92 *Journal of Electrical Engineering & Technology, Vol. 1, No. 1, pp. 92~97, 2006*

Optimal Design of a Permanent Magnetic Actuator for Vacuum Circuit Breaker using FEM

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Abstract - This paper presents the characteristic analysis and the optimal design of a permanent magnetic actuator (PMA) for a vacuum circuit breaker (VCB) using a two-dimensional finite element analysis. The purpose of this research about a PMA is to minimize the breaking time and the volume of the permanent magnet within the limits of the holding force and maximum current in the coil. The conjugate gradient method is used as an optimization algorithm. The node moving technique is iteratively implemented until the design variables of the PMA are optimized. In this paper, the optimal design of a PMA is accomplished to improve the conventional design methods.

Keywords: Actuator, Finite element analysis, Optimal design, Vacuum circuit breaker

1. Introduction

The purpose of a vacuum circuit breaker (VCB) is to protect electric power systems from various fault currents. A VCB has the advantages of long life, small size, low noise and superior isolation. The traditional mechanism of a VCB needs periodic repairs and replacement of parts, due to its great number of components such as springs and gears [1-2]. The mechanical operation parts required to control the function of a purely mechanical operating mechanism remain a disadvantage. However, a permanent magnetic actuator (PMA) for a VCB has the remarkable merits of fewer components, higher reliability, being maintenance free and more controllable electrical parameters [3-4]. The important operational characteristics of a PMA for a VCB are the holding force, maximum current and breaking time. As such, some papers have discussed the dynamic characteristic analysis of a PMA using a finite element analysis (FEA) [5] and the parameters selection for the optimal design using a magnetic circuit analysis (MCA) [6]. However, the optimal design using a MCA cannot provide solutions for field distributions occurring in the complex geometry of a PMA.

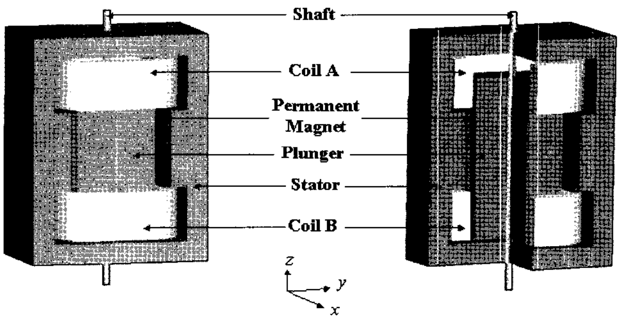
This paper presents the optimal design of a PMA for a VCB using the developed two-dimensional finite element analysis. The validity of the developed software was verified through comparison of the commercial software and the experimental results. The developed software applies to optimization of a PMA. The optimal design minimizes the breaking time and the volume of the permanent magnet of a PMA within limits of the holding force and maximum current in the coil. The conjugate gradient method is used for the optimization algorithm and the node moving technique is iteratively implemented until a PMA is optimized.

2. Characteristic Analysis

To verify the validity of the developed software applicable to the optimal design, the results of its characteristic analysis were compared with analysis results of the commercial software and the experimental results.

2.1 Analysis Model

The analysis model of this paper is the moving core type with a pair of permanent magnets and exciting coils, as illustrated in Fig. 1. The stator consists of laminated cores and the plunger. The plunger is made of a solid core in



(a) Exterior view (b) Cut-away view

Fig. 1 The view of a permanent magnetic actuator

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Received 23 August 2005 ; Accepted 21 November, 2005

order to enhance the mechanical strength. The motion of the plunger is controlled by the alternate excitation of coil A and coil B. If the current flows through coil A, the plunger is attracted upward (Y- direction) by the excited magnetic flux. When there is no excitation of the coils, the position of the plunger is strictly held by the holding force of the permanent magnet. Table 1 indicates the specifications of a permanent magnetic actuator.

Table 1 Specifications of the basic model

Specifications		
Input Voltage		125 [V]
Residual Flux Density of Permanent Magnet		1.25 [T]
Material of the Core		s23
Coil	Turn	240 [turn]
	Diameter	1.8 [mm]
	Resistance	0.733 [ohm]
Plunger	Length	139 [mm]
	Width	50 [mm]
	Moving Distance	20 [mm]

2.2 Finite Element Analysis

Fig. 2 shows the flowchart for characteristic analysis of a permanent magnetic actuator using the finite element analysis. The flux density and current are calculated by the system equation that is composed by the government equation and the external circuit equation. The thrust and velocity of the plunger are calculated by the Maxwell stress tensor and motion equation, respectively. The translating motion technique is applied to the consideration of the movement of the plunger [7-8]. This technique can use the initial boundary condition and consider movement of the plunger because the total number of nodes is not changed.

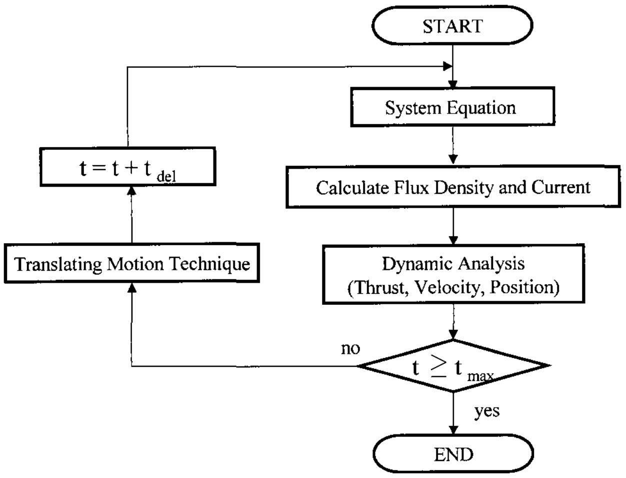
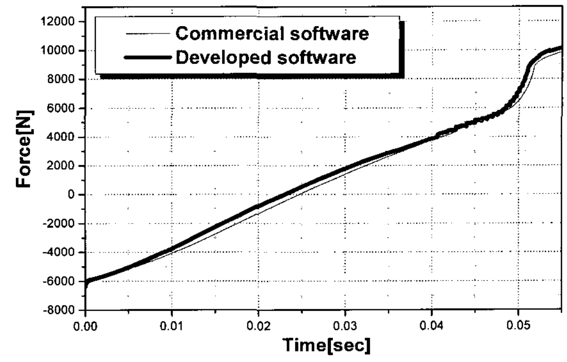
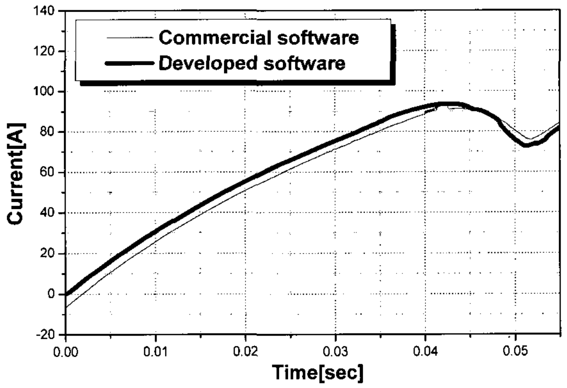


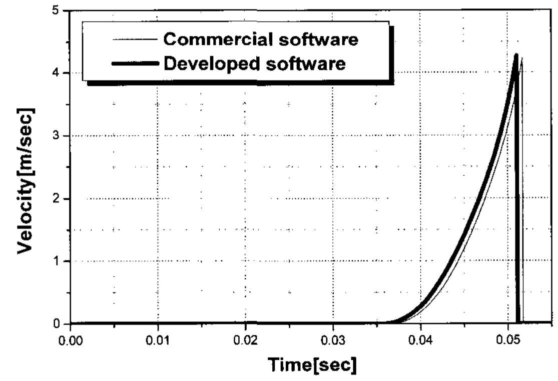
Fig. 2 Analysis flowchart using FEA



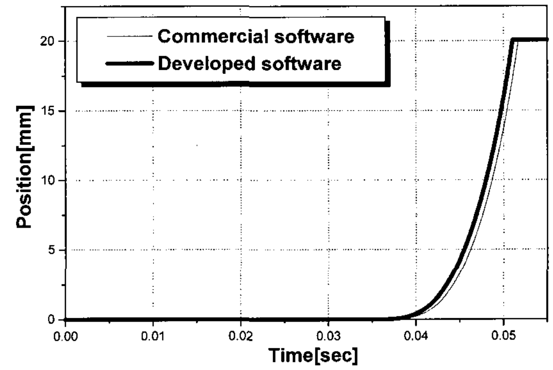
(a) Force



(b) Current



(c) Velocity



(d) Position

Fig. 3 Comparison of characteristics analysis using commercial and developed software

Fig. 3(a) shows the force characteristic of the PMA. At the initial time, the force of the plunger has negative value because of the holding force of the permanent magnet. Fig. 3(b) shows the current characteristic of the excited coil. The maximum current of the coil is about 90[A]. The difference in the current characteristic may be caused by inadequate convergence of nonlinear iterations. Fig. 3(c) indicates the velocity characteristic and the maximum velocity of the plunger reaches to 4.3[m/sec]. Fig. 3(d) shows the position characteristics and the moving distance of the plunger is 20[mm]. The results of the developed software are similar to those of the commercial software through comparison of the results.

2.3 Experiment

The experiment of a PMA is also performed to approve the validity of the developed software. Fig. 4 shows the manufactured model and the experimental set-up of a PMA. The holding force of the experimental result is 5900[N] and that of the developed software result is 6100[N]. The result of the experiment is quite similar to that of the developed software. The slight difference between these results may be due to mechanical manufacturing, assembling and experimental error. The developed software, through comparison of its results with developed software and experimental results, is applied to optimization of a PMA.

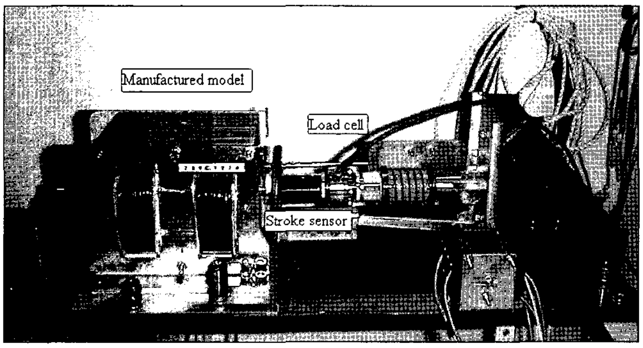


Fig. 4 Manufactured model and experimental set-up

3. Optimal Design

Fig. 5 shows the optimal design process of a PMA. The objective function, design variables and linear constraints are set to improve performance of the PMA.

First of all, the objective function is established for the optimal design. The optimal algorithm is the conjugated gradient method. The important operation characteristics of a PMA for a vacuum circuit breaker are holding force, maximum current and breaking time. The objective function is to minimize the breaking time and the volume of the permanent magnet within the limits of the holding force and maximum current in the coil, as shown in equation (1). The limits of the holding force and maximum current in the coil are established as 5500[N] and 100[A], respectively.

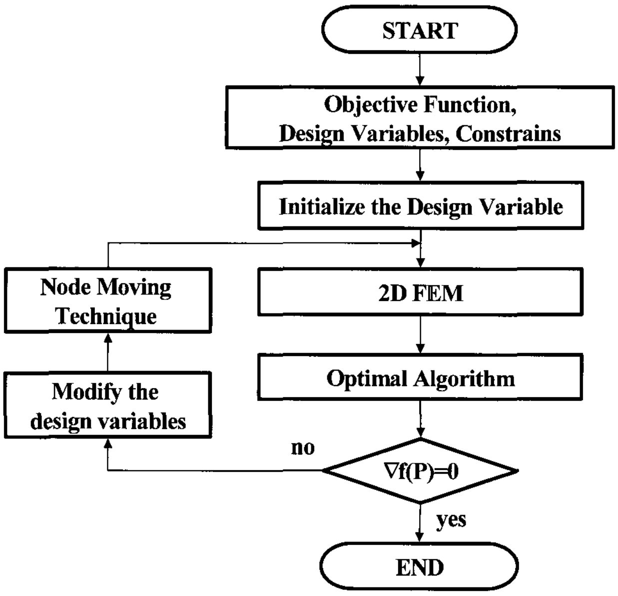


Fig. 5 Optimal design process

$$f(p) = breaking\ \ time + C_1 + C_2 + C_3 \qquad (1)$$

Where,

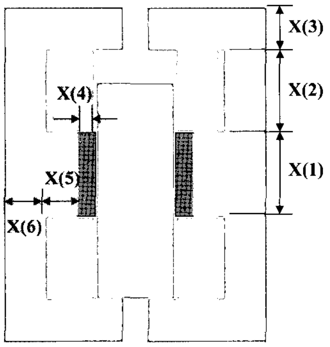
$$C_1 = \begin{cases} 0.1 & holding\ \ force \le 5500[N] \\ 0 & holding\ \ force > 5500[N] \end{cases}$$

$$C_2 = \begin{cases} 0.1 & maximum\ \ current > 100[A] \\ 0 & maximum\ \ current \le 100[A] \end{cases}$$

$$C_3 = \quad Volume\ of\ the\ permanent\ magnet$$

In equation (1), the value of the breaking time is less than 0.070[sec] because the breaking time of a PMA is less than 70[msec]. The value of C_1 and C_2 is 0.1, respectively, when the holding force and the maximum current are out of the established limits. Because the optimal algorithm is the conjugated gradient method in which it performs search for the value of design variables to minimize the objective function, the value of an over-ranged design variable is not that of the optimal design variable. The range of variation of the permanent magnet volume is less than 5×10^{-4} [mm^3] as minimum range of the breaking time. As a result, the volume of the permanent magnet affects the objective function when the breaking time is equal.

The design variables of a PMA for the optimization are as indicated in Fig. 6. The node moving technique is used for change of shape with variation of design variables. Also, the optimal design is accomplished by consideration of a leakage inductance and resistance of the coil.



Design variables	
X(1)	Length of the permanent magnet
X(2)	Length of the slot
X(3)	Outer length of the yoke
X(4)	Width of the permanent magnet
X(5)	Inner width of the yoke
X(6)	Outer width of the yoke

Fig. 6 Design variables of a PMA

The basic model for the optimal design is the model of 2D-FEA, as shown in Fig. 1. The constraints of design variables are limited by considering the size of a system, as presented in TABLE II. The linear constraints are shown in equation (2) and (3).

Table 2 Constraints of design variables

Design Variables		Maximum Value [mm]	Minimum Value [mm]
X(1)	Length of the permanent magnet	50	56
X(2)	Length of the slot	52.75	55.75
X(3)	Outer length of the yoke	24	29
X(4)	Width of the permanent magnet	7	15
X(5)	Inner width of the yoke	17.25	25.25
X(6)	Outer width of the yoke	24	29

$$X(1)+2X(2)+2X(3)\le 225[mm] \qquad (2)$$

$$2(X(4)+X(5)+X(6))+52\le 190[mm] \qquad (3)$$

4. Design Results

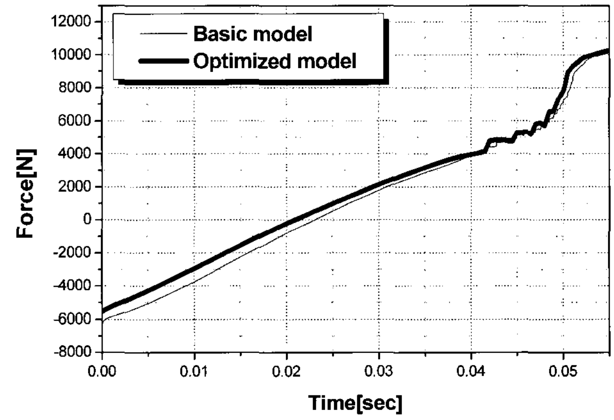
The optimal result of the design variables is satisfied with the objective function that minimizes the breaking time and the volume of the permanent magnet within the limits of the holding force and maximum current. The design variables of the basic model and the optimal model are shown in TABLE III. The optimized volume of the permanent magnet decreased 23.6[%] compared to that of the basic model. Table IV shows the specification of the optimized PMA. The diameter of the coil is determined by the optimized dimension of the slot.

Table 3 Optimal solution of the design variables

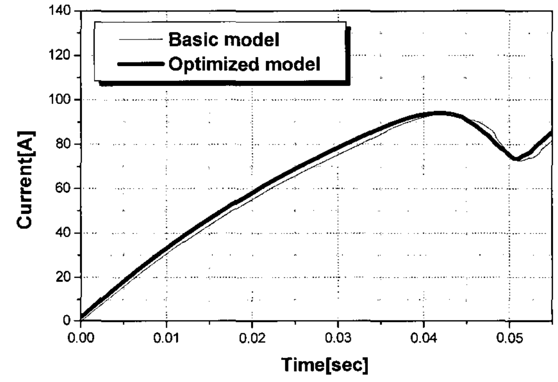
Design variables		Basic model [mm]	Optimal model [mm]
X(1)	Length of the permanent magnet	54	52.734
X(2)	Length of the slot	53.75	54.383
X(3)	Outer length of the yoke	27.25	26.5
X(4)	Width of the permanent magnet	11	8.594
X(5)	Inner width of the yoke	21.25	23.656
X(6)	Outer width of the yoke	27	26.5

Table 4 Specification of the optimized PMA

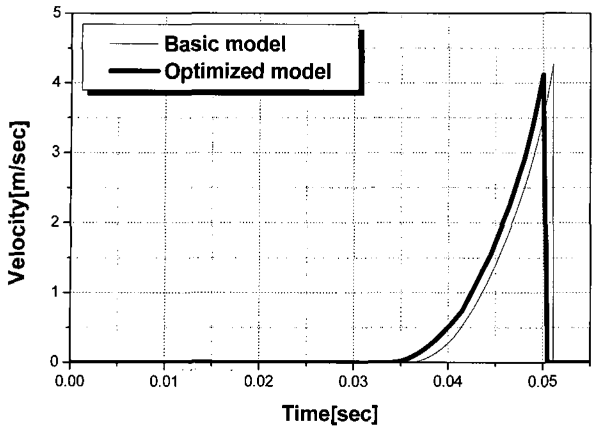
Specifications		
Coil	Turn	240 [turn]
	Diameter	1.8 [mm]
	Resistance	0.733 [ohm]
Permanent Magnet	Class	NdFeB
	Residual Flux density	1.25 [mm]
	Dimension	52×9.017×125 [mm]



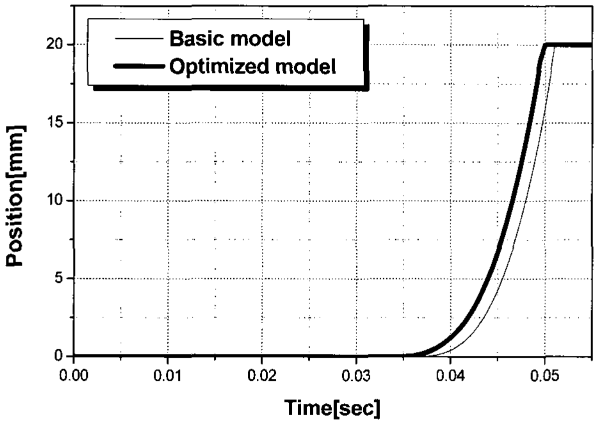
(a) Force



(b) Current



(c) Velocity



(d) Position

Fig. 7 Comparison of characteristics analysis of basic and optimized model

Fig. 7 shows comparison results of the dynamic analysis of the basic model and optimized model. Although the holding force of the optimized model is less than that of the basic model as shown Fig. 7(a), it is a proper result because the holding force is within the limit of the objective function. The maximum current of the optimized model is 92.32[A], which satisfied the current limit of the objective function, as shown in Fig. 7(b). The maximum velocity of the optimized model is 4.09[m/sec] as illustrated Fig. 7(c). The breaking time of the optimized model is 50[msec], which is less than that of the basic model, as depicted in Fig. 7(d). Consequently, the reduction of the breaking time through the optimal design is 1.05[msec].

5. Conclusion

This paper presents the optimal design of a PMA for VCB using the developed two-dimensional FEA. To verify the developed software, its results were compared with those of commercial software and experiment. The compared results are in agreement with each other. The developed software is applied to optimization of a PMA.

The optimized result of a PMA for the minimization of the breaking time, 50[msec] compared to 51.05[msec], which is the basic model, is achieved within the limits of the holding force and maximum current in the coil. The volume of the permanent magnet is also reduced by 23.6[%]. Therefore, the results of the optimized model show superior characteristics compared to those of the basic model and the proposed design technique can easily satisfy the important characteristics of a PMA.

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Acknowledgements

The author gratefully acknowledges the Vitzrotech Co. for the support in conducting the experiments.

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