d* (m)	Magnetic force *F* (N)	
					Equation	FEM
40	0.09	0.03	0.004	0.010	1623.9	1661.3
				0.005	2179.5	2138.8

I is current, *l* is length, *a* is width, *t* is thickness, *d* is distance

CONCLUSION

(1) Comparing the results of analytic method with FEM, the magnetic forces are equal approximately, generating the FEM analytic model for compensation is proved correct.

(2) Analytic method is complex and limited in electro-magnetic analysis, it is very difficult to calculate the loop line coefficient and sectional coefficient, especially, when the shape of conductive plate is irregular. FEM method is not limited to the shape of conductive plate. It is convenient and efficient by ANSYS when each of the structure parameters changes.

(3) According to the calculating result of FEM, at equivalent volume of plates, the magnetic forces of rectangle and arch are equal approximately; the values of circle and square are smaller than their half. Compensator was introduced to use rectangular plate for getting much magnetic force (arch plate is difficult to manufacture).

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