Permanent Magnet Overhang Effect in Permanent Magnetic Actuator Using 3 Dimension Equivalent Magnetic Circuit network Method

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Abstract – This paper presents an analysis of the permanent magnet overhang effect for the permanent magnetic actuator. Generally, the overhang is often used to increase the force density in permanent magnet machineries. The overhang is particularly profitable in reducing the volume after increasing the force density per volume when using the overhang effect of the permanent magnet. Therefore, the 3D Equivalent Magnetic Circuit Network Method (3D EMCN) has been used in this paper. According to the plunger position, the flux distribution per overhang length and the holding force are quantitatively compared. Furthermore, an appropriate length of the overhang has been proposed. To confirm the accuracy of the analysis method, the results of 2D FEM and 3D FEM are compared for the basic model.

Keywords: Demagnetization, Equivalent Magnetic Circuit Network Method (EMCNM), Nonlinear Analysis, Permanent Magnetic Actuator (PM Actuator)

1. Introduction

In 1987, Manchester University Energy Systems Group developed a new type of Permanent Magnetic (PM type) Actuator for a leading switchgear manufacturer [1]. This new type of actuator requires fewer parts and has a simpler structure compared with the conventional type of spring charge actuator. In addition, it can enhance the credibility and durability of operations because it uses coil energy when operating but uses coercive force when not performing service. More cases are increasingly being reported where this new type of actuator is being used as a Vacuum Circuit Breaker (VCB) based on these advantages. Under conditions requiring rapid movement, the fact that the stroke was limited to several millimeters created severe problems [4]. However, due to a great amount of research and study from 1990 onward, it was finally made possible to generate rapid movement under the long stroke condition.

The holding force between points of contact is determined according to the capacity of the breaker because proper pressure between the two points is essential This means that the volume of the actuator will be increased if the capacity of the breaker rises. As such, an increase in the actuator volume is inevitable. However, because the volume can be decreased after increasing the force density per volume when using the permanent magnet (PM) overhang effect, overhang is more helpful.

In general, it is common to perform overhang in order to raise the force density per volume in PM devices, and the research results concerning the quantitative characteristics in linear machines and rotary machines have been revealed [2, 3] Yet, there are few papers for reference that demonstrate quantitatively what the overhang effect is in the PM actuator. Therefore, the precise analysis and investigation performed by this research are necessary. 3D analysis is unavoidable because the increase of the effective flux cannot be suitably considered in 2D analysis. Hence, this paper shows the 3Dimension Equivalent magnetic circuit network method (3D EMCNM) to analyze the overhang structure of the PM actuator. According to the plunger position, the flux distribution per length of the overhang and the holding force are quantitatively compared. Furthermore, an appropriate length for the overhang is proposed.

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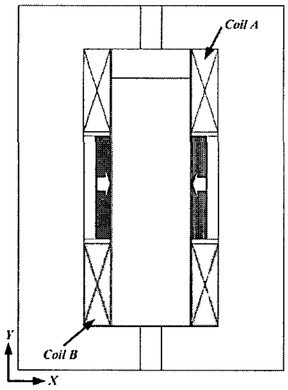
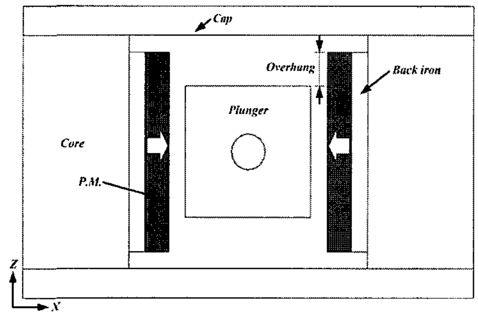
2. Method of Analysis

2.1 Analysis Model

The analysis model in this paper is the moving core type in Fig. 1 that looks like the general PM actuator of rectangular parallel type with an internal plunger moving up and down. It also has two caps in the z-axis direction to protect the permanent magnet and inner parts from mechanical shock, dust and other particles.



(a) x-y plane



(b) x-z plane

Fig. 1 Cut end of permanent magnetic actuator

Moreover, it has a very simple structure, consisting of only 7 parts. In particular, the room for the winding area toward the z-axis direction can be symmetrically used to perform the overhang of the permanent magnet.

A motion of the plunger is controlled by switching the excitation coils ON and OFF. If the current flow across coil A and its electromagnetic force are larger than the permanent magnetic one, the plunger is attracted upwards by the excited magnetic flux. When the switch is off, the plunger is held at its moved position by the permanent magnet.

The material of the permanent magnet in the actuator is Alnico9. Alnico9 has the highest residual flux density among other magnets and it also has a wide operating temperature region because the demagnetization effect at the high temperature is lower than other properties [6].

The PM actuator for the VCB generates a high temperature increase because of the arc at points of contact and ohmic loss by coils when breaking the contact, so Alnico9 is the most suitable property for this case. However, because Alnico9 has low coercive force and this

Table 1 Specifications of permanent magnetic actuator

Section	Item	Value [Unit]
Coil	Number of Turn Input Volt	1500 [turn] DC 200 [V]
Stator	Material	S23
Plunger	Material Saturation flux Density Width / Depth Length Stroke	S23 2.5 [T] 77 / 77 [mm] 232 [mm] 20 [mm]
Permanent Magnet	Material Width Thickness Length Residual flux density Force in plunger by PM	Alnico9 77 [mm] 15 [mm] 99 [mm] 1.05 [T] 3450 [N]

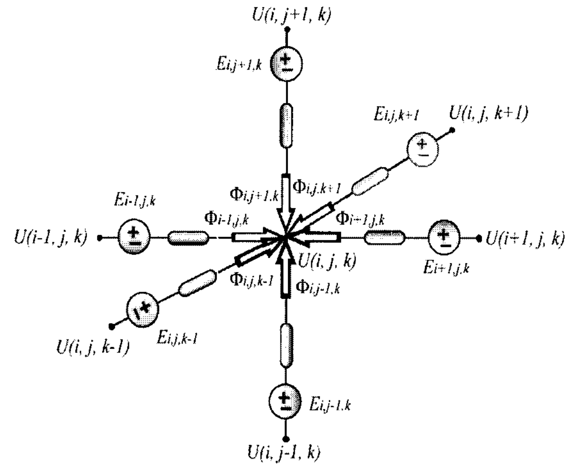


Fig. 2 Connectional map of 3D equivalent magnetic circuit

causes demagnetization by small air gaps and the coil MMF, special attention must be paid to Alnico9 when designing the magnet. In other words, to protect demagnetization from the coil MMF in the permanent magnet, the magnetized direction must be equal to the magnetic flux direction from the coil MMF. Table 1 shows the design specifications of the PM actuator.

2.2 3D EMCN Method

The 3D EMCN method is a numerical analysis method that supplements the magnetic equivalent circuit with a numerical technique. In the 3D EMCN method, the analysis model is divided into elementary volumes (elements) of fan or hexahedral form, which are decided by model shape. But the PM actuator has a rectangular shape, so the use of hexahedron elements is good for analyzing. Fig. 2 depicts the equivalent magnetic circuit network.

The field variable at each centroid, known as the magnetic scalar potential (MSP), is determined by the permeance and the magneto-motive force (MMF) involved with the adjacent centroids. The magnetic flux and magnetic flux density between the nodes (i, j, k) and (i, j-1, k) are calculated as follows:

$$\Phi_{yi,j-1,k}=P_{yi,j-1,k}\left(U_{i,j-1,k}-U_{i,j,k}+E_{i,j-1,k}\right) \tag{1}$$

$$B_{yi,j-1,k}=\Phi_{yi,j-1,k}/S_{yi,j-1,k} \tag{2}$$

where $P_{y_{i,j-1,k}}$ is permeance, $U_{i,j,k}$ is unknown MSP of node *(i, j, k)*, $E_{i,j-1,k}$ is the MMF of permanent magnet or winding between two nodes *(i, j, k)* and *(i, j-1, k)*, and $S_{y_{i,j-1,k}}$ are the cross sections of the element. The magnetic flux continuity condition in which the inflow and the outflow of the flux at a node are equal can be expressed as follows:

$$\sum_{n=1}^{6}\Phi_n=\Phi_{xi-1,j,k}+\Phi_{xi+1,j,k}+\Phi_{yi-1,j,k}+\Phi_{yi-1,j,k}$$
$$+\Phi_{zi-1,j,k}+\Phi_{zi-1,j,k}=0 \tag{3}$$

For all nodes, the system matrix is obtained by using (1) and (3) as follows:

$$[\mathbf{P}]\{\mathbf{U}\}=\{\mathbf{F}\} \tag{4}$$

where [P] is the permeance coefficient matrix, {U} is the matrix of node MSP, and {F} is the forcing matrix (Permeance × MMF of core winding or PM).

Each side of the flux densities in all of the elements are calculated by (2) and the forces are calculated by utilizing Maxwell's stress tensor.

2.3 Nonlinear Analysis with PM Demagnetization

The operating point is determined by the exterior permeance and temperature under the steady state operating. It is common for a magnetization curve to assume that it is linear and analyze it. Alnico9 has a higher residual flux density and is not easily affected by heat, but the coercive force is much lower than other PMs such as Ferrite and NdFeB. This signifies higher degree of demagnetization by air gap. Nonlinear analysis with the use of the demagnetization curve is essential to finding the exact operating point. Therefore, this paper shows the 3D EMCN analysis with regard to the nonlinear magnetic material and demagnetization curve such as in Fig. 3. To confirm the accuracy of the results for the 3D EMCN, the holding forces for a model, which has no overhang with the cap, are compared through 2D FEM and 3D FEM according to the plunger position.

2.4 A Variation of the Overhang in PM According to the Holding Force Analysis

The PM actuator has a structure in which the overhang is towards the z-axis direction and is symmetrical. The caps limit the maximum overhang length for the basic model, so the maximum length is about 65% of the z-axis plunger length. The z-axis caps are necessary to protect the actuator from mechanical shock, dust, and other particles. However, there must be some effect such as a magnetic characteristic when the actuator has the caps or doesn't have them. For the quantitative analysis between a model with the caps and a model without the caps, two-overhang simulations have been performed separately. Fig. 4 shows a mesh shape of the analysis model in which the member of the element and node are 77,880, 83700.

3. Analysis Result and Discussion

To confirm the accuracy of the analysis results using the 3D EMCN, the analysis results for a model without performing the overhang are compared with that using 2D FEM and 3D FEM separately. Fig. 5 presents the holding force using three methods according to the plunger. The analysis error between 3D EMCN and 3D FEM is within 2%, so the results are reasonably confirmed because the analysis error for the FEM is less than 5%. When performing the 2D and 3D analyses, the difference of the holding force is 32% as the stroke is 0mm. This explains that the effective flux saturation by the shaft boring though the plunger and leakage flux increase by the caps in the direction of the z-axis influences the air gap flux distribution at the bottom part. Therefore, 3D analysis is required even if the overhang in the model is not considered.

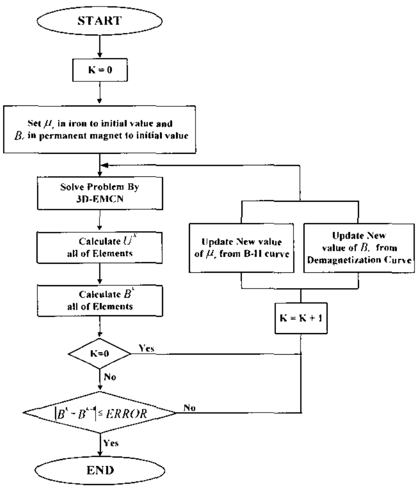


Fig. 3 Flow chart of nonlinear analysis with demagnetization.

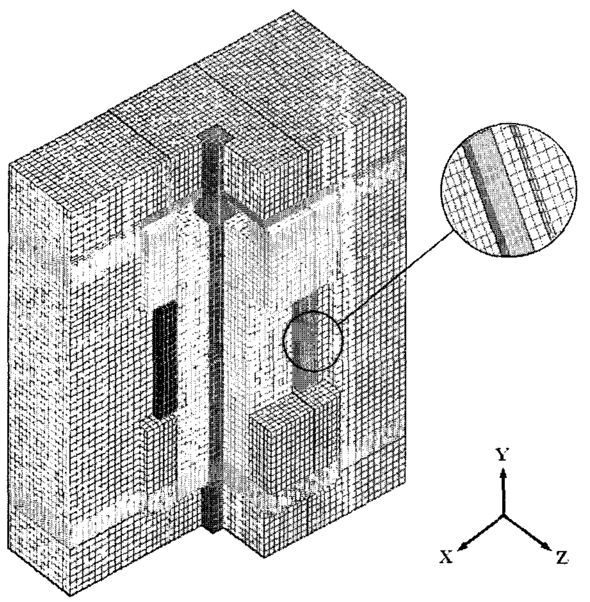


Fig. 4 Mesh shape of the PM actuator

Fig. 6 indicates the holding force of the plunger according to the overhang increase in the two models. Both of them show the holding force increase according to the effective flux increase in the air gap at the bottom part when performing the overhang. Once the overhang increases over 18%, the holding force stops increasing because of the effective flux saturation. In the model that has the caps in the direction of the z-axis, the holding force starts to decrease instead when the effective flux is saturated. This is because the amount of the leakage flux rapidly rises after a new path in the direction of the z-axis is built with the overhang increase. Figs. 7 and 8 show the leakage flux distribution towards the caps while the overhang rises. Therefore, 18% of the overhang length for this analysis model is suited, and the holding force by the overhang has gone up by about 5.5% in the model with the caps. In the model with no caps, the increase is 4.4%. Though the escalating rate of the holding force according to the overhang length in the model that does not have the caps is low, the model that does not have the caps is 7% larger than the other.

4. Conclusion

This paper shows 3D EMCN Analysis considering the PM Demagnetization Curve to analyze the influence in the PM actuator with a PM overhang condition. Furthermore, the influence of the caps in the direction of the z-axis has been analyzed. Particularly, the holding force of 8% is increased after getting rid of the caps in the direction of the z-axis. When the overhang rate, which is the value before the saturation, is 18%, the holding force increased approximately 13% compared with the model that has the caps and no overhang. Therefore, to increase holding force in the PM actuator, it is useful to dispose of the caps in the direction of the z-axis and perform the overhang if mechanical shock, dust, and other particles do not influence the mechanical performance. Therefore, removing the cap and performing the overhang increases the force density per volume and these are the most useful factors to reducing the volume of the PM actuator.

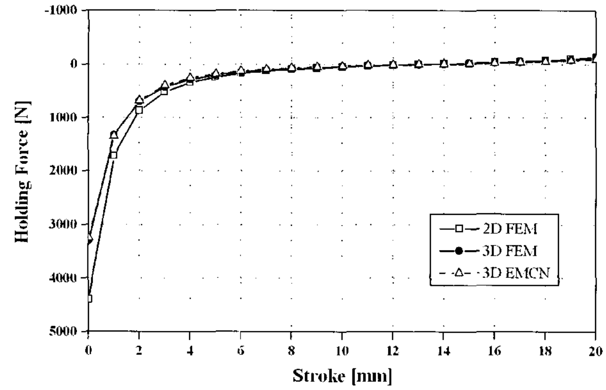


Fig. 5 Holding force at stroke

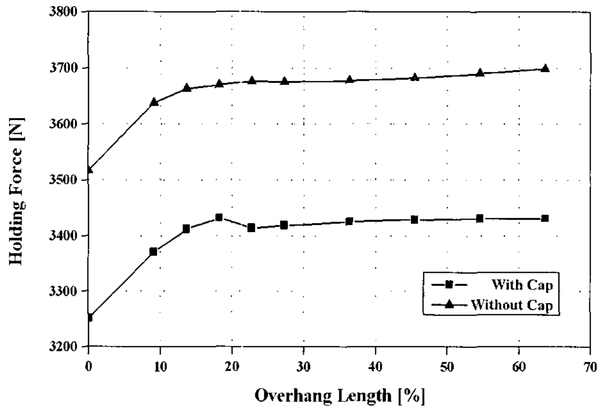


Fig. 6 Holding force according to length of overhang

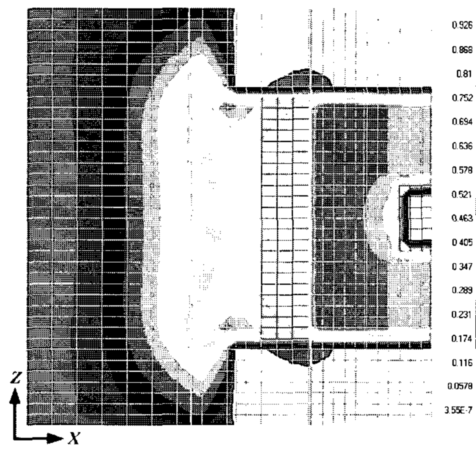


Fig. 7 Flux density distribution at overhang 0%

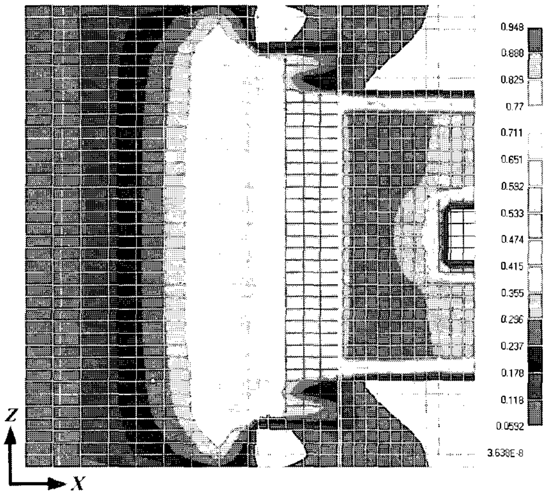


Fig. 8 Flux density distribution at overhang 36%

Acknowledgements

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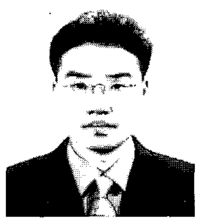

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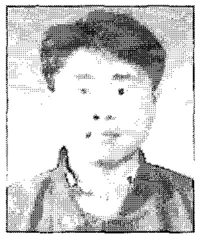

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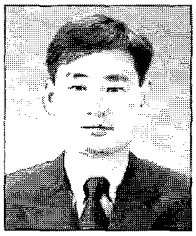

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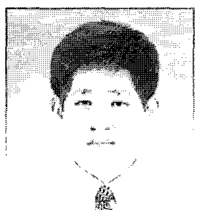

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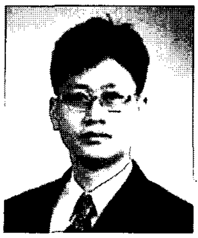

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