Analysis of Magnetic Field Characteristics of Vacuum Interrupters with Cup type Axial Magnetic Field Contacts Based on Orthogonal Design

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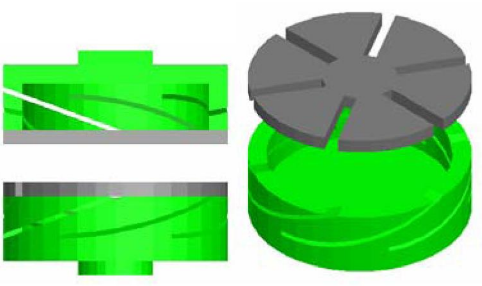
Abstract- **Seven contact parameters of cup type axial magnetic field (AMF) are used to study magnetic field characteristics by orthogonal design method. The characteristics include axial magnetic flux density, phase shift time and conductor resistance of contacts. Orthogonal experiments are done by three dimensions finite element method. Significant parameters and insignificant parameters that influence the magnetic field characteristics of cup type AMF contacts are divided by variance analysis of experiment results. Regression equations for the relation between AMF characteristics and the significant parameters are given. Applying the method of orthogonal design can reduce the quantities of computation greatly. Based on the regression equations, optimization design for AMF characteristics of cup type AMF contacts could be realized.**

I. INTRODUCTION

The invention of the AMF contacts was one of the most effective developments, contributing greatly to extending the application of vacuum circuit breakers [1]. There are many kinds of AMF contacts used in vacuum interrupter, such as cup type contacts and coil type contacts. The subject of this paper is cup type AMF contacts.

A lot of work on finite element analysis of AMF contacts has been done by many researchers [2-5]. Distributions of axial magnetic flux density, current density and phase shift time between AMF and source current are analyzed. Magnetic field characteristics of vacuum interrupter have been studied through changing single contact parameter, while other parameters are fixed. However, there are too many contact parameters. So it is useful to know significant parameters from so many contact parameters.

Orthogonal design method is a tool used to analyze multi-factor experiment. Orthogonal experiments are done by three dimensions finite element method in this paper. Axial magnetic flux density, phase shift time between AMF and source current and conductor resistance of contacts are obtained. Through variance analysis of the experiment results, significant parameters and insignificant parameters that influence the magnetic field characteristics of cup type AMF contacts are divided. And regression equations for the relation between the magnetic field characteristics and the significant contact parameters are given. Based on the regression equations, optimization design for AMF characteristics of cup type AMF contacts could be realized.


(a) (b)
Fig.1. Structure of cup type AMF contacts

II. CONTACT STRUCTURE MODEL

The structure of cup type AFM contacts is shown in Fig.1. When current is passing through the coil behind the contact plate, it produces AMF. Contact diameter is 48mm and gap distance is 8mm in this paper. Contact plate material is CuCr50, whose conductivity is 1.8×10^7 S/m. Vacuum arc is considered to be a column whose diameter is the same as that of contacts .Its conductivity is 2000S/m [4].

The numerical simulation are carried out with a commercial three dimensions finite element analysis software Maxwell 3D. Current is 1kA RMS. And its frequency is 50Hz. The eddy effects in contact plates, coil segments and vacuum arc are taken into account.

III. EXPERIMENT DESIGN

A. Orthogonal Design Table

Orthogonal design table is a table that arranges multi-factor experiment according to orthogonality. Orthogonal design table is labeled as $L_n(a^P)$, where the P is the number of rows and the n is the number of columns. The numbers in the table are integers from 1 to a. Tab.1 is an orthogonal design table labeled as $L_8(2^7)$. It arranges experiments with 7 factors and 2 levels. The symbols of columns z1, z2, ···, z7 in Tab.1 is 7

TABLE 1
ORTHOGONAL DESIGN TABLE $L_8(2^7)$

Source	z1	z2	z3	z4	z5	z6	z7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

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factors, and the number '1' and '2' are the 2 levels of the factors. $L_8(2^7)$ is choosing 8 orthogonal experiments from 2^7 screen experiments.

B. Arrangement of Experiments

Seven factors are arranged orthogonally in the experiments. They are slope angle of coil segments, sweep angle of coil segments, coil thickness, coil height, quantities of coil segments, contact plate thickness and slot width. Every factor and its level are shown in Tab.2. Orthogonal design table $L_8(2^7)$ is chosen to arrange the experiments. Interrelationship between every two factors is not considered. If full analysis of the seven factors are done, it takes 2^7 (=128) times to compute, while it only takes 8 times to compute by orthogonal design method. If factors and their levels are more, advantage of using this method is more meaningful. For instance, it takes 4^5 (=1024) times to do screen analysis of experiments of 5 factors and 4 levels, while it only takes 16 times to compute by orthogonal design method.

C. Results of Experiments

The distribution of AMF in cup type contacts is uniform. And phase shift time at the center of intermediate plane of the gap is relatively high. So the center point of the intermediate of the gap is selected as a typical point to study axial magnetic flux density and phase shift time. Orthogonal design table $L_8(2^7)$ is chosen to arrange the experiments, and the results of computation using finite element method is shown in Tab.3. B_z is axial magnetic flux density at the center of intermediate plane of the gap. T is phase shift time between AMF and source current at the center of intermediate plane of the gap. R is conductor resistance of contacts that is the sum of resistance of the two coils and the two contact plates.

IV. ANALYSIS RESULTS

A. Analysis of Axial Magnetic Flux Density

Significant parameters and insignificant parameters that influence the magnetic field characteristics of cup type AMF contacts are divided by variance analysis of experiment results. Variance analysis of the experiment results of B_z is shown in Tab.4. Because all columns of orthogonal design table are occupied by the factors, freedom degree of error term is zero. So F value and P value can't be solved by variance analysis. As shown in Tab.4, mean squares of factors z1, z3 and z7 are small, so their effect on the results can be neglected. Variance analysis is done again uniting the factors z1, z3 and z7 into error term. The results are shown in Tab.5. As shown in Tab.5, the P values of factors z2 and z5 are smaller than 0.01. It means the possibilities that z2 and z5 have little effect on the results are smaller than 1%. So sweep angle of coil segments and quantities of coil segments are factors that have highly significant effect on axial magnetic flux density.

TABBLE 2

FACTOR LEVEL IN ORTHOGONAL EXPERIMENTS

Source	Name	Unit	Level1	Level2
z1	slope angle of coil segments	(°)	19	25
z2	sweep angle of coil segments	(°)	90	100
z3	coil thickness	mm	2	4
z4	coil height	mm	13	16
z5	quantities of coil segments	/	3	6
z6	contact plate thickness	mm	2	3
z7	slot width	mm	1	2

TABLE 3

RESULTS OF ORTHOGONAL EXPERIMENTS

Source	Bz /mT	T /ms	R /μΩ
1	9.599	0.356	15.477
2	11.218	0.313	22.996
3	10.865	0.532	9.569
4	14.026	0.451	13.840
5	10.884	0.463	11.545
6	8.779	0.488	8.296
7	12.849	0.283	20.188
8	12.013	0.245	17.167

TABLE 4

VARIANCE ANALYSIS OF B_Z

Source	DF	MS	F value	P value
z1	1	0.175	•	•
z2	1	10.749	•	•
z3	1	0.158	•	•
z4	1	0.423	•	•
z5	1	7.452	•	•
z6	1	0.988	•	•
z7	1	0.009	•	•

*DF means degree of freedom. MS means mean squares. ·means the value can not be solved by variance analysis. It is the same in all of the following tables.

TABLE 5

VARIANCE ANALYSIS OF B_Z SELECTED

Source	DF	MS	F value	P value
z2	1	10.749	94.160	0.002
z4	1	0.423	3.700	0.150
z5	1	7.452	65.280	0.004
z6	1	0.988	8.650	0.060

Regression analysis is done between axial magnetic flux density and significant factors. The regression equation is

$$B_z=13.640+0.232z2+0.643z5 \qquad (1)$$

R^2 of the regression equation is 0.912, and its P value is 0.002. So the regression equation is effective. B_z increases by increase of z2 or z5. So axial magnetic flux density can be strengthened by increase of sweep angle of coil segments and quantities of coil segments.

B. Analysis of Phase Shift Time

Variance analysis of the experiment results of T is shown in Tab.6. As shown in Tab.6, mean squares of factors z7 are small, so its effect on the results can be neglected. Variance analysis is done again uniting the factor z7 into error term. The results are shown in Tab.7. As shown in Tab.7, the P value of factor z3 is smaller than 0.05. So coil thickness is a factor that has significant effect on phase shift time.

Regression analysis is done between phase shift time and significant factor. The regression equation is

$$T=-0.115+0.092z3 \qquad (2)$$

R^2 of the regression equation is 0.866, and its P value is 0.001. So the regression equation is effective. T decreases by decrease of z3. So phase shift time can be

TABLE 6

VARIANCE ANALYSIS OF T

Source	DF	MS	F value	P value
z1	1	0.004	•	•
z2	1	0.002	•	•
z3	1	0.068	•	•
z4	1	0.002	•	•
z5	1	0.002	•	•
z6	1	0.001	•	•
z7	1	<0.001	•	•

TABLE 7

VARIANCE ANALYSIS OF T SELECTED

Source	DF	MS	F value	P value
z1	1	0.004	47.890	0.091
z2	1	0.002	19.010	0.144
z3	1	0.068	869.070	0.022
z4	1	0.002	30.030	0.115
z5	1	0.002	19.710	0.141
z6	1	0.001	16.320	0.155

decreased by decrease of coil thickness.

C. Analysis of Conductor Resistance of Contacts

Variance analysis of the experiment results of R is shown is shown in Tab.8. As shown in Tab.8, mean squares of factors z2, z6 and z7 are small, so their effect on the results can be neglected. Variance analysis is done again uniting the factors z2, z6 and z7 into error term. The results are shown in Tab.9. As shown in Tab.9, the P values of factors z3 and z5 are smaller than 0.01. So coil thickness and quantities of coil segments are factors that have highly significant effect on conductor resistance of contacts.

Regression analysis is done between conductor resistance of contacts and significant factors. The regression equation is

$$R=20.329-4.072z3+1.505z5 \qquad (3)$$

R^2 of the regression equation is 0.946, and its P value is 0.001. So the regression equation is effective. R increases with increase of z2 and decreases with decrease of z5. So conductor resistance of contacts can be decreased by increase of coil thickness or decrease of quantities of coil segments.

D. Verifications of Regression Equations

In order to verify the accuracy of the regression equations, an additional experiment is done. The additional experiment parameters are as follows: Contact diameter is 48mm and gap distance is 8mm. Slope angle of coil segments is 22°. Sweep angle of coil segments is 95°. Coil thickness is 3mm. Coil height is 14.5mm. Quantities of coil segments is 4. Contact plate thickness is 2.5mm. And slot width is 1.5mm. The additional experiment is carried out by finite element method. The result is compared with that from regression equations (1)-(3). Comparison of the results is shown in Tab.10. As can be seen from Tab.10, relative error between the results from finite element analysis and regression equations is less than 15%. So the regression equations are effective. If the order of regression equations increases, the result will be more accurate.

TABLE 8

VARIANCE ANALYSIS OF R

Source	DF	MS	F value	P value
z1	1	2.745	•	•
z2	1	0.750	•	•
z3	1	132.666	•	•
z4	1	3.809	•	•
z5	1	40.771	•	•
z6	1	1.140	•	•
z7	1	1.510	•	•

TABLE 9

VARIANCE ANALYSIS OF R

Source	DF	MS	F value	P value
z1	1	2.745	2.420	0.218
z3	1	132.666	117.030	0.002
z4	1	3.809	3.360	0.164
z5	1	40.771	35.970	0.009

TABLE 10

COMPARISON OF RESULTS FROM FINITE ELEMENT ANALYSIS AND REGRESSION EQUATIONS

AMF Characteristics	Finite Element Analysis	Regression Analysis	Relative Error
Bz /mT	11.396	10.957	3.85%
T /ms	0.365	0.391	7.12%
R / μ Ω	12.503	14.132	13.03%

V. CONCLUSSION

With contact diameter is 48mm and gap distance is 8mm, seven contact parameters are analyzed by orthogonal design method. It is conclusion that

(1) Sweep angle of coil segments and quantities of coil segments are factors that have highly significant effect on axial magnetic flux density. Coil thickness is a factor that has significant effect on phase shift time. Coil thickness and quantities of coil segments are factors that have highly significant effect on conductor resistance of contacts.

(2) Regression equations for the relationship between magnetic field characteristics of vacuum interrupter with cup type AMF contacts and significant parameters are given. It is more convenient to compute magnetic field characteristics before designing new cup-type contacts.

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